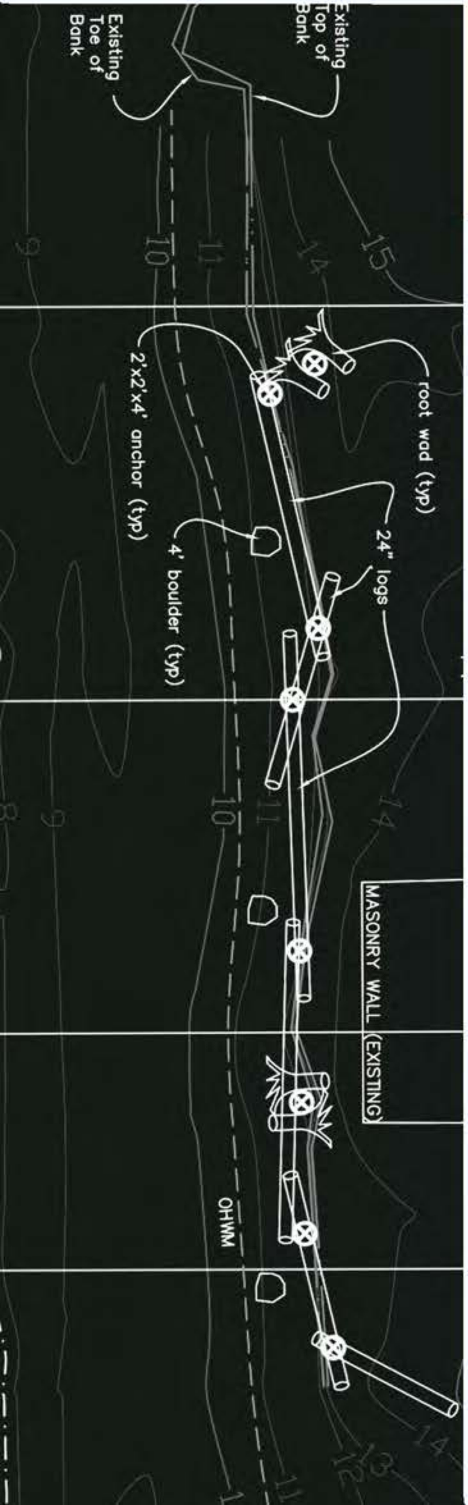
Washington State Aquatic Habitat Guidelines Program

Marine Shoreline Design Guidelines

MSDG



Marine Shoreline Design Guidelines

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Peter Goldmark - Commissioner of Public Lands

Puget Sound Partnership
our sound, our community, our chance

Washington State Department of Transportation

Washington State Recreation and Conservation Office

Prepared by:

CGS
Coastal Geologic Services

With

QWG
Applied Geology

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Johannessen, J.[1], A. MacLennan[1], A. Blue[1], J. Waggoner[1], S. Williams[1], W. Gerstel[2], R. Barnard[3], R. Carman[3], and H. Shipman[4], 2014. Marine Shoreline Design Guidelines. Washington Department of Fish and Wildlife, Olympia, Washington.

[1]Coastal Geologic Services Inc.

[2]Qwg Applied Geology

[3]Washington State Department of Fish and Wildlife

[4]Washington State Department of Ecology

Technical Editing

Michelle Redmond, MS, ELS of Scientific Notations LLC
Tracie Johannessen, MEd, EE Outcomes
Branden Rishel, CGS: Editing, graphic design
Theresa Mitchell, WDFW

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These guidelines are dedicated to Dr. Maurice Schwartz, Professor Emeritus and retired Dean of the Graduate School at Western Washington University Geology Department, who recently passed away. Maury dedicated his career to advancing our understanding and informed management of beaches of the Puget Sound region and in many other countries. Maury and his many graduate students mapped net shore-drift cells throughout Puget Sound, quantified drift rates, mapped and studied beach features, providing much of the technical foundation for shoreline management efforts. This document is also dedicated to Wolf Bauer, now 101 years old, who basically invented the field of soft shore protection in Puget Sound and Lower British Columbia. Wolf worked as a tireless proponent of understanding Puget Sound region coastal processes and working for conservation and restoration of beach and marshes, along with scores of beach creation and enhancement projects. Wolf heartily applied his hard earned knowledge gained from spending thousands of hours walking and kayaking our shores.

Reviewers

Lalena Amiotte, Washington Department of Natural Resources
Paul Bakke, U.S. Fish and Wildlife
Kathlene Barnhart, Kitsap County
Margie Bigelow, Washington State Department of Fish and Wildlife
Kay Caromile, Recreation and Conservation Office
Jose Carrasquero, Herrera Environmental
Megan Dethier, University of Washington
Nicole Faghin, Washington Sea Grant
Hugo Flores, Washington Department of Natural Resources
Margaret Glowacki, City of Seattle
Todd Hass, Puget Sound Partnership
Kollin Higgins, King County Department of Natural Resources and Parks
Garrett Jackson, Washington State Department of Transportation
Kathy Ketteridge, Anchor QEA
Betsy Lyons, Washington State Department of Fish and Wildlife
Allison O'Sullivan, Suquamish Tribe
Jim Park, Washington State Department of Transportation
Paul Schlenger, Confluence Environmental
Charles "Si" Simenstad, University of Washington
Doug Thompson, Washington State Department of Fish and Wildlife
Karen Walker, Muckleshoot Indian Tribe Fisheries Division
Jim Weber, Northwest Indian Fisheries Commission

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The Aquatic Habitat Guidelines Program

The Marine Shoreline Design Guidelines is one of a series of guidance documents being developed by the Aquatic Habitat Guidelines (AHG) Program. AHG is a joint effort among state resource management agencies in Washington, including the Washington Departments of Fish and Wildlife, Ecology, Transportation, and Natural Resources; the Recreation and Conservation Office, and the Puget Sound Partnership.

The AHG program was initiated in 1999 in support of salmon recovery efforts to ensure aquatic and floodplain restoration planning and design efforts were strategic, effective and the best use of limited resources. The scope of the program has since broadened to:

> ***The promotion, protection, and restoration of fully functioning marine, freshwater, and riparian ecosystems through comprehensive and effective management of activities affecting Washington's aquatic and riparian ecosystems .***

Guidelines developed in the AHG program employ an integrated approach to marine, freshwater, and riparian habitat protection and restoration. That is, they seek to protect and restore the structure and function of whole ecosystems by striving to consider projects in their landscape and watershed contexts. Development of guidance documents and underlying scientific surveys has involved broad participation from academic, public, and private sector practitioners, planners, and regulators.

The following other AHG products are available for download at

http://wdfw.wa.gov/conservation/habitat/planning/ahg/

Guidance Documents:

- Water Crossing Design Guidelines (2013)
- Stream Habitat Restoration Guidelines (revised 2012)
- Protecting Nearshore Habitat and Functions in Puget Sound (2010)
- Landuse Planning for Salmon, Steelhead and Trout: A landuse planner’s guide to salmonid habitat protection and recovery (2009)
- Integrated Streambank Protection Guidelines (2003)
- Design of Road Culverts for Fish Passage (2003)
- Fishway Guidelines for Washington State (2000)
- Fish Protection Screen Guidelines for Washington State (2000)

State of the Knowledge White Papers (literature reviews):

- Protection of Marine Riparian Functions in Puget Sound, Washington (2009)
- Marine and Estuarine Shoreline Modification Issues (2001)
- In and Over-water Structures in Marine and Freshwater Environments (2001)
- Treated Wood Issues in Marine and Freshwater Environments (2001)
- Channel Design (2001)
- Ecological Issues in Floodplain and Riparian Corridors (2001)
- Dredging and Gravel Removal in Marine and Freshwater Environments (2001)

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ACRONYMS and ABBREVIATIONS

AS	Accretion shoreform
BAB	Barrier beach
BE	Barrier estuary
BL	Barrier lagoon
BLB	Bluff backed beach
BMP(s)	Best management practice(s)
BN	Beach nourishment
BR	Bulkhead removal
CAO	Critical Areas Ordinance
CEM	Coastal Engineering Manual
CGS	Coastal Geologic Services
CLM	Closed lagoon/salt marsh
DEM	Digital elevation model
DOE	Washington Department of Ecology
ESA	Endangered Species Act
FB	Feeder bluff
FBE	Feeder bluff exceptional
GIS	Geographic information systems
HOWL	Highest observed water level
LiDAR	Light detection and ranging
LW	Large wood
LWD	Large woody debris
MHHW	Mean higher high water
MHW	Mean high water
MLLW	Mean lower low water
NAD	No appreciable drift
OCI	Open coastal inlet
OHWM	Ordinary high water mark
PB	Pocket beach
PL	Plunging rocky shore
PSNERP	Puget Sound Nearshore Ecosystem Restoration Project
RE	Re-slope and revegetation
RSLR	Relative sea level rise
RP	Rocky platform
RV	Rock revetment

SLR	Sea level rise
SMP	Shoreline Master Program
SPM	Shore Protection Manual
SPU	Shoreline process unit
SWD	Still water depth
SWL	Still water level
TAG	Technical advisory group
TZ	Transport zone
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
VB	Vertical bulkhead
WDFW	Washington Department of Fish and Wildlife
WDNR	Washington Department of Natural Resources (also noted as DNR)
WDOE	Washington Department of Ecology
WRIA	Water Resource Inventory Area
WSDOT	Washington State Department of Transportation
USFWS	United States Fish and Wildlife Service

GLOSSARY

Accretion: The gradual addition of sediment to a beach or to marsh surface as a result of deposition by flowing water or air. Accretion leads to increases in the elevation of a marsh surface, the seaward building of the coastline, or an increase in the elevation of a beach profile (the opposite of erosion) (Shipman 2008).

Accretion shoreform (AS): Sediment sinks or depositional shores. Areas of the marine shoreline where sediment is deposited either currently or has done so in the past.

Adjacent shores: The adjacent shores are generally considered the immediate vicinity of the project site itself from the project boundary to approximately 100-200 ft alongshore to either side. The length of adjacent shore should extend beyond the area of apparent impacts from the project.

Advance outwash: Stratified detritus (chiefly sand and gravel) removed or "washed out" from a glacier by meltwater streams and deposited in front of or beyond the end moraine or the margin of an active glacier. The coarser material usually is deposited nearer to the ice.

Aeolian: Wind driven process.

Anchored: Characteristic describing large wood placement utilizing an artificial method of holding attachment such as chain or cable.

Angle of internal friction: A measure of the shear strength of soils due to friction.

Anthropogenic: Caused or produced by humans. In the context of this document this term can be described as filling, dredging, armoring or development actions taken in the coastal environment.

Area regraded: Total area that has been reshaped to meet a slope or grade.

Armor: Rigid, permanent design techniques used to stabilize shorelines and prevent erosion.

Assessment: Processes that involve analyzing and evaluating the state of scientific knowledge and, in interaction with users, developing information applicable to a particular set of issues or decisions.

Backfill: The materials found immediately behind or landward of a coastal structure. Typically this includes cobbles from the beach, quarry spall, or earth.

Backshore: The upper zone of a beach beyond the reach of normal waves and tides, landward of the beachface. The backshore is subject to periodic flooding by storms and extreme tides, and is often the site of dunes and back-barrier wetlands (Clancy et al. 2009). Width is measured cross-shore from the waterward extent of the backshore to the waterward extent of upland vegetation or anthropogenic modifications. Backshore areas tend to be highly modified or nonexistent on developed properties.

Bank or Bluff: A steep slope rising from the shore, generally formed by erosion and mass wasting of poorly consolidated material such as glacial or fluvial sediments. The term bluff is typically used in the Pacific Northwest for a steep sea cliff composed of unconsolidated sediment that has no to moderate amounts of vegetation. The term bank is typically used in the Northwest for lower elevation sea cliff with a well vegetated bank face. Within this document bank and bluff may be used interchangeably.

Bank face: The steep section of the bank/bluff sloping towards the beach or shore.

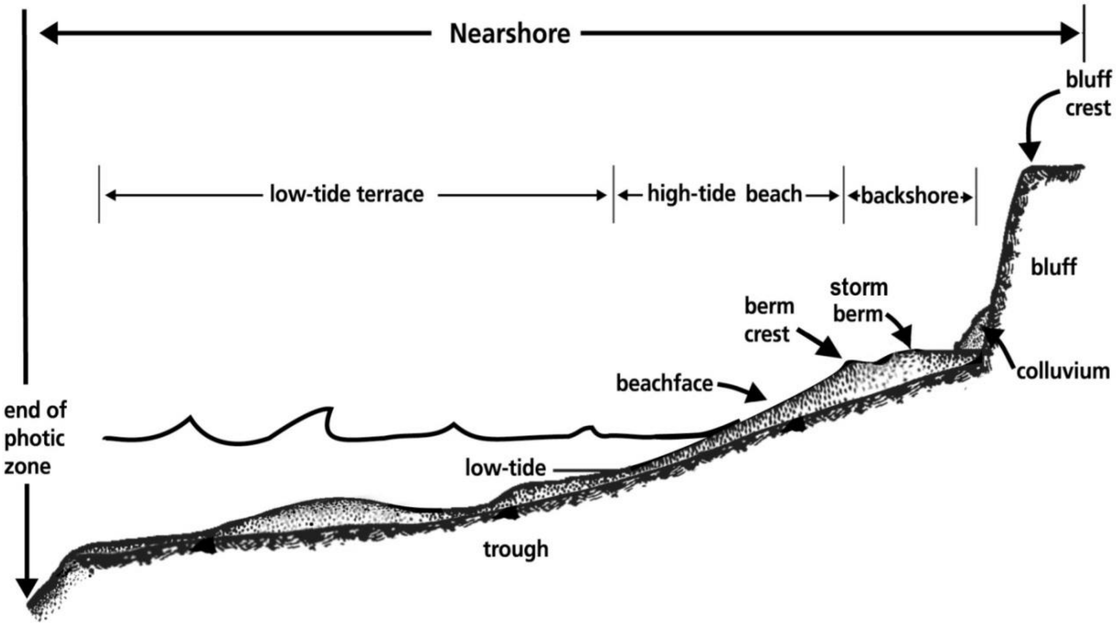
Barrier beach: A linear ridge of sand or gravel extending above high tide, built by wave action and sediment deposition seaward of the original coastline. Includes a variety of depositional coastal landforms, including spits, tombolos, cuspate forelands, and barrier islands (Shipman 2008).

Batter: A receding upward (landward) slope.

Beach: The gently-sloping zone of unconsolidated sediment along the shore that is moved by waves, wind, and tidal currents. Width is measured cross-shore from the break in slope between the upper beach and the low-tide terrace and the waterward extent of the backshore.

Beachface: The section of the beach normally exposed to the action of waves. This is typically the sloping beach between the low tide terrace and the backshore.

Beach profile: A vertical cross section of a beach perpendicular to the shoreline. Individual features on Puget Sound region beach profile are illustrated below.



Beach scarp: A steep slope produced by wave action.

Bedding: The arrangement of sediments or rock in beds or layers of varying thickness and character.

Berm: A low shelf or narrow terrace on the backshore of a beach formed of material thrown up and deposited by storm waves.

Berm crest: The waterward point of a beach berm where the sloping foreshore meets the more gently sloping backshore.

Bluff: see *bank.*

Bluff crest: The highest point of a sloping bluff or bank from which the slopes levels off as part of the uplands.

Boulder: A specific size class of gravel sediment greater than 256 mm (10.1 in) in median diameter.

Brush matting: A covering of branches spread on eroded land to conserve water and reduce erosion that also helps establish trees and other permanent vegetation, or a covering of mesh wire along streambanks that holds brush in place to slow erosion.

Bulkhead: A hard armor technique usually vertical that maintains soil and abates erosion from waves and currents using rigid material.

Cobble: A specific size class of gravel sediment 64-256 mm (2.5-10.1 in) in median diameter. Common on coarse gravel beaches in Puget Sound.

Cohesion: The force between particles within a body or substance that acts to unite them. In the context of soils, the greater the cohesion the greater the soil strength.

Colluvium: Loose heterogeneous and incoherent mass of soil and rock material deposited by surface water runoff, slow continuous creep or other erosive mechanism, usually collecting at the base of a slope.

Crenulated: An undulating or irregularly wavy stretch of shoreline.

Crest elevation: Elevation of upper vertical extent of design, usually referring to hard armor structures.

Cyclical erosion: Wearing away of the nearshore that tends to occur on a periodic basis through processes that repeat over time (e.g. transport of loose incoherent erosional deposits resulting in exposure of the bluff toe and subsequent wave-induced mass wasting)**.**

Deep-seated (instability/landslide): Sub-surface conditions that make the slope susceptible to failure/landslide associated with the area's geologic processes and features.

Delta: A deposit of sediment formed at a stream or river mouth, or other location where the slowing of water flow results in sediment deposition (Clancy et al. 2009).

Depth of beach: The vertical thickness of beach sediment veneer on the upper intertidal beach.

Depth of closure: The most landward depth waterward of which there is no significant change in bottom elevation and no significant net sediment exchange between the nearshore and the offshore.

Depth of footing: The depth of burial of the toe of the structure.

Detritus: Fragmented particles of organic matter derived from decomposition of plant and animal remains originating in the marine riparian or marsh, that provide food for marine organisms.

Down-drift: In the direction of the net longshore transport.

Drainage control: Anthropogenic surface water management devices such as pipes, swales, and drains.

Drift aligned: A beach that is orientated differently than the predominant incoming waves at breaking (after refraction in the shallow nearshore).

Drift cell: A littoral [drift] cell is a coastal compartment that contains a complete cycle of sedimentation including sources, transport paths, and sinks. The cell boundaries delineate the geographical area within which the budget of sediment is balanced, providing the framework for the quantitative analysis of coastal erosion and accretion. See Johannessen and MacLennan (2007) for further description of drift cells.

Drift sill: Low elevation groin, typically constructed of rock, installed along with beach nourishment filled up to height of sill which is sometimes used to hold or slow littoral transport of placed sediment.

Ecosystem: A dynamic complex of plant, animal, and micro-organism communities and their nonliving environment interacting as a functional unit. An ecosystem can be of any size—from a log, pond, field, or forest, to the earth's biosphere—depending upon the organisms that are the frame of reference, but it always functions as a whole unit. Ecosystems are commonly described according to the major type of vegetation, for example, forest ecosystem, old-growth ecosystem, or marine ecosystem.

Ecosystem function: The specific mechanisms through which we benefit from Puget Sound, such as production of forage fish, or wave attenuation. Functions are roughly synonymous with goods and services. Ecosystem functions are delivered through the interaction of processes and structures (Simenstad et al. 2006).

Ecosystem structure: The position and character of the physical components of an ecosystem; the character or "state" of the system. Structures are created through the effects of ecosystem processes, and in turn provide ecosystem function goods and services.

Embayment: An indentation of the shore larger in size than a cove but smaller than a gulf.

Embedded: Characteristic describing LWD placement that does not utilize an artificial method of attachment.

Emergency: An immediate threat to life, public or private property, or an immediate threat of serious environmental degradation, arising from weather or stream flow conditions, other natural conditions, or fire.

End effects: Erosion immediately adjacent to a hard armor structure due from wave refraction, bank/beach geology, wave energy at the site, the angle of wave approach, angle of the return wall, up-drift sediment supply, and the construction material of the structure.

Enhancement: Any improvement of a structural or functional attribute of an ecosystem.

Equilibrium profile: The natural form that the beach would take for a given volume of sediment under the prevailing wave climate. The equilibrium profile is affected by the presence of natural features such as headlands and structures. The equilibrium profile is a dynamic concept as the wave field and water level change constantly.

Erosion: The wearing away of land by the action of natural forces. Pertaining to a beach, the carrying away of beach material by wave action, tidal currents, littoral currents, or deflation (wind action) (opposite of accretion). Erosion may be separated into two categories: long-term erosion, which occurs over decadal or greater scales, and short-term erosion, which occurs at less than decadal scale due to individual storm events or seasonal variability. Erosion can be further classified as Background or “passive” erosion, which refers to historical coastal erosion that occurred at a site prior to project installation. This is noticeably different from “active” or “structural” erosion, which is caused by engineered structures.

Estuary: A semi-enclosed coastal body of water that extends to the effective limit of tidal influence and has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage. Sometimes it is defined more broadly to include other coastal inlets that connect lagoons and swamps to the sea.

Eustatic: Of or pertaining to worldwide changes of sea level.

Extent: A description, to include length and width, of the project area.

Fascine: A bundle of sticks bound together, in this context as pertaining to revegetation techniques using live-stake willow sticks bound together.

Feeder bluff (FB): Coastal bluff with active erosion and/or mass wasting which periodically supplies moderate volumes of sediment to the nearshore with a longer recurrence interval than feeder bluff exceptional segments. The bluff face typically has vegetation indicative of disturbance with evidence of landslides and toe erosion (MacLennan et al 2013).

Feeder bluff exceptional (FBE): Coastal bluff with active erosion and/or mass wasting which periodically supplies substantial volumes of sediment to the nearshore in greater quantities with a shorter recurrence interval than feeder bluffs. The bluff face typically has little to no vegetation with active landslides and toe erosion, and may include colluvium and toppled large woody debris (MacLennan et al 2013).

Fetch: Open water distance over which a wind can blow unimpeded and form waves.

Geotextile: Permeable filter fabric.

Glacial erratic: A rock transported by a glacier from its place of origin. Usually consisting of a boulder –sized rock, but can also be said of any size rock fragment.

Glacial till: Dominantly unsorted and unstratified material, generally unconsolidated, deposited directly by and underneath a glacier without subsequent reworking by meltwater, and consisting of a heterogeneous mixture of clay, silt, sand, gravel and boulders ranging widely in size and shape.

Grade: The top of ground. The percent slope of the ground surfaces. A particle size range of particles of soil, sand or gravel.

Gravel: Unconsolidated rock fragments (sediment) greater than 2 mm (0.08 in) in median diameter. Consisting of, in order or increasing grain sizes, granule, pebble, cobble, and boulder.

Granule: A specific size class of gravel sediment with 2-4 mm median diameter.

Gully: A small channel produced by running water in soil or unconsolidated material.

Habitat: The physical, biological, and chemical characteristics of a specific unit of the environment occupied by a specific plant or animal. Habitat is unique to specific organisms and provides all the physical, chemical and biological requirements of that organism within a specific location (Fresh et al. 2004).

Headscarp: A steep surface on the undisturbed ground at the upslope limit of the landslide, caused by movement of the displaced material away from the undisturbed ground. It is the visible part of the surface of rupture.

High tide beach: The sloping portion of the beach profile located above and landward of the low-tide terrace and below mean higher high water.

Hillshade: Cartographic portrayal of topographic relief.

Hummocky: Mounded topography that is the result of landslide activity or debris.

Hydrophilic: Having a strong affinity to water.

Imminent danger: A threat by weather, water flow, or other natural conditions that is likely to occur within 60 days of a permit application.

Immediate threat: A threat to life, the public, property, or of environmental degradation that is likely to occur within 24 hours or less.

Infrastructure: Anthropogenic upland primary and secondary structures/improvements.

Inundation: Water covering normally dry land.

Landslides: A general term covering a large variety of mass wasting and processes involving the downslope transport of soil, sediment, or rock.

Landward: A description meaning towards the land.

Large woody debris (LWD): Large logs with or without root masses attached, and can also include separate root masses.

Large woody debris recruitment: LWD being actively/recently recruited or eroded from adjacent uplands.

Littoral: Relating to the shore or a region along the shore.

Lodgement till: Glacial till deposited from slowly melting ice at the base of a glacier.

Longshore transport: Transport of sediment parallel to the shore by waves and currents, also called littoral drift and alongshore drift.

Low tide: The minimum height reached by each falling tide. The accepted popular synonym of low water in the sea.

Low tide terrace: A broad flat portion of the beach profile located near the mean lower low water level.

Man rock: Size of stones roughly based on how many men it would take to move.

Marine riparian: The transitional zone between the uplands and aquatic environments adjacent to marine waters, where marine riparian vegetation is often located.

Mass wasting: A general term for the downslope movement of soil and rock debris.

Mean higher high water (MHHW): The arithmetic average of the elevations of the HIGHER HIGH WATERS of a MIXED TIDE over a specific 18.6-year period. For shorter periods of observation, corrections are applied to eliminate known variations and reduce the result to the equivalent of a mean 18.6-year interval.

Mean lower low water (MLLW): The arithmetic average of the elevations of the LOWER LOW WATERS of a MIXED TIDE over a specific 18.6-year period. For shorter periods of observation, corrections are applied to eliminate known variations and reduce the result to the equivalent of a mean 18.6-year interval.

Morphology: The shape or form of the land surface or of the seabed and the study of its change over time.

Native bank material: The sediment composition of native soils within the marine bank/bluff.

Nearshore: As defined by PSNERP, includes the area from the deepest part of the photic zone (approximately 10 meters below Mean Lower Low Water [MLLW]) landward to the top of coastal bluffs, or in estuaries upstream to the head of tidal influence (Clancy et al. 2009).

Net shore-drift: The long-term, net effect of littoral or longshore drift along a particular coastal sector.

Net shore-drift cell: A net shore-drift sector from sediment source to deposition area along a particular coastal sector. A net shore-drift cell incorporates sediment inputs (sediment sources, locally referred to as feeder bluffs), through-puts (neutral shores or transport zones), and sediment sinks or depositional shores (accretion shoreforms).

No appreciable drift (NAD): Areas in which no appreciable littoral drift occurs.

Ordinary high water mark (OHWM): In Washington state: That mark that will be found by examining the bed and banks and ascertaining where the presence and action of waters are so common and usual, and so long continued in all ordinary years, as to mark upon the soil a character distinct from that of the abutting upland, in respect to vegetation as that condition exists on June 1, 1971, as it may naturally change thereafter, or as it may change thereafter in accordance with permits issued by a local government or the department.

Overtopping: Transport of water over the crest of a coastal structure or beach crest due to wave runup and/or waves breaking over the crest height.

Overtopping scour: The resulting scour or debris left behind by overtopping. This can be indicated by drift wood, wrack deposits or scour behind the feature being overtopped.

Pebble: A specific size class of gravel sediment with 4-64 mm (0.17-2.5 in) median diameter. Common on gravel and mixed gravel and sand beaches in Puget Sound.

Passive erosion: The gradual loss of beach in front of a bulkhead or revetment as the water deepens and the shoreface moves landward.

Permeability: The capacity of a porous rock, sediment, or soil for transmitting a fluid; a measure of the relativity ease of fluid flow under unequal pressure. This most commonly relates to groundwater flow through a bluff or bluff sediments.

Photic zone: The depth of the water in a lake or ocean that is exposed to sufficient sunlight for photosynthesis to occur.

Pocket beach: A beach that is contained between two bedrock headlands that essentially functions as a closed system in terms of littoral sediment transport.

Pocket estuary: Term used in the Puget Sound region to describe small estuaries and lagoons (types of embayments) partially isolated by their configuration from the main body of Puget Sound (Shipman 2008).

Poorly graded: An engineering term pertaining to a nongraded soil or unconsolidated sediment in which all the particles are of about the same size or in which a continuous distribution of particle sizes from the coarsest to the finest is lacking. This is the opposite of poorly sorted.

Poorly sorted: Sediment that is not sorted or that consists of particles of many sizes mixed together in an unsystematic manner so that no one size class predominates.

Primary structure: An element of anthropogenic upland infrastructure/improvements of fundamental importance. Home or residential building. State Highways and other public roads that is critical for provision of emergency services.

Process-based restoration: Intentional changes made to an ecosystem to allow natural processes such as erosion, accretion, accumulation of wood debris, etc., to occur. Process-based restoration aims to return the landscape to its pre-disturbance, self-sustaining state. Also defined as the restoration of processes that shape an ecosystem, such as sediment transport or erosion, rather than the restoration of ecosystem features, such as tidal marshes or species populations (Van Cleve et al. 2004).

Progradation: The process where a coast is built waterward by deposition and accumulation as at a spit of a delta.

Protection: Safeguarding ecosystems or ecosystem components from harm caused by human actions.

Quarry spalls: Rock used for chinking and bedding layer, typically from broken stone or concrete and approximately 4-8” diameter of each rock.

Relative permeability: The difference in fluid transport properties or capacity between two or more geologic media, affecting fluid flow direction and rate within a given geologic sequence.

Relative sea level rise (RSRL): The average height of the ocean in relation to the shoreline. Relative sea level rise integrates eustatic (global) sea level rise with local vertical land movement data to produce locally-scaled SLR projections.

Relocation: Managed retreatment and realignment of structures on eroding shorelines.

Recessional outwash: Sand and gravel deposited by meltwater streams from the glacial as it retreats.

Resilience: The ability of an entity or system to absorb some amount of change, including extreme events, and recover from or adjust to the change or other stress.

Response time: Time it takes for a beach to reach natural equilibrium after modification or disruption to its natural state.

Restoration: Returning an ecosystem to a close approximation of its pre-disturbance state in terms of structure and function (NRC 1992). This includes measures needed to protect and preserve restored systems in perpetuity.

Retrogress: A process by which the removal of material from the base of a slope removes support from the slope immediately above it, causing it to fail. This type of failure may gradually extend up the slope in the direction opposite to the movement of the displaced material. Retrogressive landslides are most common in sea cliffs experiencing continuing removal of material from the toe by coastal processes.

Return wall: A section of bulkhead that extends towards land, typically from the end of a shore-parallel bulkhead, and ties into the bank or backshore.

Revetment: A hard armor technique using stone placed on a sloping bank to protect against waves or currents.

Rilling: Small channels eroded into soil or sediment by rivulets of water.

Riprap: A layer of stone installed for erosion control.

Risk: The relative need for the given infrastructure in terms of setback distance, infrastructure type and estimated erosion rate. Erosion rates estimated from maximum measured fetch and shoreform type.

Runup: The rush of waves up the face of a beach or structure produced by breaking waves. The maximum vertical height of water above still water level is the measure of this.

Sand: A loose granular substance, classified geologically as 0.0625-2 mm (0.0025-0.08 in). Consisting of, in order or increasing grain sizes, very fine, fine, medium, coarse, and very coarse sand.

Scarp: A line of cliff or steep slopes steep slope, formed by erosion or faulting; escarpment.

Secondary structure: Element(s) of upland infrastructure that support the primary infrastructure and are not fundamental. Patios, non-living residential, gazebo, recreation/park infrastructure, minimal foundation.

Sediment gradation: The proportion of each particle size, or the frequency distribution of various particle sizes.

Sediment input: Delivery of sediment from bluff, stream, and marine sources into the nearshore. Depending on landscape setting, inputs can vary in scale from acute, low-frequency episodes (hillslope mass wasting from bluffs) to chronic, high-frequency events (some streams and rivers). Sediment input interacts with sediment transport to control the structure of beaches.

Sediment-starved beach: Description of beach that's natural supply of sediment is naturally very limited or has been artificially reduced, generally resulting in landward retreating due to volume loss.

Sediment transport: Bedload and suspended transport of sediments and other matter by water and wind along (longshore) and across (cross-shore) the beach. The continuity of sediment transport strongly influences the longshore structure of beaches.

Seawall: A shoreline armoring technique utilizing vertical or near vertical reinforced concrete or rock wall. Also referred to as a vertical bulkhead.

Seepage: Ground water seeps on the marine bank or bluff face.

Setback: Distance of the nearest major infrastructure element (primary or secondary structure) from the coast, measured from bluff crest landward where present, or from OHWM for no-bank sites.

Scour: The removal of sediment in the vicinity of a coastal structure that results in loss of hydrodynamic forces of the structure.

Sheet pile: One of a group of piles made of timber, steel, or prestressed concrete set close together to resist lateral pressure, as from earth or water.

Shoreform: A term often used in Puget Sound to describe a coastal landform. The term is generally used to describe landscape features on the scale of hundreds to thousands of meters, such as coastal bluffs, estuaries, barrier beaches, or river deltas.

Shoreline process unit: PSNERP Change Analysis designation for segments of Puget Sound shoreline where beach sedimentary processes are confined by drift cell indicators of sediment transport zone and adjacent divergence and convergence zones, or areas of no appreciable drift.

Shoretype: The Shipman typology classification for the project area (Shipman 2008). BLB=Bluff backed beach, BAB=Barrier Beach, BE=Barrier estuary, BL=Barrier lagoon, OCI=Open coastal inlet, CLM=Closed lagoon/salt marsh, PB=Pocket Beach, RP=Rocky platform, PL=Plunging rocky shore. The CGS typology classification for the project area (MacLennan 2013). FBE (feeder bluff exceptional), FB (feeder bluff), FB-T (feeder bluff – talus), TZ (transport zone), AS (accretion shoreform), MOD (modified), NAD-B (no appreciable drift – bedrock), NAD-LE (no appreciable drift - low energy), NAD-D (no appreciable drift – delta), NAD-AR (no appreciable drift – artificial).

Significant wave height: The average height of the top 33% of waves.

Silt: A granular material finer than sand and coarser than clay, classified geologically as 0.0039-0.0625 mm (0.00015-0.0025 in). Silt along with finer clay are often referred to together as fines.

Slope: The gradient of the beach or bluff face, measured as the vertical rise over a horizontal distance (V:H); may be more than one slope for complicated reslope projects.

Slope failure: An area of mass wasting at the marine bank. Identify indicators and measurements of slope failure on the site, including alongshore width of the failure, height, and approximate age.

Soft shore protection: shore protection design which entails the use of indigenous materials such as gravel, sand, logs, and root masses in designs that have some degree of flexibility, mimicking natural processes.

Solar radiation: Altered solar patterns due to hotter summers, colder winters.

Still water depth (SWD): The depth of water if there were no waves.

Storm berm: The higher elevation depositional feature, typically in the backshore of a beach, formed by infrequent large waves, located higher and more landward than the active or ordinary berm.

Storm surge: Storm surge is a rise of water associated with the influence of low pressure weather systems, wind setup, and wave setup.

Stratigraphy: The arrangement of strata (geologic layers or bedding) relative to geographic position and chronologic order of sequence and including the character of the stratified rock or sediment. The study of stratigraphy encompasses the origin, distribution, composition, succession of the geologic material.

Subsidence: The gradual caving in or sinking of an area of land.

Substrate: The material on the ground surface, typically referring to soil or sediment.

Substrate density: The density and composition of the sub-surface sediment/geology, which will inform that appropriate selection of LWD anchoring mechanism. Loose, less consolidated material would be amenable to deadman anchor. In moderately consolidated material LWD could be effectively anchored with an auger anchor. While, for sites with higher density or lithified subsurface geology (e.g. bedrock), ballasted LWD would represent the best LWD anchoring mechanism.

Surficial (stability/landslide): Surface layer (top layer of earth/ soil) Sub-surface conditions that make the slope susceptible to failure/landslide associated with the area's geologic processes and features.

Swash aligned: A beach that is generally parallel or near parallel to the predominant waves at breaking (after refraction in the shallow nearshore).

Transgression: a geologic event during which sea level rises relative to the land and the shoreline moves toward higher ground.

Tidal flow: see *tidal hydrology.*

Tidal hydrology or tidal flow: Localized tidal effects on water elevation and currents, different significantly from regional tide regimes mostly in tidal freshwater and estuarine ecosystems.

Transport zone: A bluff or bank which supplies minimal but not appreciable sediment input to the nearshore from erosion/mass wasting, and does not have an accretion shoreform present. Littoral sediment is typically transported alongshore. The bluff face typically has considerable coniferous vegetation with few signs of disturbance from landslide activity or is of very low relief such that sediment input is very limited.

Toe elevation: The juncture of the structure and existing ground at the lowest point.

Toe erosion of bluff: Erosion at the base of a marine bluff caused by wave force.

Toe erosion of structure: Erosion at the base of a marine structure caused by wave force.

Trough: A small linear depression formed just offshore on the bottom of a sea or lake on the landward side of an alongshore bar. It is generally parallel to shore and is always under water. Formed by extreme turbulence from wave and current action in the zone where breakers collapse.

Uplift: A geologic term to describe post-glacial rebound and is a rise in a land mass.

Vegetation maturity: The approximate level of establishment of a plant community.

Vertical bulkhead: *See* bulkhead.

Waterward: A description meaning towards the water.

Wave hindcasting: A method of generating a reasonable approximation of the wind wave climate at a given location using historical wind records from a nearby location.

Wave runup: see *runup.*

Wave setup: the increase in mean water level due to the presence of waves.

Width: The cross-shore dimension of the structure, include separate measurements of return walls or other associated structures.

Wind setup: The tendency for water levels to increase at the downwind shore, and to decrease at the upwind shore.

INTRODUCTION

Shore armor – the construction of bulkheads and seawalls – has become a significant environmental issue in the Puget Sound region. Shore armor (also referred to as hard armor) has been continuously constructed over the past 50 years or more for a variety of reasons including, but not limited to, protecting the shore from coastal erosion. Years of scientific study has led to the determination that hard armor profoundly influences coastal processes, alters coastal ecology, and reduces the resilience of the coast to rising sea level (Shipman et al. 2010, Schlenger et al. 2011, Johannessen and MacLennan 2007).

Many alternatives to hard armor exist for managing risk to structures and infrastructure posed by coastal erosion, including: the use of best management practices, structure relocation, and implementation of "soft shore protection" project designs. Soft shore protection projects contrast from hard armor by preserving natural coastal shoreline dynamics that are immobilized along an armored shore. Successful soft shore protection project designs must be informed by a thorough understanding of specific site conditions and work within the range of current and historical coastal processes. Science and engineering principals are combined to develop and monitor designs. This approach contrasts hard armor designs where "one design fits all" is the standard and the overarching goal is to create a static barrier between the land and the water. The *Marine Shoreline Design Guidelines* (MSDG) were developed to provide a comprehensive framework for site assessment and alternatives analysis to determine the need for shore protection and identify the technique that best suits the conditions at a given site. Design guidance was developed from the results of an in depth case study assessment in which design details, project performance, benefits and impacts, as well as site and local conditions were documented from 25 on-the-ground projects in the Puget Sound region.

Beaches on the Sound differ in many respects from those on the outer coast of Washington State and in other parts of the country. Puget Sound contains a wide variety of shoretypes and wave energies with mixed sand and gravel beaches in contrast to the high wave energy, sand beaches found on the open coast. There are many guidelines and manuals for the design of 'protection' techniques for the more typical open coast (USACE 1984, USACE 1989, De Pippo 2006, CIRIA et al. 2007, USACE 2008), but prior to the MSDG, there was almost no guidance that reflected the variety of conditions found in Puget Sound. For this reason the MSDG were created to inform responsible management of Puget Sound shores for the benefit of landowners and our shared natural resources.

Using the MSDG

MSDG is divided into distinct but related segments:

Chapters 1 and 2 provide background information which includes the geology of Puget Sound, the documented impacts of armor, and responsible shore stewardship.

Chapters 3, 4, and 5 provide a framework for conducting site and coastal processes assessments that inform an alternatives analysis resulting in the selection of appropriate management techniques for a particular site.

Chapter 6 and 7 contain descriptions, project examples, and design guidance for specific design techniques based on past project performance.

Chapters 8 and 9 discuss monitoring methods for shore projects and identify future research needs.

Appendix A provides the results of the case study assessment in which 25 existing erosion control projects in the Puget Sound region were evaluated for their (relative) success with regard to impacts and benefits.

Appendix B provides a literature review of additional references on coastal processes and shore protection for the technically inclined.

Project designers, planners, contractors, landowners, and others will approach these guidelines differently depending on their roles in the process of identifying project goals, assessing feasibility, ensuring appropriate design and construction, and monitoring to measure project performance over time. In addition, useful information regarding the science, policy, and design principles that inform responsible management decisions are included in the document. Over time, designers and all other users of this document can benefit greatly from spending as much time as possible making direct observations of processes at our diverse shores, walking our beaches on nice days and also during severe winter storms.

The Coastal Designer

These guidelines are intended to give the coastal designer an overview of all of the necessary elements to inform the development of project goals and the tools to design appropriate and environmentally responsible projects for marine shores in Puget Sound. This process begins with the *Site Assessment* (Chapter 3) and *Coastal Processes Assessment* (Chapter 4) that together provide the necessary understanding of project goals, the natural range of conditions at the site, the causes of erosion, and the area(s) within the site in which the project should be focused (project area). Chapter 5, *Alternatives Analysis*, provides a framework for the designer to evaluate the feasibility, impacts, and benefits of each technique as they apply to a particular site in order to select the design technique(s) most appropriate for the causes of erosion at that site. Chapters 6 and 7 provide descriptions and design guidance for each technique. Since the nearshore is dynamic, projects will need to be monitored in order to determine performance related to project goals and the need for maintenance. Monitoring recommendations and parameters specific to each technique are included, and monitoring is also discussed comprehensively in Chapter 8.

The Planner

The guidelines can also be useful for planners and permitters with regard to understanding coastal processes, the impacts of armor, and for use in identifying appropriate site characteristics, project goals and project design elements for the different techniques. The guidelines provide planners with information on how to determine where different types of shore protection are appropriate and feasible, the design characteristics that determine whether or not a project is soft or hard, and what monitoring requirements are appropriate. The planner should also be able to recognize where hard armor techniques are the only reasonable option due to the combination of risk from coastal erosion and site and area conditions.

The Landowner

An important goal of these guidelines is to establish engineering standards of practice that are based on a professional assessment of site conditions, so material that is technical in nature may not be directly useful to landowners. Chapters 1 and 2 provide good background for a marine shore owner to understand the processes that affect Puget Sound shores and properties, and the natural resources they contain. Careful reading of subsequent chapters, as well as referenced sources, should provide insight to landowners on the variables that inform the determination of need for shore erosion control projects, the spectrum of management techniques which may be applied, the purpose and general design parameters for different approaches, the conditions for which they are most appropriate, and permitting requirements that impact project designs. It should be understood that the design and implementation of any shore protection project requires consultation with properly trained and experienced professionals for site assessment and project design.

Appendix A Case Studies

Alternative techniques to hard armor have been applied to Puget Sound shores for decades, however previous efforts to monitor and compare the different techniques (Zelo et al. 2000, Gerstel and Brown 2006) has been qualitative and not suitable for the development of standardized design guidance. Appendix A contains an evaluative case study report of 25 individual sites across the 6 major design types (these 6 types were condensed to 5 in the guidelines). Thorough field surveys were conducted and criteria were developed to measure project impacts, benefits and effectiveness based on project goals. Data from the case study report was integral to the development of the techniques and recommendations found throughout this document and references to project examples from the case studies are included throughout.

Coastal Erosion and Protection

Approximately 27 percent of the Puget Sound shore is already armored. Between 2005 and 2011, the amount of new armoring installed averaged 1.1 miles per year and replacement armoring averaged 2.3 miles per year. The true number is likely higher as this data does not reflect unpermitted structures. Over this time period, 0.8 miles of armor per year were removed (Carman et al. 2010). Armor is most commonly installed with the goal to eliminate or slow shore erosion, however it often provides more fortification to the shore than is necessary to protect landward infrastructure or is installed only for landscaping purposes. Armor is often installed to prevent bluff erosion but is not effective for preventing erosion caused by runoff, poor vegetation management or insufficient setbacks–all of which should be addressed with the use of other management techniques (Figure 0-1). In reality, hard armor may not be the best solution to manage erosion along the many sheltered shores of Puget Sound. The extensive application of hard armor as a “one size fits all” solution has resulted in widespread impacts to the beaches of Puget Sound (Schlenger et al. 2011).


4 9'96

Figure 1. Examples of hard armor in Puget Sound. Armor is required due to inadequate setback distance and high fetch (left). Armor is ineffective at preventing landslides in unstable areas with significant upland clearing and development (right).

A significant number of hard armor structures that have been in place for decades are losing their structural integrity. Unnecessary shore armor presents an opportunity for armor removal and/or building a more suitable alternative with fewer impacts to nearshore resources. Much of this older shore armor was installed before the implementation of the Shoreline Master Programs (created by the Shoreline Management Act of 1971), and before Puget Sound coastal processes and the connections with coastal ecology were understood and documented. The combination of policy and increased understanding based on scientific study created the conditions for the development of alternative techniques.

Coastal erosion is a natural process (see Chapter 1). Waves move and sort the beach sediment from one place to the next, causing a bluff to recede here and a beach to aggrade there. But this process takes place episodically and unpredictably such that a given shore may be stable for many decades and then erode significantly in one season and then remain stable in its new configuration for many decades. Building homes and roads too close to the shore inevitably places them at risk and creates both the real and perceived need for protection measures. Precluding erosion along individual parcels results in the incremental degradation of various nearshore processes both on and off site, the cumulative effect of which can result in widespread impairment to nearshore ecosystem functions (Johannessen and MacLennan 2007, Simenstad et al. 2011).

A broad spectrum of marine shore protection approaches have been developed and applied to Puget Sound shores. These range from passive best management approaches that require minimal or no engineering to engineered soft shore protection projects to hard shore armor. Passive management techniques are discussed in Chapter 6 and include:

1. Managing surface and groundwater; preventing the saturation of the soil in the bank or the surface erosion caused by direct runoff.
2. Vegetation management; maintaining natural bluff or bank vegetation so that roots hold the soil together and foliage intercepts rainfall and breaks the impact of drops on the surface.
3. Relocation of infrastructure; moving the house, building or road away from an eroding bank rather than trying to protect it in place.

These approaches do not negatively impact the nearshore and are beneficial for erosion control at any property. Some of them are inexpensive, especially when included at the planning stages of site development.

The engineered shore protection techniques presented in Chapter 7 are listed here:

1. Beach nourishment; the addition of sand or gravel to a beach can be used as a protection or restoration technique where feasible. When designed to function with natural coastal processes this technique has low to moderate impacts and requires relatively little mitigation.
2. Large wood; strategic placement of logs and root wads that maintains/enhances natural processes, such as recruitment of drift logs, in order to build up the backshore while maintaining dynamic nearshore processes. If appropriately designed and installed there are few impacts from the technique.
3. Reslope/revegetation; creating or maintaining a stable bank slope and using vegetation to stabilize it. Generally, there are few impacts from this technique.
4. Bulkhead removal and/or restoration of natural beach. Of the formal techniques, this has the fewest impacts and will restore natural beach processes.
5. Hard armor; rock revetment (placement of stationary sloping rock, rip rap) and vertical bulkheads (constructed of concrete, sheet pile, rock, or wood). These techniques are necessary at high risk sites but will fundamentally alter natural beach processes and therefore require substantial mitigation.

Choosing the most appropriate course of action for a site from these various alternatives begins with a careful assessment of the site and conditions within the larger net shore-drift system and supporting coastal ecosystem processes. Proceeding stepwise through these guidelines will provide a solid foundation for assessing risk from coastal erosion, determining the need for and type of action that is the best alternative for the site, and using site characteristics and coastal processes to inform appropriate designs. This will help meet the overarching goal of marine shore protection and restoration.

Aquatic Habitat Guidelines

MSDG was produced through The Aquatic Habitat Guidelines program, which is a group of state agencies and stakeholders whose mission includes the promotion, protection, and restoration of fully functioning marine, freshwater, and riparian habitat through comprehensive and effective management of activities affecting Washington's aquatic and riparian ecosystems. Project participants include the Washington Departments of Fish and Wildlife, Ecology, Transportation, and Natural Resources; the Recreation and Conservation Office; and the Puget Sound Partnership. This broad group produces guidance that has become essential in the design and permitting of aquatic projects in Washington State.

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Chapter 1. THE GEOMORPHIC SETTING OF PUGET SOUND: IMPLICATIONS FOR SHORELINE EROSION AND THE IMPACTS OF EROSION CONTROL STRUCTURES

This material was originally published as a chapter in a U.S. Geological Survey Scientific Investigations Report 2010-5254*, Puget Sound Shorelines and the Impacts of Armoring—Proceedings of a State of the Science Workshop*, May 2009 (Shipman et al. 2010). It is reproduced here with permission of the U.S. Geological Survey. Minor changes have been made to the formatting, units, citations and some terms to be more consistent with the style of these guidelines.

Introduction

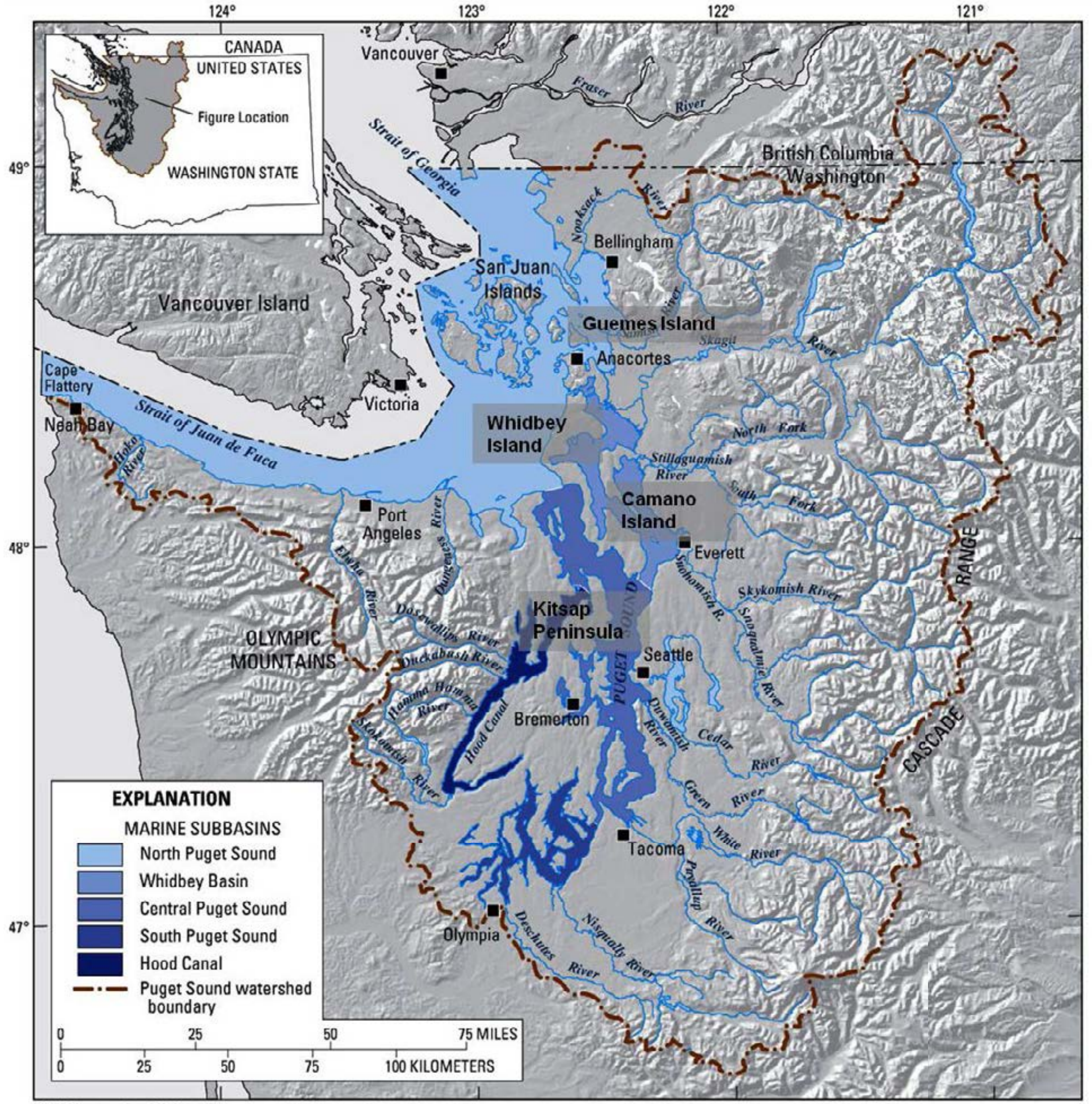
Puget Sound has approximately 4,000 km (2,500 miles) of shore, much of it consisting of beaches and coastal bluffs subject to chronic erosion. Many segments of this shoreline are heavily developed, with roads, homes, and industry along the water's edge, particularly along the Sound's urbanized eastern shore. Other shoreline areas remain relatively unaltered, but are under increasing pressure as demand for coastal property rises within the rapidly growing urban region. This increased development of shorelines, and the attendant desire to protect and improve property, has resulted in the widespread construction of seawalls, revetments, and other forms of armor.

These efforts, however, have raised concerns about the long-term impact of erosion control practices on shoreline dynamics, coastal ecosystems, and public responsibilities for managing the coast (Macdonald et al. 1994, Broadhurst 1998). Shorelines by their nature lie on a narrow boundary between the terrestrial and aquatic landscapes, are ecologically important, and are managed under a complex suite of regulations (Carman et al. 2010). To make matters more challenging, erosion is not just a threat to shoreline property but is also an important natural geomorphic process that builds beaches and maintains coastal habitats (Johannessen and MacLennan 2007).

Understanding the effectiveness of shore armor, such as revetments and bulkheads, and its potential environmental impacts requires an improved knowledge of the factors that influence erosion, the movement of sediment, and the complex contribution of erosion to the long-term maintenance of shorelines and coastal ecosystems. The purpose of this chapter is to review the geology and coastal processes that shape Puget Sound shores and to summarize the issues that have emerged regarding the management of erosion on the region's beaches.

Geologic Setting

The Puget Lowland occupies a north-south trough between the Cascade Mountains on the east and the Olympic Peninsula on the west (Figure 1-1). This depression is a major geologic feature resulting from the subduction of the Juan de Fuca Plate beneath the western edge of North America. Besides creating the broad physiographic setting of the greater Puget Sound, tectonic processes have led to a complex distribution of older bedrock (Burns 1985, Shipman 2008). In much of the region, this bedrock is deeply buried under Pleistocene sediments and is not exposed at the shore, but in some areas, such as in the San Juan Archipelago, rocky shores are common.



PSNERP base map from U.S. Geological
Survey digital data 1:2,000,000, 1972
Albers Equal-Area Conic Projection
Standard parallels 47° and 49°, central meridian 122°
Washington shaded relief, USGS, 30 meter DEM
British Columbia shaded relief, NASA, SRTM 90 meter

Figure 1-1. The Puget Sound basin, showing major rivers, oceanographic subbasins, and selected locations referred to in this chapter.

The modern landscape of the Puget Lowland is largely a legacy of the Vashon glaciation (15,000–20,000 years BP), the most recent of several glaciations that have shaped the region (Easterbrook 1986). This glacial history has influenced both the configuration of Puget Sound's shore and the sedimentary composition of its bluffs and coastal watersheds. Meltwater flowing southward beneath the ice is believed to have scoured the major troughs that define Puget Sound today (Burns 1985, Booth 1994). The glacier left a distinct north-south grain to the region's hills and valleys, which are superimposed on a broad outwash plain about 100 m (328 ft) above modern sea level (Booth 1994). Much of the sediment exposed on the edges of river valleys and along the coastal bluffs is glacially derived, consisting of a diverse suite of lake-bed clays, outwash sands and gravels, coarse-grained till and glacial marine drift, and interglacial fluvial deposits.

Oceanographic Setting

Puget Sound, together with the Strait of Georgia to the north, form an inland sea connected to the Pacific Ocean through the Straits of Juan de Fuca. The Sound consists of a complex network of deep glacial channels and basins. The nearshore zone is typically restricted to a narrow platform, confined between a steep terrestrial landscape and deeper water offshore.

Sea-level history exerts an important influence over shoreline evolution. Post-glacial isostatic rebound had different effects in northern and southern Puget Sound, but occurred rapidly and was generally over by 8,000 years ago (Finlayson 2006). During the late Holocene (the last 5,000 years), most regional shorelines have generally experienced gradual submergence similar to the global eustatic trend – tide gauge records in Seattle indicate an annual submergence of about 2 mm/yr (Mote et al. 2008). Tide gauges and leveling indicate that Washington’s Pacific Coast and western portions of the Olympic Peninsula are emerging, but that this pattern does not extend into the Puget Lowland (Mote et al. 2008). There is also local evidence of abrupt co-seismic subsidence and emergence associated with Holocene faulting, which has profoundly affected shorelines near the faults, but that has not had regional-scale influence (Bucknam et al. 1992).

Puget Sound experiences mixed semi-diurnal tides, with the diurnal range increasing from about 2 m (6 feet) on the Strait of Juan de Fuca to more than 4 m (14 feet) in southern Puget Sound. The mixed tides are skewed towards the upper half of the tidal range, so waves most commonly interact with the upper portion of the foreshore (Finlayson, 2006). Although tidal currents may influence the evolution of the shoreline, they are not generally believed to be a major factor in shoreline erosion when compared to waves. Atmospheric pressure and other meteorological conditions contribute to local tidal surge, which can elevate water levels more than 0.5 m (1.6 feet) above normal levels during low-pressure winter storms. Annual sea level is subject to variability as a result of periodic El Nino events, which may result in sea level 20–30 cm higher along the west coast (Mofjeld 1992, Subbotina et al. 2001).

Pacific Ocean waves and swell have little influence on Puget Sound except near the entrance, so wave generation is directly linked to local wind conditions. Because of the relatively small bodies of water, waves are fetch-limited and rarely exceed significant heights of 1–2 m or periods of greater than 3 seconds during storms (Downing 1983, Finlayson 2006). The fetch-limited conditions do not just result in smaller waves, but lead to significant longshore variability in the wave environment due to local variation in the orientation and length of fetch (Finlayson and Shipman 2003, National Research Council 2007).

Coastal Processes

The modern shoreline of Puget Sound developed as rates of global sea-level rise began to slow during the last 5,000–6,000 years. Rivers have continued to deliver sediment to the coast, building large estuarine deltas at their mouths. Streams have carried sediment from small coastal watersheds to the shore, contributing to the gradual evolution of small estuaries. Wave action has eroded the coastline and transported sediment, forming beaches and leading to the evolution of a wide variety of coastal landforms (Downing 1983, Shipman 2008). Of the Sound’s 4,000 km (2,500 miles) of coastline, about half consists of bluffs and small barriers, with the remainder comprising bedrock shores, several large river deltas, and hundreds of sheltered estuaries and back-barrier lagoons.

Beaches on the Sound consist of a wide mixture of sediment sizes, dominated by coarse sand and gravel. Composition varies rapidly alongshore, reflecting heterogeneity of sediment sources, changes in the wave environment, and complex transport dynamics (Finlayson 2006). Beaches are typically composed of a steep, coarse-grained beach face and gently-sloped, sandy low tide terrace.

Mixed grain-size beaches, such as those on Puget Sound, exhibit complex patterns of both cross-shore and longshore sediment transport (Adams et al. 2007, Curtiss et al. 2008, Warrick et al. 2009). Like other estuarine beaches, those on Puget Sound are characterized by a veneer of mobile beach sediment, low longshore transport rates, and strong segregation of the shoreline into discrete littoral cells (Nordstrom 1992, National Research Council 2007). The beach face often exhibits a gravel surface layer overlying a more heterogeneous mix of gravel, sand, and shell fragments (Finlayson 2006). Typical of beaches on other glacially influenced coastlines, coastal processes on Puget Sound are strongly controlled by the inherited glacial topography, the compartmentalization of beaches by resistant headlands, and an abundance of coarse-grained and varied sediment sources (Ballantyne 2002).

Ultimately, beach behavior is not simply a function of wave environment and sediment size, but is a complex function of geologic controls, such as sediment supply, resistance to erosion, and antecedent topography and bathymetry (accommodation space). Local features such as cobble lags, stream mouth deltas, and historical landslides may exert significant influence over beach processes. Seasonal fluctuations in elevation and grain size occur on some beaches, but may be as much due to changes in dominant local direction of longshore transport as to cross-shore transport related to cyclical changes in storm waves and swell. Puget Sound resembles other relatively low-energy systems lacking swell components in that beach profiles may represent a persistent response to larger storms and storms may tend to generate a shore-parallel retreat of the beach face (Nordstrom and Jackson 1992, Finlayson 2006).

The largest waves on Puget Sound are generated by winds that are topographically channeled along the north-south water bodies, leading to wave action that is often highly oblique to the shore, strengthening the role of longshore sediment transport in shaping the shoreline (Finlayson and Shipman 2003). Redistribution of coastal sediment has resulted in the widespread occurrence of spits, cuspate forelands, and other types of barrier beaches (Figure 1-2).

The strength and direction of wave action can vary significantly in the longshore direction, leading to significant changes in potential sediment transport. This may contribute to both complex evolution of coastal landforms (Ashton and Murray 2006) as well as to local variability in erosion patterns. The irregular shape of the shoreline, combined with the fetch-limited wave environment, leads to the division of the coast into hundreds of discrete littoral cells, each with its own sources and sinks of sediment (Schwartz et al. 1989). Transport rates are orders of magnitude smaller than those typically found on ocean coasts (Wallace 1988) in part due to the lower wave energy, but also due to the coarse-grained material and the fact that some beaches may be sediment-limited (the capacity of waves to move sediment may exceed the amount of sediment available).

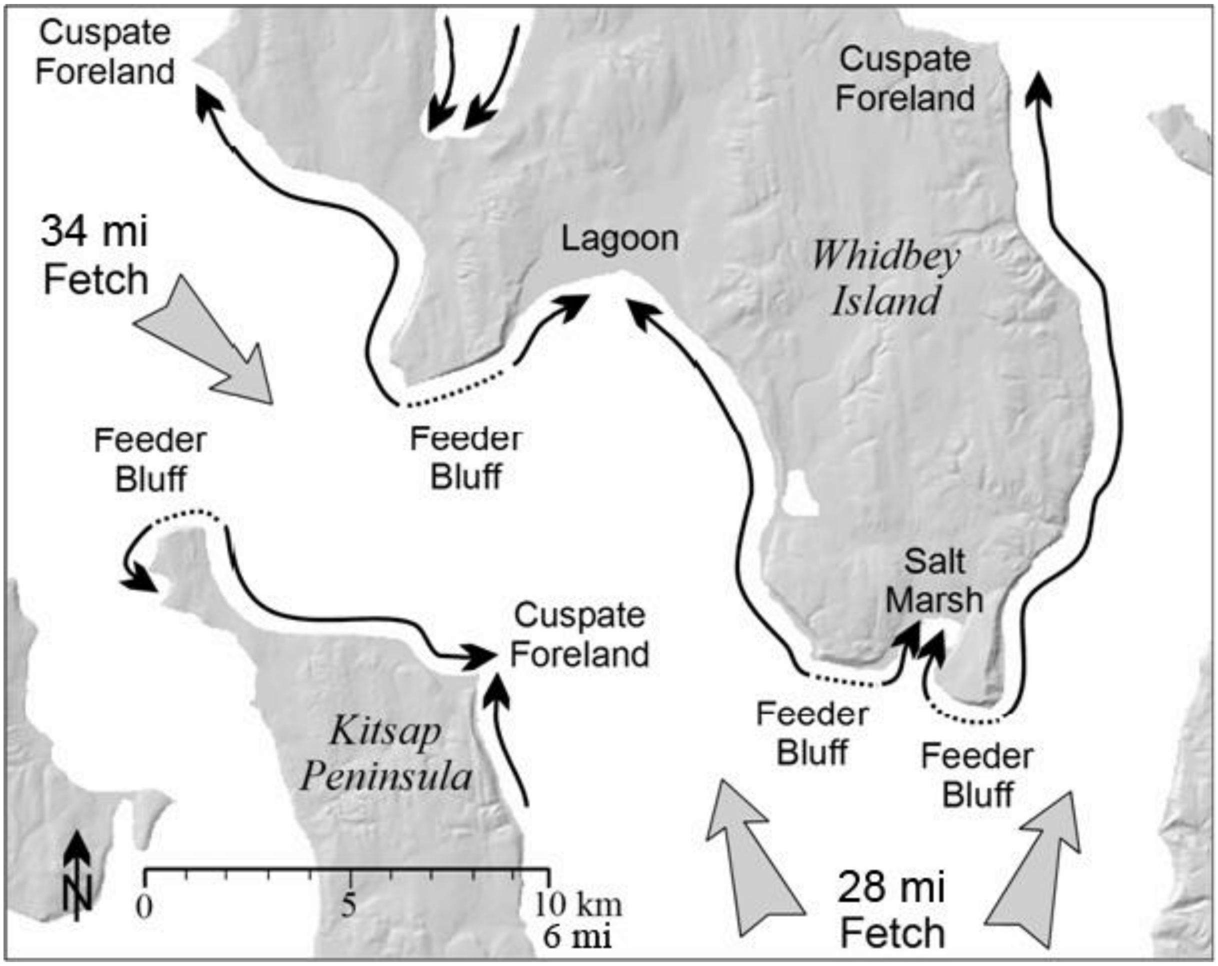


Figure 1-2. The complex pattern of longshore sediment transport (black arrows) and littoral cells in north central Puget Sound (from Finlayson and Shipman 2003). Net transport patterns reflect the combination of maximum fetch (large arrows) and the predominance of southerly storm waves.

Eroding coastal bluffs are the primary source of beach sediment on most Puget Sound beaches (Keuler 1988, Johannessen and MacLennan 2007), although sediment abundance and size varies significantly, even over short reaches (Figure 1-3). Small streams may be a source of sediment on some shorelines where coastal drainages yield large amounts of sediment and where the configuration of the stream mouth allows transfer of sediment out of the estuary into the beach system. Conversely, larger rivers such as the Skagit, Nooksack, or Nisqually carry large volumes of material into Puget Sound (Downing 1983), but are not considered major sources of beach sediment, as most empty into the heads of bays, where the coarser grained sediment is retained within the river delta. The Elwha River is a notable exception, as its configuration and location along the Strait of Juan de Fuca make it a significant element of the local coastal sediment budget (Galster and Schwartz 1990).

Figure 1-3. Eroding bluff on Guemes Island. 100-130 ft high bluff consists of a diverse assemblage of Pleistocene glacial and glaciofluvial units and a wide range of sediment types, from silt to coarse gravel and boulders.

Shoreline Erosion

Much of Puget Sound's shoreline is subject to erosion and retreat, as demonstrated by the widespread occurrence of steep coastal bluffs and eroding barrier beaches. Mechanisms and rates vary significantly from one location to another and are influenced by the wave environment, the resistance of coastal materials to erosion, the nature of the landform (bluff, barrier beach, or artificially filled shoreline), and the character of the adjacent beach. Patterns of erosion reflect the complex geologic and wave environment and therefore vary significantly from one location to another. Erosion mechanisms differ among landforms. Erosion is most often associated with coastal bluffs, spits and other barrier beaches, and with anthropogenically-modified shorelines.

Erosion and retreat of coastal bluffs is a complex function of wave-induced toe erosion, driven by major storms coupled with high water levels, and hillslope mass-wasting, typically triggered by heavy rainfall and elevated groundwater levels (Gerstel et al. 1997, Hampton et al. 2004). The rates and mechanisms of bluff erosion vary significantly due to differences in bluff height, geology and hydrology, wave exposure, and other factors (Figure 1-4). Bluff erosion is highly episodic and usually occurs as discrete slope failures (Shipman 2004, Johannessen and MacLennan 2007), although mass-wasting events can range from shallow debris avalanches to large, deep-seated landslides subject to periodic reactivation.

Figure 1-4. Contrasting examples of bluff erosion and mass wasting in Kitsap County. Top photo, low bluff of glacial till subject to wave-induced erosion. Bottom photo, large deep-seated landslide.

Bluff erosion also has a complicated relationship with beach condition, since beaches on Puget Sound derive much of their sediment from bluff erosion and a broad beach or high storm berm can provide substantial protection to the bluff toe from wave action. Long-term bluff erosion depends on both the ability of wave action to erode the toe of the bluff and the capacity of waves to transport eroded sediment away from the site so that direct erosion of the bluff toe can continue (Keuler 1988).

Barrier beaches are classified as depositional landforms, and on Puget Sound these beaches are often locally referred to as *accretion beaches*. This terminology derives from the long-term constructional nature of these landforms, but can lead to confusion, since barriers are often subject to erosion and can be highly dynamic landforms. Barriers erode either by thinning and narrowing due to transport of sediment away from the site (offshore or alongshore) or by overwash and landward migration, examples of both of which can be observed on Puget Sound. Erosion typically occurs during major storms, when waves can erode the beachface or overwash the berm (Figure 1-5). Barrier landforms often have complex configurations, and it is common for some portions to erode while others remain stable or accrete. In addition, barriers are often associated with stream mouths or tidal inlets where additions of sediment or currents can complicate erosion/accretion patterns. Barrier erosion and landward migration is an inherent aspect of long-term coastal retreat, but it can be aggravated by changes to local sediment budgets due to anthropogenic activities (Komar 2000, Johannessen and MacLennan 2007). This may be most notable adjacent to jetties and large groins where sediment transport is blocked, but can also result from the armor of up-drift bluffs and the loss of sediment supply, as has occurred at Ediz Hook near Port Angeles (Galster and Schwartz 1990, Komar 2000).

Although erosion is most widely associated with bluffs and barrier beaches, it can occur in other settings as well. Bedrock shores may erode, although rates are low or negligible in more resistant lithologies. Marshy shores, typical of deltas and estuaries, can also erode, although forcing mechanisms may be very different than on beaches, relating to changes in fluvial sedimentation patterns and tidal channel evolution. Some of the most significant erosion on Puget Sound occurs along historically filled shores where armor is lacking or is poorly maintained – such as on old, inactive industrial sites. Fill materials are often easily erodible and have, by definition, been placed seaward of the original shore, steepening the profile and increasing exposure to wave action during a greater range of tides.

Few studies of erosion rates have been carried out on Puget Sound, in part because determining reliable long-term rates is made difficult by the generally slow and highly episodic nature of erosion and the lack of reliable historical data on shoreline position. Shipman (1995) summarized data on erosion rates from numerous studies in the region and found they generally ranged from a few centimeters to several tens of centimeters per year. These studies were largely of coastal bluffs and may have been biased to sites with high erosion rates. Erosion typically occurs in pulses, associated with rainfall-induced landslides or with large storms during very high tides, and commonly are separated by long intervals of relatively little change (Johannessen and MacLennan 2007). Given the variability of rates from year to year, Keuler (1988) suggested that at least 20 years of record were necessary to establish a reliable long-term average. A general observation on many Puget Sound bluffs is that a bluff may retreat approximately 1 m (3 feet) in a typical landslide, and that such slides might occur every 40 years. This corresponds to a rate of 2.5 cm/yr (1 inch/year), or 2.5 m (8.2 ft) in a century.

Rates of erosion can also vary spatially, even over short distances, due to changes in geologic conditions, variation in wave exposure, differing human activities, or variability in the local availability of beach sediment (Komar 2000). Even along coastal reaches with similar wave energy and geology, bluff retreat rates can vary significantly due to differences in the character of the beach (Keuler 1988, Shipman 2004) and its ability to protect the coast from wave action.

Figure 1-5. Examples of barrier beach erosion. Top photo, barrier beach on Camano Island. Gravel deposits on the landward side of the berm (arrows) are recent overwash from a major high tide storm. Bottom photo, eroding barrier and dunes on northwestern Whidbey Island, indicated by fresh scarp and fallen trees.

Armor on Puget Sound

Seawalls, bulkheads, and revetments have been constructed on approximately one third of Puget Sound's shore, although on a local scale the proportion varies regionally due to differences in development patterns and shoreline type (Berry et al. 2001). Armor is most extensive on the heavily developed eastern shore between Everett and Tacoma and generally less pervasive along portions of northern and western Puget Sound, where development levels are lower and bedrock shores more common. Historically, most armor was associated with the protection of agricultural dikes and levees in river deltas, the construction of railroads and roads along the shore (Figure 1-6), and the reclamation of intertidal and low-lying areas for industrial development (Macdonald et al. 1994). Much of this type of development occurred in the 19th and early 20th centuries. In the 1950s, coastal development activities had shifted to larger shoreline residential communities, many with elaborate canal configurations. This often involved large-scale dredging and filling of coastal wetlands and was largely ended by the adoption of environmental regulations of the early 1970s. Most new armor on Puget Sound takes the form of seawalls and bulkheads in conjunction with residential development, along with ongoing repair and replacement of older structures. The high value of coastal property, widespread occurrence of eroding shorelines, and relatively mild wave environment make armor both desirable and effective. Although armoring activities are more tightly regulated than they were historically, the practice remains common (Carman et al. 2010).

Figure 1-6. Railroad along the shoreline between Seattle and Everett. The seawall was constructed in the early 1900s to protect the railroad, which had been built on the beach below the high bluffs (Johannessen et al. 2005). The upper beach is buried by the railroad grade. This photograph was taken at an extreme low tide; a normal high tide would extend to the seawall, leaving no beach exposed.

Erosion control structures on Puget Sound differ widely in design and construction, reflecting not just site conditions and cost, but also historical practice and local contractor expertise (Downing 1983, Terich 1989). Vertical bulkheads (the terms bulkhead and seawall are often used interchangeably on Puget Sound) are standard practice on residential sites and may be constructed of rock, concrete, wood, or other materials (Figure 1-7). Currently, the most widely used technique is a near-vertical placed-rock wall (locally called a rockery or a rock seawall). Sheet-pile walls and riprap revetments are commonly employed in industrial and urban settings, particularly where structures were built farther seaward and at lower tidal elevations.

Figure 1-7. Typical examples of residential erosion control on Puget Sound. In each case, high tides would reach the seawall. Top photo, rock seawall in Kitsap County. Middle photo, timber pile bulkhead on Camano Island. Bottom photo, concrete bulkhead on a barrier spit in Anacortes.

There have been significant changes in armoring practice over time, reflecting increased regulation of shoreline activities and a shift from large-scale reclamation of intertidal areas to more conventional erosion control on naturally eroding shorelines. Whereas historically, structures were often built in conjunction with extensive intertidal fill, new structures are usually required to be kept as high on the shore as feasible. Much new armor is either replacement of older structures in heavily developed areas or the construction of new structures on less developed rural and suburban shores.

The role of shore armor varies among sites. On bluffs, armor may be designed to reduce toe erosion or be part of a more complex slope stabilization effort. On low-lying shorelines, armor may be intended primarily to reduce overtopping and flooding or to minimize storm damage from waves and drift logs. On historically filled sites, armor is necessary to retain fill material and may also support marine activities such as boat moorage and freight handling. Armor is often placed to protect other shoreline structures such as pier abutments, stair landings, boat houses, stormwater outfalls, and utility infrastructure. The widespread use of armor on residential shorelines is attributable not just to its need for protecting upland structures from erosion, but to its role in site planning and landscaping, creating safe and convenient access to the water, improving recreational use of the shoreline, and to its contribution to both perceived and real property value.

Impacts of Armor

Concerns about the potential adverse impacts of erosion control structures on Puget Sound have risen in recent years due to a greater awareness of the role of beaches and riparian zones in the greater Puget Sound ecosystem (Gelfenbaum et al. 2006, Quinn 2010), new studies from other regions suggesting a range of environmental problems associated with hardened shorelines (National Research Council 2007), and the continuing local trends in new seawall construction.

The effects of armor on Puget Sound shores are strongly related to the geologic processes that shape the shoreline and maintain beaches and coastal habitats. Successful control of erosion of coastal bluffs (feeder bluffs) removes an important source of beach-forming sediment. It may also reduce the natural supply of large wood and detritus to the shoreline ecosystem that accompanies natural erosion events. The significant role of longshore sediment transport on Puget Sound increases the likelihood that alterations to sediment processes in one location may eventually impact conditions elsewhere within a littoral cell. The construction of seawalls and bulkheads on eroding coastlines may effectively protect upland areas, but does not prevent continued retreat of the beach itself, with the result being the gradual narrowing of the upper beach and loss of upper intertidal habitats. The lateral heterogeneity of Puget Sound beaches means that the effects of armor may vary considerably from one location to another and that long-term trends in shore condition may be difficult to separate from natural variability in short-term investigations.

Several reviews of the impacts of armor on Puget Sound have been undertaken, examining relevant local and national research on both physical and biological processes (Macdonald et al. 1994, Thom et al. 1994, Williams and Thom 2001). In addition, assessments of armoring have been made within specific geographic regions of the Sound, such as Thurston County (Herrera Environmental Consultants 2005), King and Snohomish Counties (Johannessen et al. 2005), and on Bainbridge Island (MacLennan and Johannessen 2010). More focused studies of beaches have looked at biological responses to armor and altered riparian connections (Sobocinski 2003, Rice 2006) and the geological responses of shorelines to changes in the delivery and the transport of beach sediment within the littoral system (Galster and Schwartz 1990).

These regional studies suggest a broad range of potential effects of erosion control structures on Puget Sound shores. In general, these can be categorized as follows:

- *Loss of upper beach and backshore*. Even when built high on the beach profile, seawalls typically eliminate a narrow zone of the high tide beach. On Puget Sound, this may result in the absence of accumulated drift logs and beach wrack and the loss of dry beach at high tides, which may in turn reduce the area available for forage fish spawning (Penttila 2007) and for recreation.
- *Aquatic-terrestrial connectivity*. Armor modifies the natural transition between terrestrial and aquatic ecosystems. This can affect movement of materials and organisms between systems, reduce the quality of riparian functions, and introduce discontinuities to this narrow ecotone and ecological corridor. Structures also tend to result in alterations to the pattern of natural drainage to the beach.
- *Passive erosion*. Most shores in Puget Sound are naturally eroding. A seawall or revetment may effectively stabilize the area landward of the structure, but does nothing to address the underlying retreat of the beach face or shoreline, which will continue on the seaward side of the structure (Fletcher et al. 1997, Griggs 2005). With time this results in narrowing of the remaining beach, the loss of the upper beach, and increased interaction of the structure with waves. This is a significant impact of armoring, but one that may take many decades to appear.
- *Sediment delivery and transport*. Seawalls on coastal bluffs stop the natural erosion of feeder bluffs, thereby reducing the delivery of sediment to the littoral system and reducing the overall budget of the local littoral cell. Bulkheads that encroach across the beach, either because of their original construction, or because of subsequent erosion of adjacent shores (passive erosion), may act as groins, impeding longshore transport of sediment and leading to localized erosion on down-drift properties.
- *Altered wave action*. At higher water levels, waves can reflect off of structures, possibly increasing erosion and scour and in some case influencing longshore sediment transport patterns (Griggs 2010, Ruggiero 2010). Engineers have long been aware of localized end effects adjacent to wall ends associated with bulkheads and other coastal structures (Kraus and McDougal 1996).

Documenting the impacts of armor is challenging due to the significant spatial and temporal variability associated with beach systems, the long-term nature of some of the responses, and the cumulative impact of shoreline modifications. In addition, separating the effects of armor from the effects of other shoreline activities can be difficult. Examples include increased stormwater runoff, loss of forest cover, modification of natural drainages, and construction of other marine facilities such as piers, access stairs, outfalls, and boat launches. In some cases, seawalls can facilitate development closer to the water than might otherwise occur, increasing the likelihood and magnitude of these other impacts.

Increasing concerns among regulators about the possible impacts of armor have led to closer examination of proposed projects, including requirements that proponents more rigorously demonstrate the threat from erosion and demonstrate that they have considered alternative designs (Carman et al. 2010). Within the Puget Sound region, interest has grown in “softer” approaches to erosion control, such as beach nourishment, biotechnical methods (erosion control and slope stabilization using vegetation), and structures employing natural elements such as cobble and large wood (Zelo et al. 2000, Shipman 2001, Barnard 2010). In addition, the restoration community has taken an active interest in opportunities to remove or modify existing armor as a way of restoring natural shoreline ecological functions and improving beach-oriented recreational opportunities (Hummel et al. 2005, Cereghino 2010).

Summary

Shoreline erosion will remain a major issue on Puget Sound during coming decades. Regional population growth will lead to more development along the coast, and the prospect of higher sea levels raises the possibility of faster erosion and increased storm damage. At the same time, concerns about protecting and restoring the Puget Sound environment, including its coasts and beaches, will increase attention on activities such as armor that have long-term impacts on shore functions. Making decisions about how, where, and whether to armor the shore will be important to addressing this potential conflict, but will require better understanding of both the processes that shape Puget Sound's coast and the range of strategies that can be employed to reduce both hazards and loss of natural resources.

A number of areas of scientific inquiry would contribute to improving the science related to erosion and the impacts of shore armor on Puget Sound. These include:

- Better information about erosion rates, sediment budgets, and patterns of shore change. Some of this information can be derived from local studies, but some may come from careful application of work done in other regions that is applicable to the unique conditions of Puget Sound (for example mixed sediment beaches, bluff-dominated systems, and fetch-limited shorelines, including lakes).
- Improved understanding of the factors influencing erosion and the sensitivity of beaches and shores to changes in sediment supply and to long-term changes in water levels.
- Interdisciplinary efforts among geologists, biologists, and engineers. Many of the most damaging impacts of armor may be related to the response of ecological systems to changes in physical and geomorphic characteristics of the shore. Evaluation of short-term effects of structures and of alternative methods of controlling erosion involves engineering and design skills, as well as better biological and geological understanding.
- Well-designed empirical studies comparing armored and unarmored sites. These will benefit from collection of environmental data (waves and water levels), coordinated physical and biological measurements, and judicious selection of both spatial and temporal sampling intervals. Long-term studies will be particularly valuable.
- Development of long-term, placed-based studies of longer shore reaches, where investigations of environmental conditions, sediment processes, and biological responses can be carried out simultaneously. In the absence of such work, it may be difficult to gain understanding into the complex relationships between geologic, oceanographic, and ecologic processes.
- Evaluations of the geomorphic and engineering response of shores to a variety of conventional and alternative stabilization measures and the effectiveness of these methods in controlling erosion. Care will need to be taken in assuring comparable conditions between sites.

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Chapter 2. STEWARDSHIP

Background

Puget Sound and its shores provide habitat for many ecologically important species of fish, shellfish, birds, marine mammals, and other wildlife. It also supports a variety of important services for humans including recreation, commerce, and development opportunities. With substantial increases in population expected in the Puget Sound region in the future (OFM 2010), conflicts in land use between humans and the needs of ecologically important biological resources will intensify. Structures placed along the shore to halt erosion and protect upland structures or properties are commonly called “shoreline armor”. These familiar shoreline alterations are the focus of current efforts to implement alternative approaches that limit impacts to natural shore functions while meeting human needs.

Shore armor is common throughout Puget Sound with approximately 27 percent (666 miles) of the shore currently armored (Schlenger et al. 2011). Additional armor continues to be added each year furthering impacts to shore processes and biological functions. Based on data from the Hydraulic Project Approval (HPA) database maintained by the Washington Department of Fish and Wildlife (WDFW), 7.4 miles of armor was added to Puget Sound shores between 2005 and 2011 (WDFW unpublished data). Concurrently, restoration projects removed 0.8 miles of armor resulting in a net increase of 6.6 miles of new armor during this period. While the data show an increase in the amount of armor removed each year, the quantity of new armor installed still far exceeds removal efforts. Additionally, 16.2 miles of existing armor was replaced, thus extending the lifespan and impacts of these structures on the nearshore environment.

These data also indicate that most armor removal occurred on public/government owned properties (68% or 0.5 miles), whereas most of the new armor was constructed on single-family residential properties (70% or 5.2 miles). Consequently, reversing the current trend requires efforts aimed at increasing the use of alternative approaches to armor on residential shore properties. This starts with fostering a sense of informed stewardship of marine shores and providing satisfactory alternative approaches to traditional hard armor structures.

What is Stewardship?

Environmental stewardship means voluntary commitment to behavior and action that results in environmental protection or improvement (EPA 2013). In this context, stewardship refers to an acceptance of personal responsibility for actions to improve environmental quality and to achieve sustainable outcomes. Stewardship involves lifestyles and business practices, initiatives and actions that enhance the state of the environment. Environmental stewardship is a critical component to conserving natural resources and promoting sustainable outcomes for Puget Sound shores.

Stewardship of Puget Sound shores necessarily involves understanding and observing how coastal features are naturally created and sustained, how they are impacted by development activities, and making informed management decisions that protect important nearshore processes. Marine shores are dynamic features in Puget Sound. Beach sediment is regularly moved by water, wind, and wave action to create and sustain the features we see along our shores such as spits, lagoons, and mudflats. Without continual input of beach material from the uplands onto the shore via erosion or landslides, beaches and coastal features such as spits can become sediment-starved; altering their composition and size, or causing them to disappear completely over time. While the immediate concern of a landowner may be to halt shore erosion, environmental stewardship requires that the benefits of erosion for sustaining the shore are integrated into decisions and actions.

Shore processes and functions occur at larger scales than common land-use designations such as parcel and ownership boundaries, and are dependent upon sediment input that may occur some distance away. Because of this, actions taken on one part of the shore can often have impacts well beyond the boundaries of that parcel. For example, an eroding Puget Sound bluff deposits sediment onto the adjacent beach. Wind and waves move this material along the shore, supplying beach sediment to properties down-drift of the eroding bluff. If shore armor is installed on the eroding bluff to stop erosion, a physical barrier now exists between the uplands and the shore causing a diminished sediment supply to the beach. For parcels located down-drift of this new armor, wind and wave energy continues to move existing beach sediment away from these properties. Due to the up-drift armor, replacement sediment formerly supplied from the eroding bluff for this section of beach is now impounded behind armor. This reduced sediment supply can result in increased erosion of the down-drift properties and result in construction of additional shore armor. This scenario can repeat itself along the length of a drift cell leading to extensive armor on the shore and resultant degradation of shoreforms and processes.

Stewardship involves making responsible decisions about our marine shores. While this responsibility may seem to lie largely in the hands of marine shore landowners, all Puget Sound area residents can practice stewardship that benefits our marine shore and the resources it supports. Examples of stewardship include: living or conducting business in such a way as to minimize or eliminate pollution at its source; using energy and natural resources efficiently; decreasing the use of hazardous chemicals; recycling wastes effectively; and conserving or restoring forests, wetlands, rivers, and public park shores (EPA 2013). Other examples of stewardship include tribal, government, and regulatory agencies providing information to landowners and professionals to improve decision making related to determining the need for armor and considering alternatives to hard armor. Finally, stewardship can be practiced by technical professionals, designers, and contractors by using their skills to develop viable options that balance the needs of their clients with the needs of environmental sustainability.

Why Be a Good Steward?

Puget Sound shores are important to all those who are fortunate enough to live nearby and enjoy their picturesque setting. They are also important to millions of citizens living and working in the greater Puget Sound region who use the shore, or the resources it supports, for recreational, economic, and cultural purposes. Without a healthy and sustainable marine shore, not only do we risk decline or loss of biological resources, but we risk our health, our economic well-being, and our ability to enjoy recreational opportunities.

As an example, small fish such as surf smelt and sandlance use beaches with specific grain sizes and elevations to lay their eggs. Larger fish, such as salmon, eat these smaller fish. And larger animals, such as Puget Sound’s iconic Orca whale, eat salmon. If shores are impacted to the degree that beaches required by surf smelt and sandlance for laying eggs are no longer present, there will be less food for salmon which means less food for Orcas, with potential repercussions for their populations. This would be harmful not only from an ecological perspective, but also from an economic perspective.

Maintaining a functional shore that can provide the full range of these services is important for long-term sustainability of our natural resources in Puget Sound. Current hard armor techniques aimed at preventing erosion disrupts these natural functions and necessitates further human intervention, which is both costly and inefficient. Responsible stewardship must include discovering ways to balance the needs of marine shore property owners while preserving the natural processes that sustain the shore.

Being a good steward has the benefit of providing a valuable example for others. People are often hesitant to try new approaches if they are unfamiliar with them. Offering successful examples of alternative techniques can help others to become more comfortable with these approaches, thereby influencing their decisions. In the face of growing population and development in the Puget Sound region, advocacy and information sharing is crucial to the long term sustainability of our nearshore resources.

Shore owners, regulators, scientists, designers, and contractors are all critical to moving beyond highly impactful management approaches including traditional hard armor. Best management practices and soft shore design techniques such as those presented in this document need support and action from all of these individuals. In addition, contractors and technical professionals that responsibly recommend and apply these practices have an opportunity to capitalize upon the growing demand for “green” and “environmentally-friendly” products and services.

How to be a Good Steward of the Shoreline

Coastal erosion is an essential natural process that forms and maintains Puget Sound beaches and shoreforms. In most locations this type of erosion occurs episodically and at a relatively slow rate. A decision to install shore armor is often initiated by a noticeable erosion event, even though there may have been years or even decades of minimal erosion. Such decisions are often prompted by the belief that any amount of erosion is a problem. Before decisions are made regarding the need for installation of any type of shore protection it is important to seek assistance from a trained professional with experience in assessing sites for potential causes of erosion, usually a geologist. Qualified professionals can evaluate site specific conditions to assess causes of erosion and potential risks and develop management recommendations that address specific causes and landowner concerns. If shore protection is needed, information from a professional site assessment provides the foundation for selection of appropriate techniques and project design.

In many cases shore erosion is not posing an immediate threat to upland infrastructure or personal safety and the need for conventional hard armor is not warranted. Moreover, wave energy may not be the cause of the bluff erosion that is occurring. In these cases, implementing steps to manage upland runoff, maintain appropriate vegetation for slope stability, and other best management practices will provide more effective and appropriate solutions than hard shore armor.

Finally, education is critical to being a good steward. Recognizing there are alternatives to traditional hard armor that support natural nearshore processes is vital to improving management of our shores. Consideration of these alternatives should become standard practice in evaluating site specific needs and avoiding unnecessary installation of armor. As stated before, this is not just the responsibility of the landowner, but of all the people and organizations involved in shore development and use decisions.

Workshops, lectures, and educational information on websites provided by local governments, tribes, and non-profit organizations are good venues for learning more about how our nearshore functions and the elements of designs that are compatible with shore processes. Some local jurisdictions provide educational workshops that include visits to local beaches to see examples of the variables that inform site assessments and alternative shore protection designs. There are also local groups that convene meetings with technical experts to explain the physical and biological processes that occur on Puget Sound beaches (e.g., Beach Watchers: http://www.beachwatchers.wsu.edu/regional/index.php).

Several voluntary programs that encourage stewardship of Puget Sound shores are in their beginning stages. In some cases, grants are available to fund armor removal actions, conservation easements, or land acquisitions. In addition, new programs are being developed to support property tax reductions or provide low interest loans for those who exercise wise stewardship of their shore property. Further information on the availability of these programs can be obtained through your local city or county planning offices.

Regulatory Information

There are several government agencies that provide regulatory oversight for work along the shore. It is often beneficial to engage these agencies early in the design process to ensure a desirable outcome. Using the design guidance provided in this document will help minimize project review time. Some regulatory agencies and their roles are identified below.

Utilizing the state's **Office of Regulatory Assistance** is a good first step in determining which permits may be necessary for your project and for answering permitting and regulatory questions. Their website can be found at http://www.ora.wa.gov/resources/permitting.asp.

City and County Planning offices are responsible for implementing local Shoreline Master Programs (SMPs) that apply the Shoreline Management Act at the city and county level. The Act was adopted by the public in 1972 to provide guidance for shore management. Local planning offices also implement the Critical Areas Ordinance (CAO) and the State Environmental Policy Act (SEPA). Contact your local jurisdiction's planning office for more information on SMP, CAO, and SEPA.

United States Army Corps of Engineers is responsible for protecting many of the nation's aquatic environments (commonly termed waters of the United States) including oceans, rivers, lakes, streams, ponds, and wetlands. Work in, over, or under these waters may require a permit from the Corps. Regulatory authority over shore armor originates from two laws: Section 10 of the Rivers and Harbors Act (governs work impacting navigable waters) and Section 404 of the Clean Water Act (for placement of dredge or fill material into waters of the U.S.). http://www.nws.usace.army.mil/Missions/CivilWorks/Regulatory.aspx

Washington Department of Fish and Wildlife is responsible for the protection of fish life through issuance of a Hydraulic Project Approval (HPA). Chapter 77.55 RCW provides authority over construction or performance of work that will use, divert, obstruct, or change the natural flow or bed of any of the salt or freshwaters of the state. http://wdfw.wa.gov/conservation/habitat/permits_regs.html

Washington Department of Ecology checks for compliance with the policies and procedural requirements of the local Shoreline Master Plan and the Shoreline Management Act (Chapter 90.58 RCW). The overarching goal of the Act is "…to prevent the inherent harm in an uncoordinated and piecemeal development of the state's shorelines." http://www.ecy.wa.gov/programs/sea/shorelines/index.html

Washington Department of Natural Resources is the proprietary manager of state-owned aquatic lands and issues use authorizations for projects taking place on or over these lands. At statehood in 1889, Washington's Constitution established state ownership to the "…beds and shores of all navigable waters in the state…" (Article XVII). This includes about 2,000 square miles of marine waters – beaches, tidelands, and bedlands of Puget Sound and the coast, and most of the navigable rivers, streams, and lakes. http://www.dnr.wa.gov/BusinessPermits/Topics/ShellfishAquaticLeasing/Pages/aqr_aquatic_land_leasing.aspx

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Chapter 3. SITE ASSESSMENT

Role and Purpose

The *Marine Shoreline Design Guidelines* provides a structured process to determine the best approach to manage coastal erosion at a given location based on site conditions, which include both natural processes and the built environment. The optimal coastal erosion management technique for a given site should appropriately match the range of conditions at the site, including the causes of erosion and risk to infrastructure, and impact nearshore processes and ecology as little as possible. The goals of this site assessment approach are as follows:

- Reconcile the perceived versus real risks to property and public health
- Assess and measure site conditions including erosion/mass wasting processes
- Identify and quantify site characteristics relevant to the alternatives analysis and the technique design

Due to the high degree of natural variability in site conditions and development features, having a qualified professional visit and investigate conditions at the property is required for a thorough site assessment. Once the site assessment is complete and the components are well understood, the information collected can be integrated with the *Coastal Processes Assessment* (Chapter 4) to inform the selection of an appropriate design technique (Chapter 5). The designer or applicant can then refer to Chapters 6 and 7 for guidance on developing design techniques that address the specific erosion issue(s) at the subject location.

Site Assessment Approach

The site assessment takes into account the site-scale or “footprint” of the subject property and erosion area to determine the mechanisms, potential causes, and driving forces of erosion at the site. The assessment entails evaluating site conditions both in the field and through conducting background research and includes the following:

- An evaluation of existing conditions and processes occurring at and immediately adjacent to the site
- Locations and potential causes of erosion and/or mass wasting
- Human infrastructure at the site, including existing erosion control measures
- Risks to infrastructure, property, and public safety
- The extent and types of nearshore habitats and shoreforms

Is ANY erosion acceptable?

- Erosion may not threaten a house or improvements if there is an adequate setback from the beach or bluff crest (depending on site).
- Landslides typically do not recur in one place for 25–50 years.
- Erosion may be easier to live with than *costly* permitting and installing hard or soft shore protection.

When is erosion “control” NOT recommended?

- On-site evidence suggests a coastal structure will not abate landslides due to upland processes.
- Shore change analysis indicates only a few feet of erosion over 50 years, the site is relatively *stable*.

Figure 3-1. Considerations for erosion and erosion control and whether action is needed (including no-action scenario).

The site assessment is critical to determine if action is required and, if so, what type of approach will be the most effective (Figure 3-1). ***No Action*** as a viable option should be considered by the assessor and communicated with the client or landowner. The no-action scenario, which is discussed further in Chapter 6, may be appropriate if there is minimal risk to infrastructure or improvements at the subject site. A cumulative risk model was developed for this study to provide users with a quantitative approach to measuring risk (see

How to Measure Cumulative Risk section below). If action is required, data from the site assessment will be used to select and design an appropriate erosion control approach that will minimize negative habitat impacts to the extent possible. Shoreline recession of inches or a few feet in one erosion or landslide event can trigger a perceived need for erosion control, even when overall erosion has been minimal for the previous 50 years. Reconciling the perceived versus real need for erosion control is also a part of the site assessment. An inquiry into the landowner concerns associated with erosion should be conducted during the site visit.

This chapter describes how to conduct a site assessment in order to develop a better understanding of site conditions and the coastal and upland processes affecting them. A formal site assessment should be completed by a qualified professional with proper training and experience (see *Necessary Level of Expertise* section at the end of this chapter). A landowner can also gather information as part of an informal site assessment when considering treatment options and for use in discussions with appropriate technical professionals. See the *Glossary* at the beginning of this document for definitions of terms and acronyms.

Conducting a Site Assessment

First and foremost the scope, or level of detail, necessary for any particular site assessment should be considered. This will typically be dependent on the following:

- Landowner concerns and specific project objectives
- Degree of erosion or slope instability
- Complexity of the site geology, wave climate, and hydrology
- Risks posed to public safety and site infrastructure
- Permitting and local regulations

Clear project objectives guide the assessment and design process, and balance the needs of the landowner within the constraints of natural coastal and slope processes. The project objectives should be placed within the appropriate regulatory context (the requirements of local, state, and federal regulations) including constraints imposed by the presence of critical habitats. Some site assessments begin with clearly defined objectives, which are sometimes complicated by limitations identified during the site assessment process. Under these circumstances, integrating several solutions may be required. Unstable, rapidly eroding sites may require more detailed data collection, particularly where structures are at risk. Other sites such as small parcels with readily identified causation of erosion require a more streamlined site assessment process. More complex sites (e.g., a site with multiple drivers of erosion, or with a home at risk and forage fish spawning habitat present) require more detailed data collection and analysis. Specific site assessment approaches used for assessing drainage issues are included in Myers et al. (1995) and vegetation management for erosion control in Menashe (1993) and Myers (1993).

The site assessment procedure for marine shores is divided into the following sections which are expanded upon in more detail throughout this chapter:

1. Background information and remote sensing
2. Site visit and characterization
3. Defining and identifying the problem
4. Preliminary assessment of risk

Background Information and Remote Sensing

Researching background information and compiling existing data is crucial to the value of a site assessment. Background information consists of site development history and changes to the shoreline, existing reports, land use and permitting regulations, anecdotal information from local residents, best available regional science publications, and any remote sensing data available such as aerial photos, LiDAR, and coastal and geologic maps. Background information provides an initial perspective on site conditions and processes, a framework for site observations, insight into constraints for accessing the site, and an initial perspective for potential design work.

Site development history should include predevelopment conditions of the site if available, and any upslope changes in land use. The assessment should delineate areas of existing fill or excavation, identify any drainage and septic systems that may be leaking or otherwise vulnerable, describe any buried contaminated debris, and identify historical wetlands (Clancy et al. 2009). Puget Sound Change Analysis (Simenstad et al. 2011; see online data resources below) data sets can be referenced to identify fill areas, changes to the current configuration of the shore, and the presence of historical wetlands. Fill data included in Simenstad et al. (2011) is coarse in scale and far from comprehensive, so additional field investigations should be conducted to determine if fill is present at the site. Site development history can be obtained through review of county or city records and historical aerial photographs, as well as through interviews with the client, landowner, neighbors, or other members of the community.

Determining the ***history of shore change*** at a site can inform what type of design technique may be appropriate, as well as potentially inform design. Beach or bluff erosion rates can often be measured by careful comparison of historical maps or aerial photographs with current conditions. This work is typically conducted in GIS and requires systematic attention to proper image selection, orientation, and correction. Recommendations for shore change work in Puget Sound are outlined in Johannessen (2009), and include documenting erosion rates over a long enough time (ideally more than 50 years) to dampen the effect of short-term changes. Aerial photography is often available at a sufficient scale for this type of analysis going back to the 1960s or earlier. Imagery at scales greater than 1:20,000 is not appropriate for this application, though qualitative observations can be useful. The US Coast and Geodetic Survey's Topographic Sheets (T-sheets; see online data resources below) show predevelopment shoreline mapping from the 1800s. These maps are often very valuable for understanding historical conditions. Where available, detailed maps or survey drawings are also very useful. Assessment of shore change at the landscape scale is discussed in Chapter 4.

Current and historical land use and associated ***land use regulations*** may have implications as to what actions may be taken on the site and how those actions might be accomplished. For example, land that is zoned for commercial use may have different regulatory restrictions regarding mitigation actions than sites zoned for single-family residential use. A project proponent should become familiar with local Shoreline Master Program (SMP), Critical Areas Ordinance (CAO), zoning, and other regulations. SMP and CAO regulations are put into place by city and county jurisdictions to identify environmentally sensitive natural resources and protect and preserve the natural environment's ecological resources in the context of responsible development and growth management.

Permitting requirements for a given site will vary. Typically, a Joint Aquatic Resources Permit Application (JARPA) and a State Environmental Policy Act (SEPA) checklist will be filled out for the project and submitted to the appropriate jurisdictions. JARPA information can be found at www.epermitting.wa.gov and SEPA information can be found at www.ecy.wa.gov/programs/sea/sepa/e-review.html. These websites are a good starting point for understanding permit requirements but a professional scientist or permit coordinator may be needed to ensure the project complies with regulations. A working knowledge of the types of permits and jurisdictions administering the permits can expedite the permitting process and help to outline appropriate data to collect during the professional site visit. Additionally, permit constraints can modify project objectives.

Washington Department of Fish and Wildlife (WDFW), local entities including city and county governments, and sometimes Indian tribes and the US Army Corps of Engineers (USACE) typically have jurisdiction on marine shoreline projects in the Puget Sound region. The Washington Department of Ecology (Ecology) and Washington Department of Natural Resources (DNR) are other state-level agencies that can have a role depending on project location and constraints. If the project does not fall under any other federal agency domain due to project location and constraints, the Federal Emergency Management Agency (FEMA) may also have jurisdiction in ensuring the Endangered Species Act (ESA) is being upheld. Local jurisdictions administer Shoreline Exemption or Substantial Development permits as well as other building and land disturbance permits. In order to comply with regulations, additional documentation may be needed, such as ESA documentation (Biological Assessment [BA] or Biological Evaluation [BE] depending on project constraints), a Critical Areas report, or local building and land disturbance permits.

It is also important to note that the marine shores of the Puget Sound region have been used by people as habitation sites and for subsistence activities for thousands of years. Evidence of this history is commonly discovered during work in the nearshore. As a landowner, it is important to recognize that marine shore properties are sensitive areas that could contain items and materials left by prior inhabitants; these materials are broadly referred to as cultural resources (i.e., archaeological and historic sites or isolated artifacts). Investigating whether a site has known cultural resources prior to the site visit will inform how to proceed.

Recommended ***online data resources*** to support the site assessment process include, but are not limited to, those listed below. The reader may also be referred back to this section from points later in the chapter where items in the Site Characterization Checklist (Table 3-1) are described.

PHYSICAL DATA:

- Ecology Coastal Atlas includes aerial photographs, as well as slope stability, coastal habitat, and other information about Puget Sound https://fortress.wa.gov/ecy/coastalatlas/
- WDNR provides surficial geology data http://www.dnr.wa.gov/researchscience/topics/geosciencesdata/pages/gis_data.aspx
- The WDNR Geologic Information Portal provides limited subsurface boring data http://www.dnr.wa.gov/researchscience/topics/geosciencesdata/pages/geology_portal.aspx
- The LiDAR data set includes digital elevation model (DEM) and hillshade components, which can be used to give approximations of elevations and larger “lay of the land” (physical) features that may affect the site http://pugetsoundlidar.ess.washington.edu/
- Individual city and county geodata and GIS centers on planning, public works, and natural resources department websites increasingly provide natural resources maps and data available for viewing or downloading.
- Survey monument data and benchmarks can be found in the Washington State Department of Transportation (WSDOT) Survey Monument Database http://www.wsdot.wa.gov/monument/

BIOLOGICAL DATA:

- WDFW Priority Habitats and Species (PHS) data are available on the WDFW website http://www.wdfw.wa.gov/conservation/phs
- The PSNERP website (see below in Best Available Science) has technical reports on marine birds, salmon, forage fish, shellfish, and submerged aquatic and marine riparian vegetation.
- Shorezone Inventory of nearshore habitats including eelgrass is available for download at http://fortress.wa.gov/dnr/app1/dataweb/dmmatrix.html

HISTORICAL DATA:

- 19th century US Coast and Geodetic Survey T-sheets are available at http://riverhistory.ess.washington.edu/data.php
- Historical vertical aerial photos can be found through city and county planning departments, the WDOE Coastal Atlas, WSDOT, DNR, and by request through the National Archives http://www.archives.gov/

BEST AVAILABLE SCIENCE PUBLICATIONS:

- The Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) library provides technical reports on topics ranging from restoration principles to ecosystem services to habitats and species http://www.pugetsoundnearshore.org/

PERMITTING:

- The Ecology introduction to shoreline permits is available at http://www.ecy.wa.gov/programs/sea/sma/st_guide/administration/index.html

Site Visit and Characterization

Characterizing a site takes place through information gathered by a professional during a site visit and involves describing physical aspects (conditions and processes) of the site and the adjacent areas, making observations, and investigating the potential cause(s) of erosion and mass wasting (landslides). Characterization provides an understanding of the interactions of coastal, geologic, and ecological processes at a site which constitutes the foundation for determining the best course of action for that site. Variability in beach and upland conditions often occurs within a parcel and in many cases a subject site may need to be split into smaller more homogenous reaches of shore. This is common where sites include multiple shoretypes or drift cells or areas in which armor or other design techniques are already employed (see Chapter 4).

Seasonality should also be considered when conducting a site assessment, as the beach profile often changes form from summer to winter. Winter profiles are often more eroded and steeper, while summer profiles can have a lower gradient. In some cases this variability may require additional assessments to capture the nature of the site conditions during the alternate season.

The *Site Visit Checklist* (Table 3-1) is provided as a guide for the types of data to collect in the field during a professional site visit. Sketches and photographs for site documentation are also a fundamental part of the site visit to show spatial relationships of key features and the possible interaction between coastal, upland, and ecological processes.

Preparation of a site plan that shows data collected during the site visit is typically required as a basis for detailed assessment findings and later design work. Figure 3-2 shows an example site plan generated from collected field data for a residential site.

Table 3-1. Site visit checklist to guide data collection and questions to assess site-based causes of erosion.Key listed items are further detailed below in bold italics.

Site Visit Checklist

Geology and geomorphology

- ☑ geology: units/stratigraphy, slope character
- ☑ landslide activity: year and type, potential drivers*
- ☑ groundwater, relative sediment permeability, hydrophilic vegetation
- ☑ geomorphology: shoretype, localized beach features, erosion scarps*
- ☑ wave climate & coastal flooding
- ☑ evidence of coastal erosion*
- ☑ beach sediment & grain size
- ☑ backshore features: dimensions, LWD, vegetation
- ☑ alongshore site segments: delineation & descriptions
- ☑ cross sections: elevations, bluff top & toe, backshore features, MHHW, slope & toe of beach, water line

Upland surface water drainage

- ☑ general watershed conditions, streams, wetlands
- ☑ seeps and springs
- ☑ drainage control: water sources: stormwater systems, discharge points, impervious surfaces*

*See below, Defining and Identifying the Problem: Site-Based Causes of Erosion.

Site vegetation, habitat, and species

- ☑ native vegetation, plant species present, erosion control*; indicate processes*
- ☑ vegetation condition, communities
- ☑ juvenile salmon, forage fish habitat
- ☑ animal species present, animal usage

Cultural resources

- ☑ potential historical use, shell midden or other evidence

Site development features

- ☑ primary structures/ locations: houses, roads, septic; setbacks, potential to relocate
- ☑ secondary features: sheds, garages, driveways, unattached patios; potential to relocate
- ☑ irrigation and water features: irrigation, ponds, fountains
- ☑ presence of fill or excavated areas
- ☑ potential for contaminated sediment or debris

Erosion control structures

- ☑ type of structure and material used
- ☑ condition of structure
- ☑ structure elevation

Determining Site-Based Causes of Erosion

- ☑ Where on the site is erosion occurring?
- ☑ What type of erosion or mass wasting is occurring?
- ☑ Why is erosion occurring?

  Potential causes:
  - ♦ Wave attack
  - ♦ Historical beach gravel mining (on site)
  - ♦ Historical fill (only) eroding
  - ♦ Bluff geology
  - ♦ Adjacent coastal structures
  - ♦ Surface/ground water management
  - ♦ Vegetation clearing
  - ♦ Site excavation or other modifications
- ☑ How fast is erosion occurring?
  - ♦ On-site evidence
  - ♦ History and type of landslides
  - ♦ Aerial photograph measurements
- ☑ Is erosion short-term or cyclical?
  - ♦ Temporary storm damage
  - ♦ Seasonal erosion/accretion
- ☑ What development or improvement is at risk?
  - ♦ Substantial, such as house or septic system
  - ♦ Roads or utilities
  - ♦ Other unsubstantial improvement

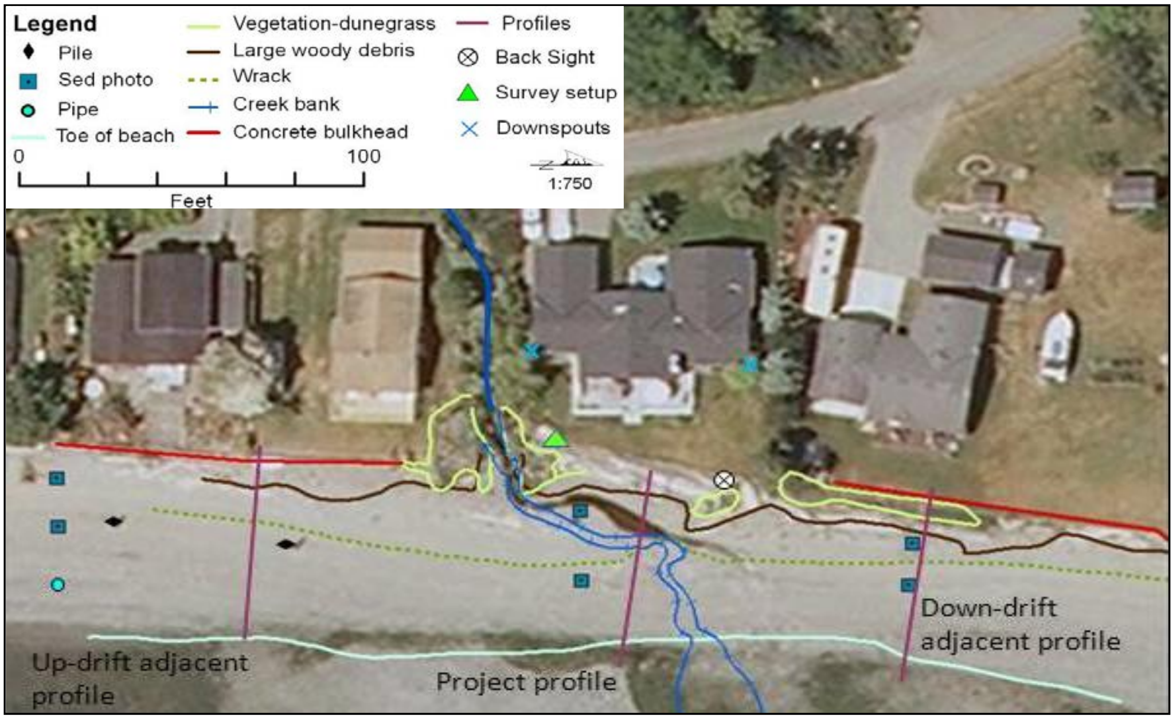


Figure 3-2. Example site plan created following a residential site assessment conducted by CGS (Oak Bay Case Study site detailed in Appendix A).The features on this map reflect items in the Site Visit Checklist (Table 3-1). Not all items in the checklist were relevant to the objectives of this specific site assessment.

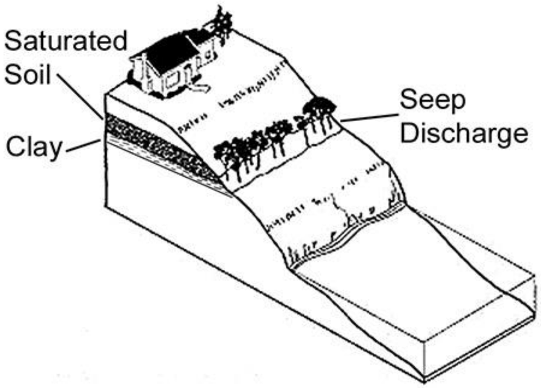
Geology and Geomorphology

Geologic, geomorphic, and hydrologic conditions of a bluff or beach site may be interdependent or influenced by one another. These features are assessed collectively, but described separately.

In assessing the ***geology*** at a site, field data collection should include descriptions and measurements of the different geologic units including soil and rock unit descriptions and classifications, and where the unit was found at the site. The stratigraphy, or relative position of different geologic units, may play a key role in the mechanism and magnitude of erosion or mass wasting that takes place at a site due to the strength and relative permeability of particular geologic units (explained below). Stratigraphy can usually be determined from bluff exposures at the site; however, at large industrial-scale sites where investment is high and bluff exposures are lacking, subsurface boring data may also be needed. The site assessment should describe slope inclination, form, and aspect of the bluff as each of these elements are relevant to the stability of the bank and the recession rate.

Evidence of past ***landslide activity*** can include landslide colluvium at the bluff/bank toe, bowl-shaped slope morphology, hummocky ground, leaning trees or bowed trunks, recently exposed soil or sediment, or even-aged immature vegetation (Shipman 2004). Toe erosion can destabilize slopes by undermining the toe of the bluff and should be mapped if present. Locations and years or relative ages of landslides should be documented if possible. Investigation by a qualified professional into groundwater, bluff stratigraphy, and upland-related processes may identify ways to minimize both shallow and deep-seated instability.

Groundwater ponding in the uplands or seeping from a bluff face or slope toe can indicate the presence of potentially destabilizing processes. This topic is also discussed in Chapter 1 and Technique 3 (*Reslope/revegetation*) in Chapter 7. Subsurface data from geotechnical borings and nearby water-well logs also provide useful information on potentially destabilizing slope processes. ***Relative sediment permeability***, or differences in permeability between stratigraphic layers, can affect groundwater flow, weaken certain layers, and trigger instability. For example, groundwater moves easily through sand and gravel strata, but tends to perch on underlying fine-grained strata. This is a typical stratigraphic sequence in Puget Sound bluffs (Figure 3-3). ***Hydrophilic vegetation*** (water-loving vegetation) at distinct locations across or in localized groups on the bluff face should be noted, as it may also indicate groundwater seepage at the interface between stratigraphic layers. Groundwater seeps and other vegetation clues can help identify slide surfaces and other potential areas of bluff instability (also see Chapter 6).



Vegetation Clues to Slope History and Stability:

- Hydrophilic vegetation = seeps and springs
- Examples include willow, alder, cedar, horsetail
- Groups of even-aged trees across a slope = slide area, groundwater discharge, impervious strata
- Leaning trees = soil creep, shallow slides, deep-seated rotational slides (trees tilted up-slope)
- Bluff face devoid of vegetation = recurring erosion/ landslides, soil that cannot support vegetation

Figure 3-3. Water-loving vegetation as indicator of seepage, and other useful vegetation clues (Menashe 1993).

Geomorphology pertains mainly to landforms and processes that shape them. Observations and measurements based on shoretype, aspect, beach slope, and other localized features such as berms, seeps, and scour should all be noted (Figure 3-2). Impacts to the beach from existing shore armor, such as erosion scarps adjacent to the structure, should also be noted; see additional detail in the section below entitled *Defining and Identifying the Problem: Site-Based Causes of Erosion*.

Wave climate refers to the wave conditions at a subject site as defined by wave height, period, direction, and angle of approach with respect to shore orientation. It is dependent on intensity of waves (driven by fetch, the length of open water distance over which wind waves can form, or exposure of the site to swell) and orientation of the site to the prevailing and predominant wind direction. Wave climate at a site can be researched beforehand (Table 3-2) by determining the fetch and prevailing wind direction as well as the orientation of the shore with respect to the prevailing wind direction. In the greater Puget Sound region, the relative wave energy can be classified by site fetch as seen below in Table 3-1 (adapted from Cox et al. 1994). Wave climate has a strong influence on the character of the beach and associated erosion potential. Typically, drift-aligned (see *Glossary*) and/or high-wave-energy sites can have higher erosion potential when compared to swash-aligned or low-energy shores. Low lying coastal areas, susceptible to ***coastal flooding***, can also be affected by wave climate. Flood zone mapping on the WDOE Digital Coastal Atlas can be referenced to determine if the site is located within an area vulnerable to coastal flooding.

Any evidence of ***coastal erosion***, such as beach scarps, should be documented and described, as it is often an indicator of wave attack and marine erosion (Figure 1-5). Damage to infrastructure apparently caused by wave attack should also be noted, along with approximate timing of the damage. The exposure of the underlying strata through a lack of beach sediment can be indicative of beach erosion.

Table 3-2. Relative wave energy based on fetch (for southern quadrant and prevailing winds). For northern quadrant the measured fetch should be halved to assign the relative wave energy category.

Fetch	Relative Wave Energy
0–1 mile	Low
1–5 miles	Moderate
5–15 miles	High
15+ miles	Very High

Beach sediment and grain size should be documented at different elevations on the beach, such as in the upper intertidal beach and in the backshore. This informs the determination of habitat conditions and potentially design details. Describing beach sediment size also has relevance for potential future monitoring and seasonal changes to the beach profile. Sediment composition can be documented during the site visit with a scaled grid or common objects for reference (Figure 3-4). Various sampling methods for beach sediment size classification exist, including surface and subsurface sampling at distinct beach elevations. For larger sites a sieve analysis of the samples can then be conducted and categorized based on the Wentworth Size Class (Wentworth 1922), which offers a size scale of grade and associated terms of clastic sediments, or on the Unified Soil Classification System (USCS), which classifies soils based on texture and grain size (ASTM 1985). Natural seasonal variation of beach elevation and sediment size may occur at the site and may require additional assessment during different seasons.

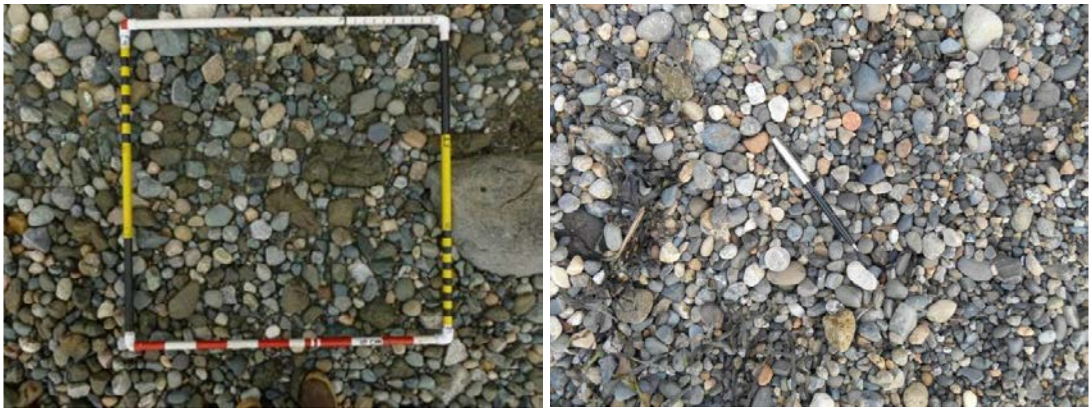


Figure 3-4. Documentation of beach sediment size through photos with a scaled grid or a common object such as a pencil.

The character and configuration of the ***backshore*** at the site is particularly relevant to what design technique is appropriate for the site. No backshore is present where armor covers the backshore or where there is a low-energy bluff shore. Backshore measures such as width, length, the presence of storm berms, and associated elevations should be documented. Large woody debris (LWD) abundance and location should be measured and described including the most landward extent of LWD, which can be indicative of high water events. Backshore vegetation cover and community composition should be described. The backshore, or lack of, is an essential component to document in the cross section (see below).

Dividing the site alongshore, or ***site segmenting***, can aid in describing the site. These segments (also referred to as reaches) can be delineated based on initial site observations of different shoretypes, areas that may require different actions, or presence and absence of development features. Each segment should be well-defined and include descriptions, photographs, GPS measurements, and sketches to highlight site features of interest

(Figure 3-5). This process can demonstrate spatial relationships and interactions of site features that may be contributing to erosion at the site.

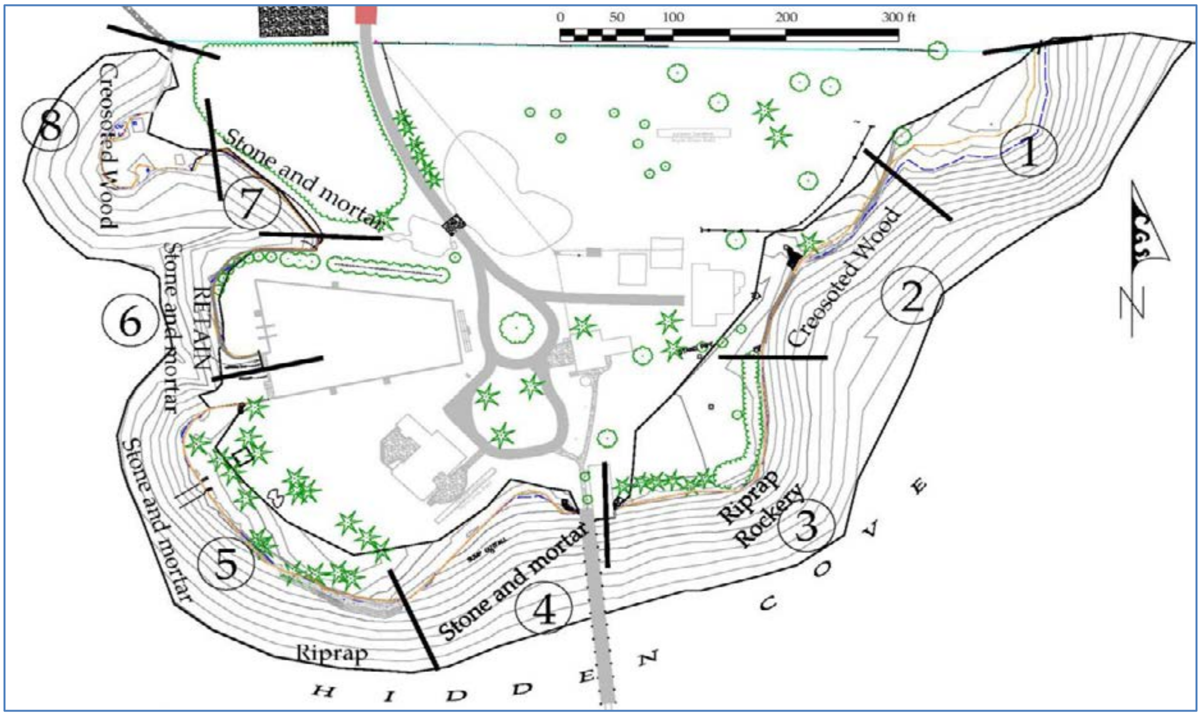


Figure 3-5. Site segmenting based on potential armor removal action as shown in plan view (CGS 2011).

Cross sections represent measured beach, bluff, and development features observed perpendicular to the shore. Measurements should include length, height, and elevation of key or defining features (Figure 3-6). Cross sections associated with elevations of beach features are also referred to as beach profiles (Downing 1983). Cross sections at bluff sites can include stratigraphy and hydrology.

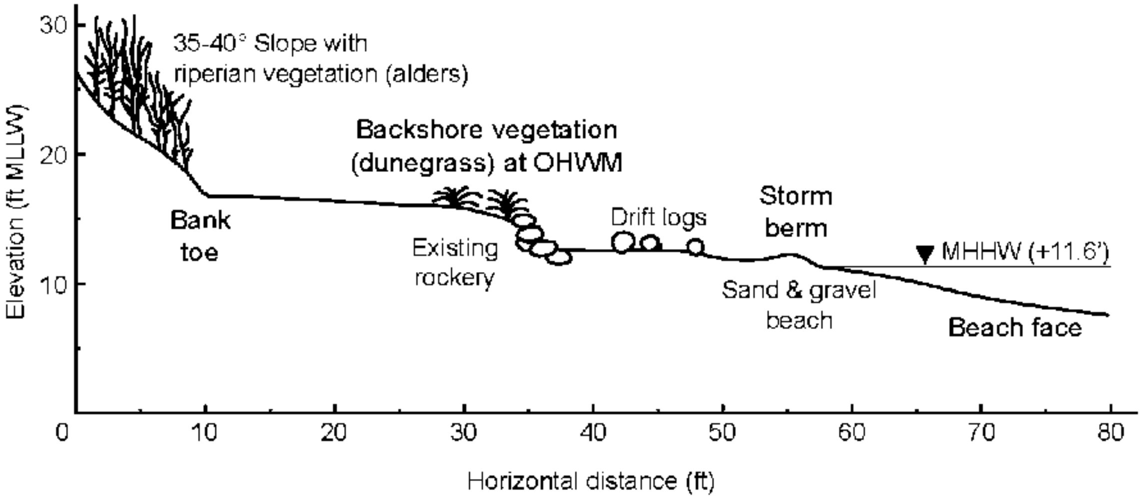


Figure 3-6. Cross section of existing conditions for a bulkhead removal project site (Johannessen et al. 2011).

Cross sections may include, but are not limited to the following features (also see terms in *Glossary*):

- Beach toe or low-tide terrace
- Beachface and storm berm
- MHHW and OHWM
- Drift log line
- Backshore or salt marsh vegetation
- Shore armor structure(s)
- Bluff or bank toe
- Stratigraphy, slope, bluff crest
- Riparian vegetation
- Groundwater seepage on bluff face
- Upland development/drainage features
- Setback distances for upland structures

The location and elevation of all of these features within the cross section will guide the design process for potential erosion control measures or enhancement approaches for a site. For example, removal of salt marsh vegetation is typically not allowed. If considering a large wood project, the location and elevation of the natural drift log zone is a key piece of information to show on cross sections. Example cross sections drawn to the appropriate scale for the project objective are available for each of the case study sites in Appendix A of this document.

Upland Surface Water Drainage

Conditions up-slope from a site influence water input and slope stability. Whenever wet or moist soils are encountered, or if there is a concern regarding landslides at the site, upland water drainage should be examined.

Watershed conditions, stream or drainage contributions, and wetlands upslope of, or adjacent to, the site should be noted as this may influence drainage regimes at the site.

Seeps and springs apparent in the uplands or bluffs should be noted and investigated. This includes features associated with the action of groundwater movement through the bluff face, including piping, wet layers within stratigraphy, and hydrophilic vegetation. If seeps and springs appear to be causing erosion or mass wasting on the bluff or if the erosion is in close proximity to the seeps or springs on the bluff this should be noted. As shown in Figure 3-3, seeps can indicate slip surfaces for bluff failure and are often marked by specific vegetation types.

Drainage control features associated with the infrastructure should be noted; these include gutter downspouts, trench drains, and drainage pipe size and material (such as “8-inch diameter HDPE tightline”). The relationship of the drainage infrastructure components, as well as any potential damage or vulnerability to the infrastructure, should be described. If drainage outlets coincide with erosion or landslide areas, this should be noted. Water sources including stormwater systems, discharge points, and impervious surfaces should be located and described. Figure 3-7 illustrates potential sources of surface water related to infrastructure.

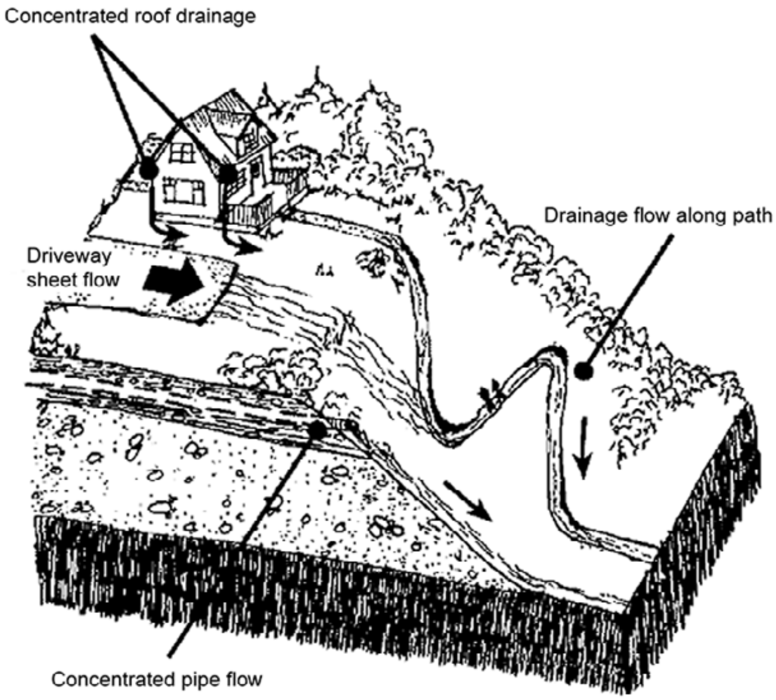


Figure 3-7. Illustration of potential on-site sources of surface water drainage to a coastal bluff (Myers et al. 1995).

Site Vegetation, Habitat, and Species Considerations

Site vegetation, habitat, and species considerations are interrelated. The condition of the flora and fauna at the site can inform the quality of habitat, degree of habitat degradation, and the processes taking place at the site.

Native vegetation representing a natural landscape provides the best benefit to any nearshore habitat and can also provide a high degree of erosion control and slope stability. The slope stability properties of native vegetation are well known and are therefore included in this document as an erosion control technique *Reslope/revegetation*. Vegetation can protect slopes by reducing erosion, strengthening soil, and inhibiting landslides to increase general slope stability (Myers 1993, Menashe 1993). In particular, dunegrass and marine riparian vegetation have been successful in preventing or reducing coastal erosion. Performance of vegetation as erosion control has been evaluated in the Reslope/revegetation design technique case studies in Appendix A.

Vegetation present at a site can indicate processes operating at the site. For instance, hydrophilic vegetation (see Figure 3-3) can inform slope processes and nearshore salt-tolerant vegetation can inform extent of coastal processes (Figure 3-8).The presence of salt-tolerant species can offer visual indication of local tidal elevations or areas that are susceptible to wave runup and inundation.

The ***vegetation condition*** and vegetation communities at the site should be described, as well as the appropriateness of existing vegetation for the location (for example, salt tolerant plants closer to shore and native plant assemblages as opposed to lawn and ornamental species) and whether the vegetation conditions for the existing habitat can be improved. Site vegetation can provide indicators of habitat health based on species utilization. Key ***vegetation communities*** to locate at the site include the following:

- Submerged aquatic vegetation, in particular eelgrass and bull kelp, provides vertical habitat structure to these zones; many species use this habitat for rearing, foraging, and protection.

- Salt-tolerant vegetation such as pickleweed (*Salicornia virginica*) and saltgrass (*Distichlis spicata*) typically grows in the upper intertidal and above (Figure 3-8).
- Backshore vegetation communities, including dunegrass (dune wild rye; *Leymus mollis*), add an erosion control component to the nearshore.
- Marine riparian vegetation provides benefits for habitat and erosion control.

Figure 3-8. Pickleweed (left) and saltgrass (right) are vegetation indicators of tidal elevations (Photos from Weinmann et al. 1985.)

Observed or documented presence of animal species may impact future project considerations and permitting. The habitat needs of ***juvenile salmonids*** include a degree of complexity in shore morphology, presence of marine riparian vegetation, and a percentage of overhanging vegetation alongshore for production of terrestrial macroinvertebrates (Brennan 2007). ***Forage fish*** spawning habitat needs include beach sediment size between 0.5 mm and 7.0 mm at the upper beach and presence of overhanging marine riparian vegetation for shading and temperature control (Penttila 2007).

WDFW produces a record of Priority Habitats and Species that includes forage fish (sand lance, surf smelt, and herring holding and spawning), salmonid species (presence/migration, known juvenile rearing, and known spawning), shellfish species, marine birds, and marine mammal habitat usage areas. These data represent sensitive species; therefore, the data are distributed from the agency at their discretion as a map or a GIS database (http://www.wdfw.wa.gov/conservation/phs/maps_data/).

The following are key species for habitat consideration in the nearshore:

- Forage fish with potential spawning areas in the upper intertidal (suitable spawning sediment is 1–7 mm for surf smelt and 0.5–3 mm for sand lance)
- Juvenile salmonid species (known presence, known usage, or presence verified by sampling)
- Any other species listed under the Endangered Species Act as threatened or endangered

Any animal species or evidence of their presence found on the site should be included in site visit notes. Observations of marine invertebrates, shellfish, fish, sea birds, and mammals based on habits, tracks, remains, or actual sightings can provide valuable baseline documentation and suggest implications for habitat conditions. Animal usage of the nearshore, for example animals nesting, burrowing, or grazing, may also affect or be affected by coastal erosion. For instance, bank swallows build nest cavities in bluffs, mammals create paths and trails down bluffs to access the water, and deer and other animals graze on vegetation which can reduce the success of vegetation establishment.

Cultural Resources

Many coastal sites in the Puget Sound region were historically the homes of Indian tribes. Some level of archaeological work may be required before a project can move forward. Otherwise, work may be put on hold at these culturally sensitive areas in order to conduct a cultural resources evaluation. The evaluation will determine the appropriate preservation or mitigation measures, as discussed in the *Permitting Requirements* section above. Examples of evidence that may be found during a site visit indicating a culturally sensitive area include shell middens, fire pits, and burial grounds. Cultural materials must be adequately characterized and documented to determine the appropriate preservation or mitigation measures. Early consultation with a professional archeologist with experience in the project area is recommended if cultural resources are found or anticipated.

Site Development Features

Surrounding site development should be fully investigated and documented during the site visit. The example in Figure 3-9 shows development features to be measured in relation to the position of the beach and bluff.

Appropriate setbacks of ***primary structures*** from a potentially receding bluff crest should be considered based on site conditions already assessed. Primary structures include houses and valuable buildings. Questions to consider include:

- Does the setback seem adequate given the current conditions of the bluff?
- Will the structures be at risk in the near future (such as within 3 years)?

If risk to structures is imminent, explore if there is space to relocate the structures landward or otherwise out of reach of the erosion.

The location of ***secondary structures*** and infrastructure such as sheds, garages, driveways, or unattached patios should be measured as distance from bluff crest. These secondary structures are often movable, thereby mitigating any threat from coastal erosion. Also, the landowner should be aware that loss of lawn and landscaping will not justify installation of erosion control structures.

Irrigation and water features including irrigation systems, ponds, and fountains should be located and assessed to determine whether they are functioning properly. Any discharge points should be inspected. These systems can contribute additional water to the site and further destabilize existing conditions.

Fill and excavated areas at the site as observed or determined from prior land uses or mapping should be documented. The presence of fill can introduce unstable areas that react differently to surface and groundwater movement and erosion processes. Excavated areas can introduce pathways for water flow that alter the natural land configuration and destabilize areas within the site.

The presence of any ***contaminated sediment or debris*** resulting from prior land uses should be determined. At urbanized or industrialized sites a legacy of contamination is common. The presence of contamination can drastically change the scope of the project. WDOE maintains a database of known contaminated sites which can be referred to.

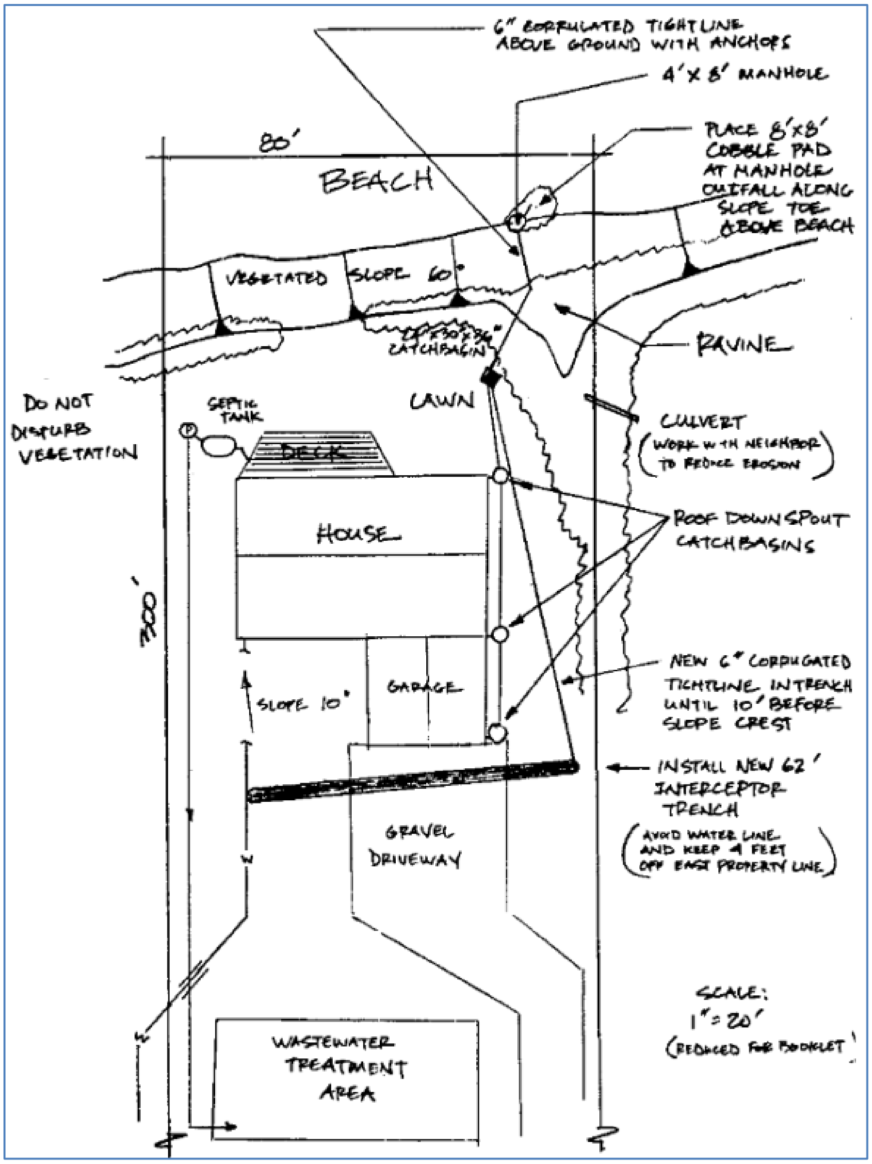


Figure 3-9. An example sketch of development features and measurements, including location of structures and surface water drainage points, as well as their setback location relative to the beach and bluff (Myers et al. 1995).

Erosion Control Structures

Existing erosion control structures should be described in detail. The ***type of structure and material used,*** along with dimensions and approximate quantities, should be documented and included on the cross section drawing.

The ***condition of the structure*** should also be documented, as this may influence future actions taken at the site. Features to look for include cracks, toppling, rot, and other types of degradation which impact the integrity of structures.

The ***structure elevation***, including the toe and crest of the structure should be determined. If elevations are not known accurately, the elevation relative to local MHHW can indicate if habitats have been buried and the degree of habitat degradation. This is especially important if there is consideration for rebuilding, repairing, or removing the structure. Erosion associated with the structure as observed, measured, or possibly caused by the structure should be documented. This would include undermining of the toe of the structure.

Other Considerations

Construction access should be evaluated while conducting the site visit to allow potential planning for project implementation. Access routes to the site are a key constraint on many small properties and determination of whether any heavy equipment should access the site via land or water should be noted. Accommodations may be necessary in either case. For land access, there may be an existing access road or installation of a temporary access may be needed. For water access, a path may need to be temporarily cleared of large boulders in the intertidal for a barge landing. This information will be useful for the design stage.

When collecting field measurements it is often useful to establish and record fixed monuments or to use existing fixed points for potential future monitoring at the site. Beach profiling, taking simple beach elevation measurements related to key site issues, or creating simple measurement stations to the crest of a receding bluff could be useful for better understanding the site-based and coastal processes acting upon a site. Obtaining these data while at the initial site visit could assist in shaping future project actions or treatments. Monitoring is discussed in greater detail in Chapter 8.

Identifying the Problem: Site-Based Causes of Erosion

The site assessment and subsequent analysis of assessment data need to examine the types, locations, and causes of erosion occurring at the site. This section focuses on site assessment data which indicates that erosion in specific areas is caused by specific site features or conditions. This is in contrast to erosion which is caused by features or conditions away from the site, often in the up-drift portion of the drift cell. These off-site or coastal processes-based causes of erosion are outlined in Chapter 4.

Coastal erosion is often driven by more than one factor; however, identifying the main driver of erosion at the site can help determine the best management approach or approaches. This section summarizes how to identify the dominant type of erosion or mass wasting using data from the site assessment. This is typically considered to be the primary “problem” at the site. In cases where multiple causes exist, several approaches may be necessary to address each. Beach erosion can be caused by a single or a number of factors in Puget Sound. Bluff erosion/ mass wasting is commonly caused by a combination of factors, as seasonal factors such as storms interact with locally variable bluff geology and surface/groundwater, surficial instability, deep-seated instability, and management practices (Macdonald et al. 1994, Johannessen and MacLennan 2007).

It is important to accurately collect assessment data, to use these data to determine and substantiate causes of erosion or bluff retreat, and to assess existing site management practices (surface water runoff, drainage conveyance, fill placement, structures, other) and upland processes (road culverts, large-scale land-use practices, excessive irrigation, other) relative to geologic/hydrologic or coastal processes. Table 3-3 draws linkages between common types of erosion or mass wasting and common causes.

Erosion or mass wasting at a site can be characterized by the location or area affected and should be associated with potential causes if appropriate. Although wave attack is a natural force that can cause erosion with or without anthropogenic modifications, erosion can be exacerbated and focused by modifications to the site. Examples of erosion specific to barrier beach and bluff sites and causes associated with each are shown in Figure 3-10.

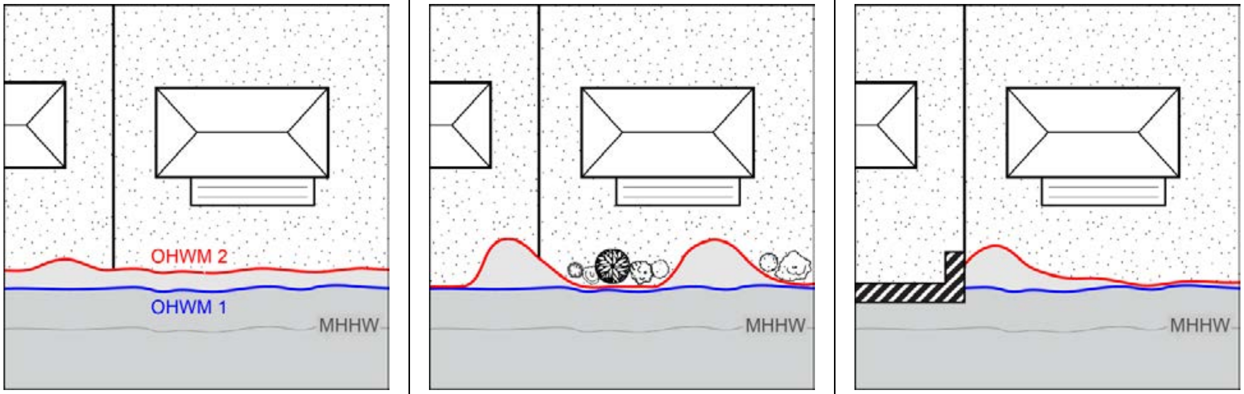
Table 3-3. Types of erosion or mass wasting linked with site characterization data and potential causes.

Type of Erosion or Mass Wasting	Location	Site Characterization Data	Potential Causes
Beach/backshore erosion—entire site	Upper beach/backshore	Erosion scarps, erosion rate, sediment size	Wave attack, decreased sediment supply or transport, boat wakes, on-site gravel mining
Beach/ backshore erosion—specific area	Upper beach, backshore, or adjacent to structures	Erosion scarps; extent and timing of erosion; sediment size; structure location, elevation, and character	Altered wave action at structures, vegetation management
Bluff toe erosion	Toe of bluff	Evidence of beach erosion, extent of toe erosion, bluff composition and slope	Wave attack, decreased sediment supply, altered wave action at structures
Mass wasting (landslide)	Lower to middle bluff face	Extent of mass wasting, bluff composition, groundwater, surface water	Wave attack, altered wave action at structures, bluff geology, vegetation clearing, deep-seated slide
	Bluff crest to upper bluff	Extent of mass wasting, bluff composition, groundwater, surface water	Bluff geology, vegetation clearing, bank loading, surface/groundwater management, deep-seated slide
Rilling or gully formation	Discrete area of bluff	Extent of erosion, bluff composition, surface water and control	Uncontrolled, focused, or poor site drainage affecting surface water drainage, vegetation clearing

In these barrier beach examples (Figure 3-10), the left hand frame illustrates natural and area-wide backshore erosion which was not caused by site-based conditions. For this determination, it is first necessary to ensure that the erosion is not occurring in fill. There may be coastal processes causation for widespread erosion, which is addressed in Chapter 4. The center frame illustrates localized wave overwash into the backshore in areas where robust vegetation was not present and only lawn was present. This is a site-based expression of localized erosion which could be caused by natural wave processes and which could be exacerbated by coastal processes. It is critical to bear in mind that infrequent wave overwash that does not directly damage improvements is a natural occurrence and does not by itself constitute a need to take action. The right frame shows a barrier beach site with very localized erosion caused by end effects (also called end-erosion; see Chapter 1) from an adjacent bulkhead.

The location of erosion or mass wasting at a bluff is influenced by impacts from wave-induced erosion, upland processes, development, or cumulative issues affecting the observed condition, as outlined in Chapter 1 (Shipman 2004, Hampton et al. 2004). For example, the left frame in Figure 3-10 shows randomly distributed landslides after a severe winter, without a site-based cause. The center frame illustrates end effects from an adjacent bulkhead, a site-based cause similar to at a barrier beach site. The right frame illustrates redirected and concentrated surface water flow and improper drainage management which caused erosion and mass wasting, another site-based cause of erosion (Table 3-3).

BARRIER BEACH SITES



Entire shore eroded:

- Caused by natural/passive erosion or coastal processes impacts

- Caused by natural/passive erosion, not a site-based cause of erosion

Specific area(s) of wave overwash:

- Intermittent only, influenced by site conditions (gaps in vegetation here)

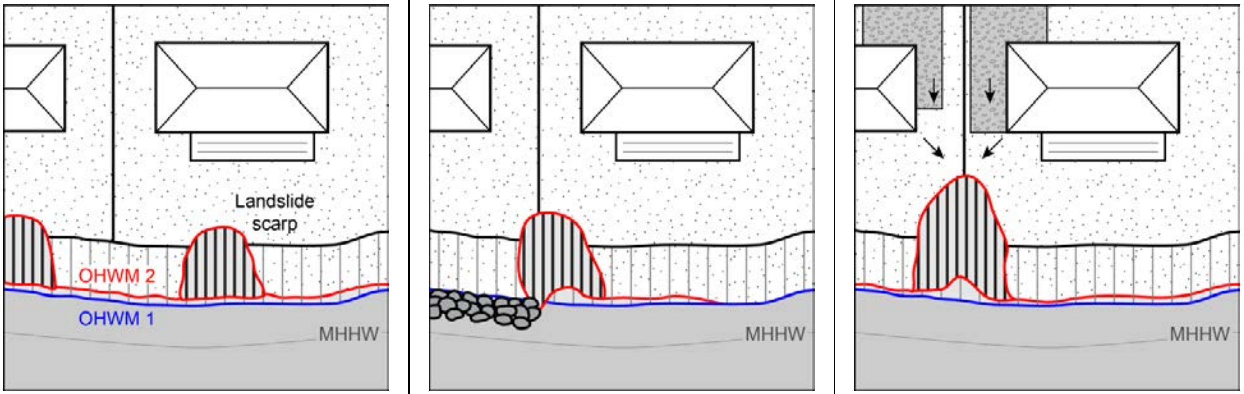
- Caused by high water events affecting areas lacking vegetation for erosion control

Specific area eroded:

- Caused by adjacent bulkhead end-effects; persistent

- A site-based cause

BLUFF SITES



Bluff subjected to toe erosion and intermittent landslides:

- Caused by natural/passive erosion, not a site-based cause

Specific bluff area eroded at toe, which leads to landslides:

- End erosion caused by adjacent up-drift rock bulkhead

- A site-based cause

Specific bluff area eroded where surface water runoff concentrated:

- Impervious surfaces draining to one part of the bluff crest

- A site-based cause

Figure 3-10. Examples of common site based causes of erosion/mass wasting at barrier beach and bluff sites.

How to Measure Cumulative Risk

A cumulative risk model was developed for these guidelines which integrates natural conditions with risk to infrastructure (Table 3-4). The model was calibrated and refined using data from the 25 case study sites, along with some additional site data from Shipman et al. (unpub.) and unpublished data from other sites. The first step of the risk model entails quantifying the erosion potential of the site by evaluating its shoretype and maximum fetch. Shoretype mapping (sometimes called feeder bluff mapping) was recently compiled and completed for Ecology (MacLennan et al. 2013). The sites with the greatest erosion potential are high bluffs with considerable wave exposure that are characteristically receding and contributing large volumes of sediment to the nearshore (feeder bluff exceptional and feeder bluff, in order). Shoretypes that typically have minimal erosion (accretion shoreforms) receive a lower score under erosion potential, while bedrock and low energy shores (with no appreciable drift – NAD-LE), get the lowest score. Sites with greater fetch have greater erosion potential; hence the shoretypes with greater fetch receive a higher score in this category. The shoretype score is then added to the fetch score to give the resultant erosion potential score (Table 3-4).

Table 3-4. Cumulative Risk Model. **Fetch** = whichever is greater: maximum fetch from southern quadrant or half of maximum from other aspects. **Setback distance** = measured distance from bluff crest (or OHWM for no-bank) to most waterward infrastructure.

CUMULATIVE RISK MODEL			
EROSION POTENTIAL			
Shoretype	**Score**	**Fetch**	**Score**
No Appreciable Drift (NAD)-Bedrock/Low Energy	0	0–1 mile	1
Modified, Accretion Shoreform, NAD-Delta	1		
NAD- Artificial , Transport Zone, Pocket Beach	2	1–5 miles	2
Feeder Bluff	3	5–15 miles	3
Feeder Bluff Exceptional	4	15+ miles	4
Erosion Potential Score =		**Shoretype Score + Fetch Score**	
INFRASTRUCTURE THREAT			
Setback	**Score**	**Infrastructure Type**	**Score**
>60 ft	1	Property without structures	1
36–60 ft	2	Septic drainfield or unattached residential infrastructure, not lived in	2
21–35 ft	3	Home or residential building	3
0–20 ft	4	Major infrastructure	4
Infrastructure Threat Score =		**Setback Score + Infrastructure Type Score**	
CUMULATIVE RISK TOTAL (product):		**Erosion Potential x Infrastructure Threat**	

Because the natural processes of erosion and mass wasting do not pose a risk unless infrastructure is threatened, the type and proximity of infrastructure are critical to qualifying risk at a site. Minimal risk is assumed for shores in which structures are adequately setback from the shore, regardless of value or erosion potential. The magnitude of the risk directly corresponds to the setback distance, type of infrastructure, its value, and whether or not it can be relocated. Landscaping features are not considered for risk scoring as they are assumed to be mobile and therefore not a true risk. The setback distance from either the bluff crest, or from OHWM for sites without a bluff or bank, to the infrastructure provides an indicator of the magnitude of cumulative risk: the lesser the setback, the higher the setback score risk number (Table 3-4). The highest score for infrastructure type is given to major infrastructure such as primary commercial or industrial buildings, or public roads, followed by a home or residential building. The two infrastructure threat variables (setback and structure type) are then added together to estimate the infrastructure threat.

The final step in the cumulative risk model is to multiply the erosion potential score by the infrastructure threat score to provide the cumulative risk score, which represents the magnitude of risk. With this model, the highest possible cumulative risk score is 64. The highest cumulative risk score for the 25 MSDG case study sites was 42 (Appendix A).

Examination of the cumulative risk model results (Appendix A) allowed for determination of different risk classes (e.g., low, medium, high) as follows:

- Low risk scores between 0–15
- Moderate risk scores between 16–36
- High risk scores greater than 36

The cumulative risk model score helps to distinguish the perceived and actual need for erosion control at the subject site. The risk model score along with other site characteristics will help define which design techniques are appropriate for the subject site.

Necessary Level of Expertise

Finally, conducting a site assessment to evaluate erosion issues at a given site may require input on a range of topics by several different specialists or may involve more limited issues that can be addressed by one specialist. The spectrum of professional experts includes:

- Geologist/coastal geologist/geomorphologist
- Engineering Geologist
- Geotechnical Engineer
- Structural Engineer
- Biologist
- Botanist or Arborist
- Archeologist
- Shoreline Planner or Permitting Specialist

Figure 3-11. Graphic showing the range of site issues from geologic interpretation to engineering, and the related spectrum of professionals.

Finding the appropriate professional(s) to conduct the assessment and gather the necessary data from which to develop the project design is of the utmost importance. Any professional conducting a site assessment should have a broad understanding of the interaction of coastal, upland, and ecological processes, as well as the regulatory framework of shoreline management and the permitting process.

Different jurisdictions may require that practitioners carry licensing for specific tasks and reports being submitted to obtain project permits. These requirements will be specified in Shoreline Management Program documents. For example, a licensed engineer is often required for structure modifications, a licensed geologist or engineering geologist is often required for a geologic assessment, a licensed engineering geologist or geotechnical engineer may be required for earth-moving design work, and a licensed hydrogeologist may be required for conducting groundwater monitoring and assessing on-site drainage and infiltration. Sites with active coastal processes and coastal erosion are best assessed by an experienced coastal geologist/geomorphologist.

The exact title of the professional being contracted is less important than ensuring that they have the appropriate expertise, experience, and any necessary licenses. Potential consultants should be interviewed to find out what experience they have, particularly with the sorts of issues identified at the site; whether they have the necessary licenses; and whether they understand project goals, including landowner objectives.

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Chapter 4. COASTAL PROCESSES ASSESSMENT

Role and Purpose

The objective of the coastal processes assessment is to attain understanding of the natural range of conditions at the site and identify landscape-scale causes of erosion such as alterations to nearshore processes that could inform the selection of an appropriate management technique and inform design. The information gathered from the site visit (Chapter 3) should be used together with results from the coastal processes assessment to identify the most appropriate management technique which will achieve project objectives with the least possible impact to nearshore processes, structure, and function. Ultimately, this leads to the selection of passive techniques (Chapter 6) and/or appropriate design techniques (Chapter 7).

A defining element of soft shore design techniques is that they integrate and work with coastal processes. A thorough understanding of historical and current conditions and their relationship to coastal processes provides the foundation for appropriate design. The coastal processes assessment generally entails three elements:

- First, the net shore-drift cell, shoretype, and general coastal processes (such as change rates) are evaluated as a means of better understanding the natural range of physical conditions at the site. For example, does the drift cell naturally have a low, moderate, or high volume of sediment in transport? What is the tidal range at the site?
- The second element includes an assessment of how intact or degraded nearshore processes are as compared to historical or pristine conditions, and the potential repercussions of current processes on site conditions. For example, is the sediment supply degraded due to armored feeder bluffs up-drift of the site?
- Finally, the assessment should include an evaluation of how the site will respond to sea level rise and other implications of climate change.

Conducting a Coastal Processes Assessment

For reference, a list of questions that should be explored in the coastal processes assessment is found in Table 4-1. These will be described in context in subsequent sections, along with available data sets in the *Compiling Data* section.

Compiling Data

The first step in conducting a coastal processes assessment is to compile and review all relevant data. Relevant data include the following at a minimum:

- GIS data sets pertaining to physical processes for the area
- Historical and current aerial photographs
- Geology maps, ideally 7.5-minute quadrangles at the 1:24,000 scale
- WDFW priority habitat species data
- LiDAR data

Table 4-1. Coastal processes assessment checklist, including all factors that should be explored to understand drivers of erosion at the reach (landscape) scale and identify which elements should be referenced during forthcoming stages of alternatives analysis and design. Most entries are discussed in the text, other less important and self-explanatory entries are not.

Coastal Processes Assessment Checklist	Informs	
	Alternatives Analysis	Design
The following will help inform the range of natural conditions in the reach:		
Where is the site located within the drift cell (origin, mid-cell, terminus)?	X	X
What is the direction of net shore-drift?	X	X
Is the subject shore drift or swash aligned?	X	X
What is the natural drift cell sediment budget (low, medium, high)?		X
Are adjacent sites exhibiting similar erosion problems?	X	
Does the site or do adjacent shores have a history of deep-seated landslides?	X	
What is the exposure and shore orientation?	X	X
What is the tidal range at the site (macro, micro, meso)?	X	X
Compared to the rest of the reach, is the backshore wide or narrow?	X	X
Are down-drift habitats sustained by sediment from the subject site?		X
Are there intact sediment sources up-drift of the site?	X	X
Is the site located within the 100-year flood zone?	X	X
Is there much LWD recruited or deposited along this reach of shore?		X
What is the general wave climate? (Use conditions above to calculate)	X	X
Is there a large tidal channel or stream channel located near the site?	X	X
Is there a bedrock promontory that could result in wave focusing?	X	X
The following will help inform how altered natural conditions are within the reach:		
Is there armor along adjacent shores? Does the armor extend below MHHW?	X	X
Are up-drift bluffs armored?	X	X
Has the drift cell changed from its historical conditions? (e.g., is it truncated?)	X	X
Are there any major obstructions to sediment transport up-drift of the site (groins or breakwaters)?	X	X
What is the process evaluation framework estimation of sediment supply (PSNERP)?	X	X
Has fill been placed or has regrading occurred adjacent to or up-drift of the site?	X	X
Is there a dredge channel up-drift of the site?	X	X
Is there a significant source of boat wake in the vicinity?	X	X

Relevant GIS data sets include:

- Puget Sound feeder bluff mapping with updated net shore-drift cell mapping (MacLennan et al. 2013)
- PSNERP Strategic Needs Assessment process evaluation framework (degradation) data (Schlenger et al. 2011): http://wagda.lib.washington.edu/data/geography/wa_state/#PSNERP
- Puget Sound Change Analysis shoretype (current and historical shoretypes) and stressor data sets, particularly armor and groins (Simenstad et al. 2011): http://wagda.lib.washington.edu/data/geography/wa_state/#PSNERP
- Washington State ShoreZone Inventory includes habitat data, tidal range and other information relevant to characterizing Puget Sound shores: http://www.dnr.wa.gov/researchscience/topics/aquatichabitats/pages/aqr_nrsh_inventory_projects.aspx
- Washington State surface geology mapping (1:100,000 scale): http://www.dnr.wa.gov/ResearchScience/Topics/GeologicHazardsMapping/Pages/geol_mapping_100k.aspx

For assessors not running GIS, several of these data sets can be accessed on the Washington State Department of Ecology's Digital Coastal Atlas as well as SoundIQ (http://www.iqmap.org/icSoundIQ/website/index.html).

Use of Net Shore-Drift Data to Assess Natural Conditions

The three-dimensional sediment transport system in the littoral zone is the framework to understand the processes controlling conditions at a site, (Johannessen and MacLennan 2007). While littoral drift may vary seasonally in direction, net shore-drift is the long-term direction of sediment transport along a particular coastal sector (Jacobsen and Schwartz 1981). Net shore-drift and net shore-drift cells are the terms used in Washington, and the latter term is analogous to littoral (drift) cells. An idealized drift cell is defined as consisting of three components: a site that serves as a sediment source and origin (usually an erosional or feeder bluff); a zone of transport, where sediment may be deposited temporarily and waves transport sediment alongshore; and an area of deposition (and transport), which is the terminus of a drift cell. The entire shore of Puget Sound has been delineated into distinct net shore-drift cells and areas of "No Appreciable Drift" (NAD) (Figure 4-1). Each of these areas typically represent broad, landscape-scale reaches of shore that are composed of multiple shoretypes. These are sometimes referred to as "process units" (Simenstad et al. 2011). An example of geomorphic shoretype mapping is shown in Figure 4-2.

NAD areas are typically the result of a lack of sufficient wave energy to transport sediment or a lack of available sediment to be transported. NAD areas occur in large-scale river deltas where littoral drift does not occur and fluvial sediment processes predominate, at bedrock shores, and also in heavily urbanized shores where shorelines are so modified that only minimal sediment transport can occur. Bedrock shores commonly contain isolated pocket beaches.

The net shore-drift data should be used to define the spatial extent of the assessment area. If the subject site is located within a net shore-drift cell, then the assessment area should include that entire drift cell. If the site is located within a NAD area, then the assessor should refer to shoretype mapping in Simenstad et al. (2011) to determine the full extent of the processes affecting the subject site. If the site is at a pocket beach, then the full extent of the pocket beach should be assessed in lieu of a drift cell.

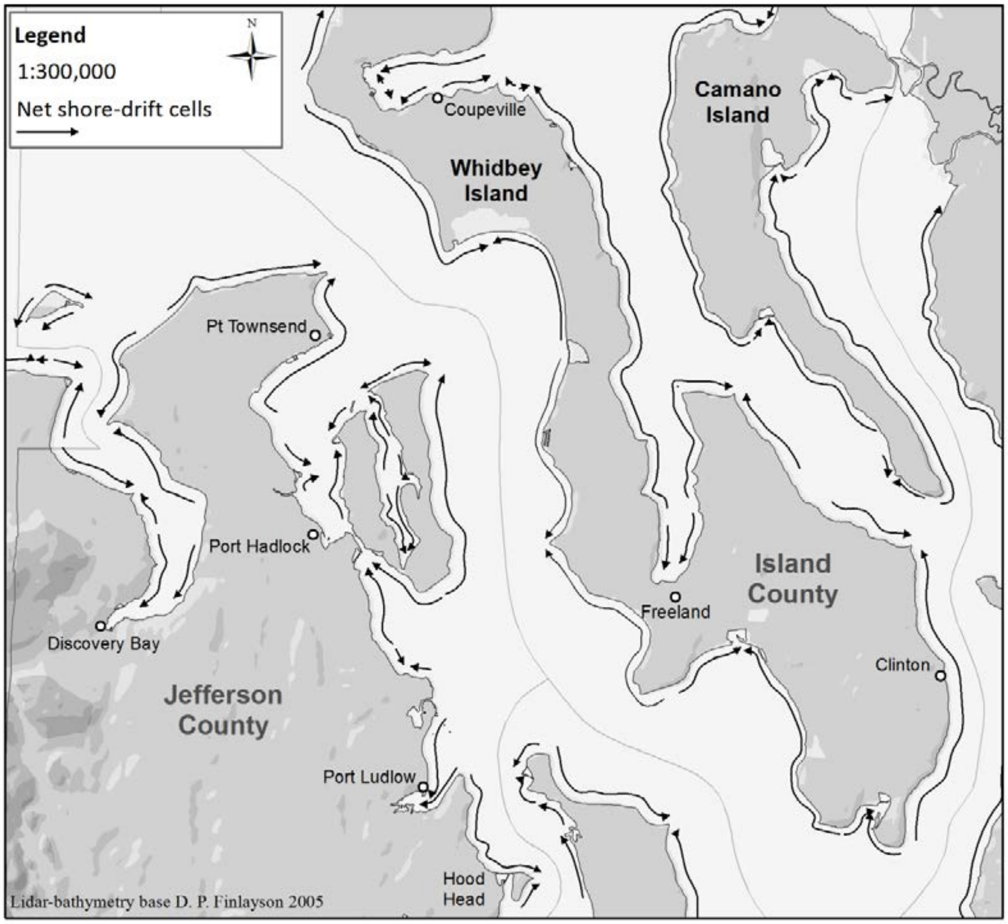


Figure 4-1. Variability of net shore-drift cell lengths and orientations in portions of Island, Jefferson, and surrounding counties, Washington (adapted from Keuler 1988, Johannessen 1992, MacLennan et al. 2013).

Most shores occurring within NAD areas, excluding pocket beaches, are less likely to require erosion control as they are usually less vulnerable to marine-induced erosion. For example, bedrock shores are relatively resistant to erosion. Embayments are characteristically sheltered shores where a lack of wave energy precludes sediment transport. Therefore neither shoretype commonly has erosion rates that require erosion control measures. In contrast, pocket beaches, which are located between bedrock headlands, may have considerable exposure (fetch), which *can* result in marine-induced erosion and the perceived need for erosion control.

Shores occurring within drift cells are also influenced by wave processes and therefore vulnerable to marine-induced erosion (Johannessen and MacLennan 2007). Due to the largely fetch-limited environment of Puget Sound area beaches, waves have the most impact on the beach during storms that coincide with high water. These are often referred to as “change events.” Delta shores are also subject to fluvial processes, and should be assessed by combining the approaches discussed in this chapter with the reach assessment methods described in the Washington State Aquatic Habitat Guidelines Program’s Integrated Streambank Protection Guidelines 2003 (Cramer et al. 2002).

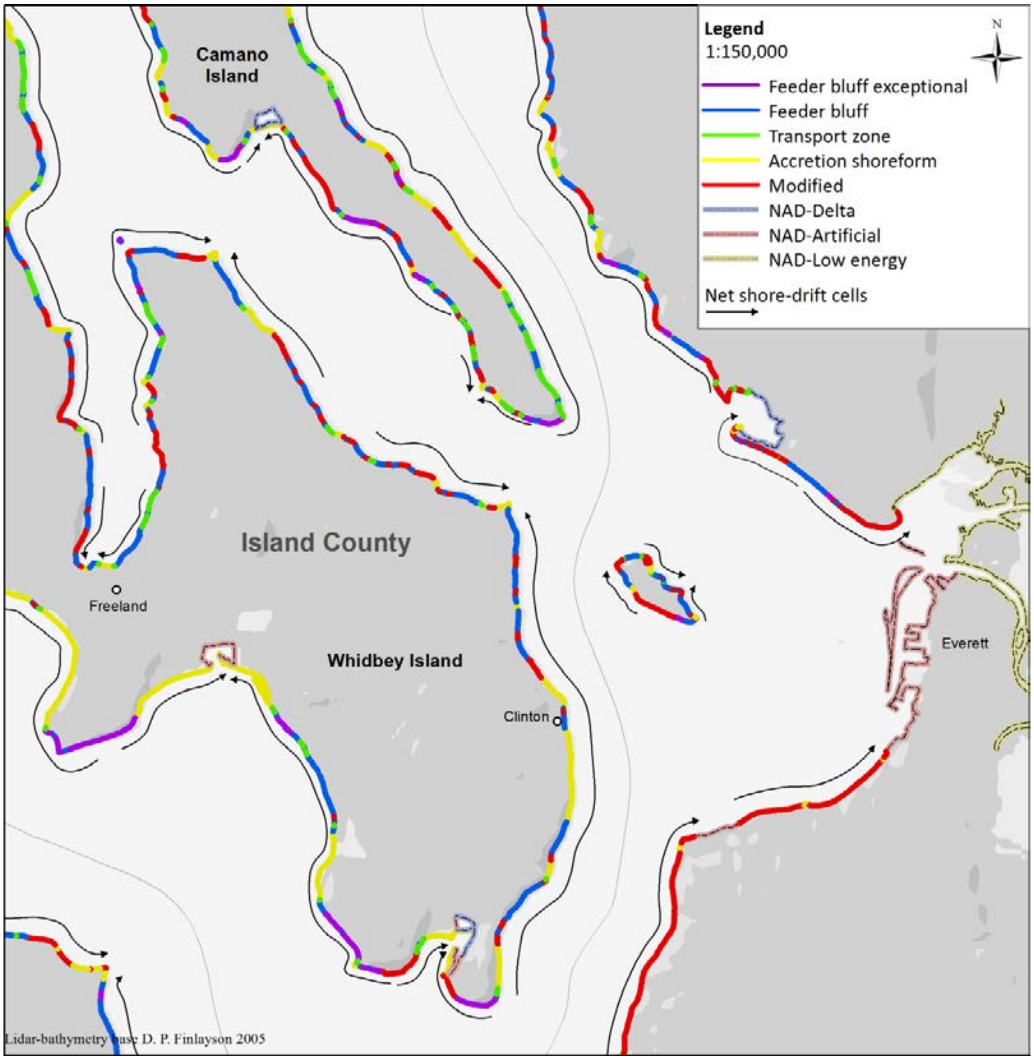


Figure 4-2. Variability of shoretype composition of drift cells in portions of Island and Snohomish counties (MacLennan et al. 2013).

The direction of net shore-drift, which is often a product of the predominant wave direction, provides additional context for the subject site. Net shore-drift direction is symbolized as either “left to right” or “right to left” facing the shore. Transport direction is relevant to design in several ways such as orienting engineered structures, determining the geometry of beach nourishment placement, or designing placement of large wood to capture sediment or LWD in transport.

Longshore (littoral) sediment transport is greatest at drift aligned beaches, which by definition have an oblique wave approach that results in the development of beach drift and longshore currents that entrain and transport sediment. However, considerable variability exists within the length and shoretype composition of drift cells across the Puget Sound region (Figure 4-2). The extent to which the drift cell is composed of active sediment sources (feeder bluffs) relative to other shoretypes and how it compares to other drift cells throughout the region can provide insight into the volume of sediment transported in the drift cell. For example, longer drift cells with several miles of feeder bluffs are likely to have higher volume sediment budgets than shorter drift cells with a shorter feeder bluff length. Similarly, bluff height affects the sediment transport volume. Some drift cells contain only low bluffs while others have feeder bluffs that exceed 200 ft in height (Johannessen 2010).

The drift cell context ties directly to site conditions. For example, sites within high transport volume cells typically have a greater volume of sediment on the beach. In contrast, a drift cell with a low transport volume may have an intermittently exposed shore platform, which could be misinterpreted as a sign of significant beach erosion. Understanding baseline conditions can help the assessor to determine whether a given beach has incurred erosion due to some undetermined driver or if site characteristics are within the natural range of conditions for that particular net shore-drift system.

The site's position within the overall drift informs what the natural range of conditions at the site. Beaches typically exhibit a gradient of decreasing exposure and sediment size, and increasing sediment volume, moving down-drift in a drift cell. However, high natural variability exists in Puget Sound (Johannessen and MacLennan 2007). Sites located near the drift cell origin are typically more erosional, are subject to greater wave energy, are composed of coarse sediment, and have lower volumes of sediment on beaches compared to down-drift portions of cells (Jacobson and Schwartz 1981). One implication is that it is unusual to observe a dramatic coarsening of beach sediment moving down-drift in the absence of significant changes in shore orientation or bluff geology, or due to anthropogenic changes.

Use of Shoretype Data to Assess Natural Conditions

The shoretypes found adjacent to the site of concern are also relevant to understanding baseline conditions. For example, if the site is an accretion shoreform (broad beach or spit) located between two broad reaches of unarmored feeder bluffs, then it is less likely that degraded sediment supply is driving erosion issues at the site. In contrast, if the site is adjacent to a long reach of armored feeder bluffs, it is probable that the lost sediment supply could be affecting beach characteristics—in addition to localized wave scour adjacent to armored shores. In the latter example, design techniques should ensure there are no impacts to sediment transport.

The geology of the feeder bluffs in drift cells has a direct influence on the sediment composition of down-drift beaches. Geologic units composed of finer sediment (fine sand to clay) will contribute much less beach-building sediment than bluffs composed of coarser sediment (coarse sand to gravel). In addition, landslide mapping should be referenced to assure there are no deep-seated landslides landward or adjacent to the site.

The rate of sediment transport is a function of wave energy and orientation. In general, larger waves have the capacity to transport greater substrate size and quantity than smaller waves. However, residential marine shoreline projects do not typically have adequate financial resources to develop detailed wave and sediment transport models. The erosion potential or wave climate at a given site can be characterized by a few simple fetch measurements. Maximum fetch should be measured for all sites from both the predominant and prevailing wind directions, as this provides a surrogate for the wave energy at the site (as outlined in Chapter 3). Sites with greater exposure typically have greater erosion rates (Coastal Geologic Services 2013) and are more vulnerable to wave-induced erosion.

Pocket beaches theoretically function as part of a closed system. The condition of areas outside of the pocket beaches is less relevant to pocket beach dynamics, but the condition of the entire pocket beach should be assessed. Pocket beaches vary in character considerably throughout the region and can range in length from a few tens of feet to thousands of feet (Figure 4-3). They are typically swash aligned, meaning they are oriented facing the predominant wave approach. In some cases, sediment is supplied from eroding banks landward of all or a part of a pocket beach. It is important to note any sediment input of this nature. Other influences on the local wave climate should also be assessed, such as large glacial erratics and offshore bedrock promontories.

Figure 4-3. Contrasting conditions of pocket beaches in San Juan County. Left frame shows a broad beach with lagoon while right frame shows a narrow beach with less sediment input subjected to greater wave energy (Washington Department of Ecology images).

Tidal range is variable throughout the Puget Sound region, with greater tidal ranges exhibited further from the Pacific Ocean (Strait of Juan de Fuca). Beaches with a narrow tidal range are narrower and, due to the semi-diurnal tides, the swash zone (upper beachface) also occurs along a narrower band of the beach (Finlayson 2006). This can result in more upper beach erosion along shores with a narrower tidal range.

Nearshore Habitats

The presence of nearshore habitats that could be impacted by erosion control should also be assessed. Priority Habitat Species (PHS) data from WDFW should be reviewed for the entire shoreform as well as the down-drift shore if the subject property is located within a drift cell.

Anthropogenic Change to the Nearshore

The next element of the coastal processes assessment entails evaluating the degree to which anthropogenic change has occurred within the drift cell, with subsequent alterations to the subject site. Shoreline development and structural modifications such as shore armor, breakwaters, and navigation channels alter patterns in nearshore processes such as sediment input and transport, which in turn can affect conditions along broad reaches of shore off-site. These alterations and impediments to nearshore processes can be evaluated using aerial photography and regional data sets such as the Puget Sound feeder bluff mapping data (MacLennan et al. 2013) and nearshore process degradation data assembled for PSNERP (Schlenger et al. 2011). Puget Sound feeder bluff mapping data can be used to inform the degree to which sediment supply up-drift of the site has been altered by shore armor. Modified shores that were historically feeder bluffs can be identified by reviewing the historical feeder bluff attribute for all “modified” shoretypes (Figure 4-4). If considerable portions of the historical feeder bluffs in the drift cell were armored, then degraded sediment supply could be a driver of erosion at the subject site.

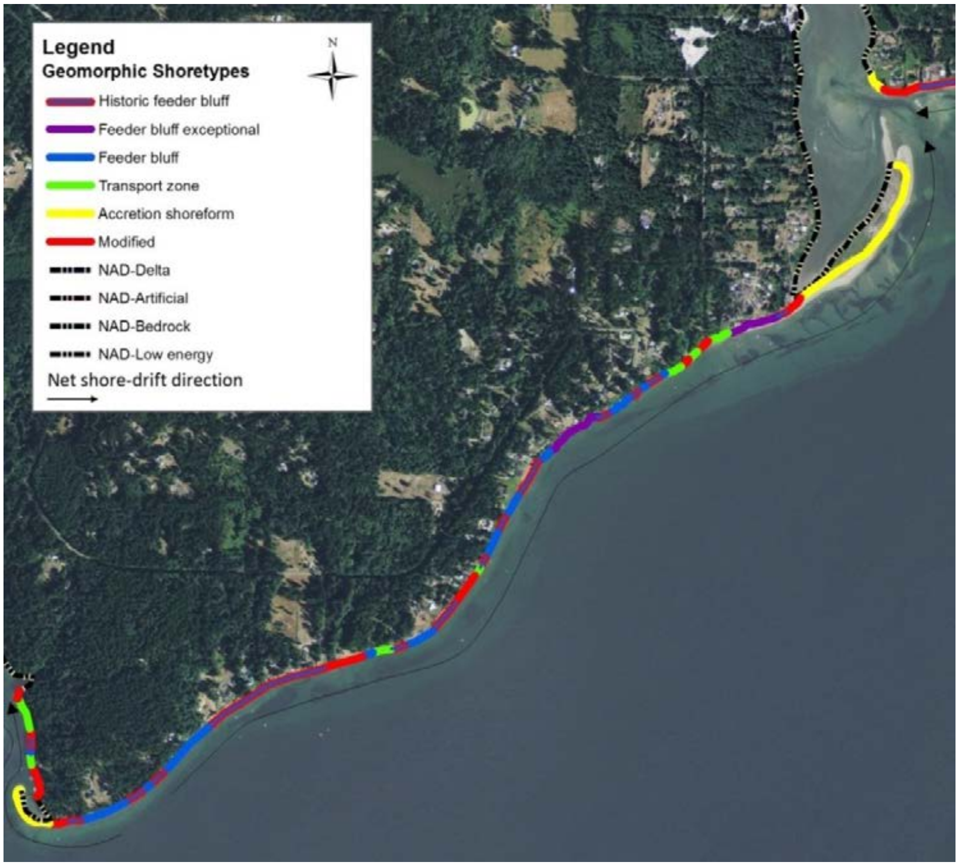


Figure 4-4. Reduction in sediment input caused by numerous shore modifications (armor in red) near Glen Cove, Carr Inlet, Pierce County, Washington (using Feeder Bluff Mapping; MacLennan et al. 2013).

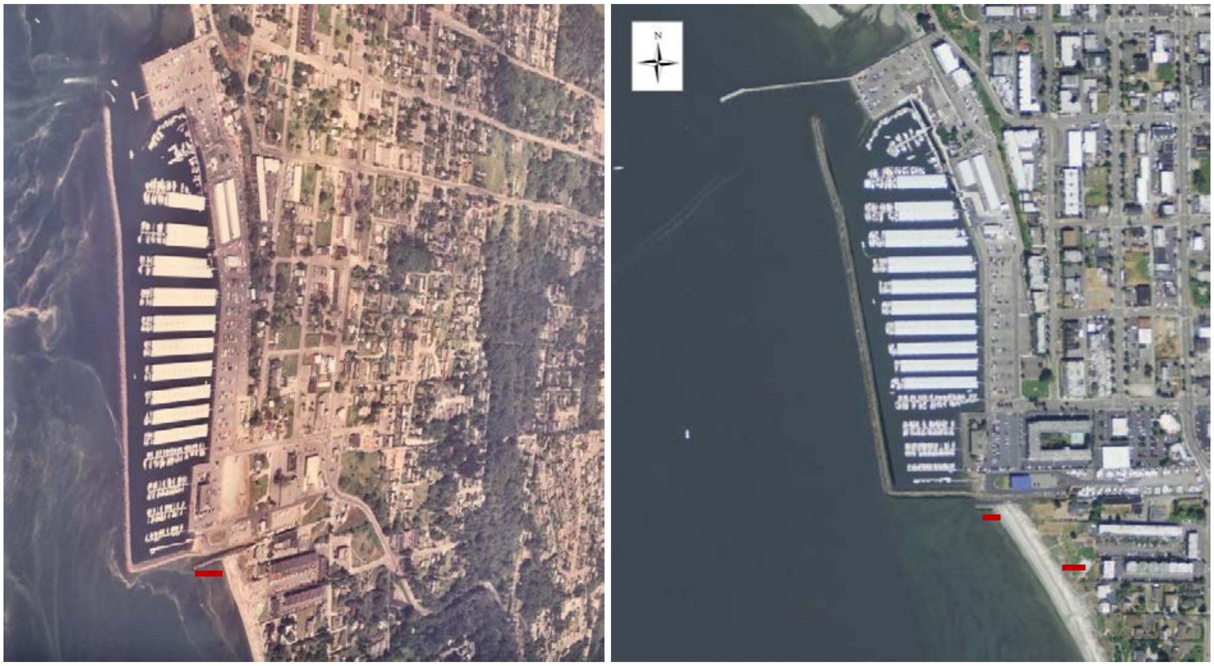


Figure 4-5. Northward sediment transport is impeded by the Des Moines marina breakwater, located south of Seattle.Note beach progradation south of marina breakwater between 1977 (left, Ecology oblique image) and 2011 (right, NAIP imagery) and vegetation landward of beach (waterward of pool).

A qualitative ranking of degradation to eleven different nearshore processes (including sediment supply, sediment transport, sediment accretion, and physical disturbance) is included in the PSNERP *Change Analysis* (Simenstad et al. 2011). Process degradation is categorized ranging from “none” to “most degraded” throughout each process unit (net shore-drift cell) in the Puget Sound region (see example in Figure 4-6). The level of degradation throughout a given unit for each nearshore process was measured by evaluating the co-location of shoretypes and specific stressors that are known to degrade nearshore processes. For example, groins within a barrier beach or bluff-backed beach would disrupt any active sediment transport. These data are relatively coarse in scale and are appropriate only for making large-scale observations. The data also do not accurately reflect the condition of pocket beaches, as the results are merged with the adjacent bedrock shoreforms. More information on the methods can be found in the Strategic Needs Assessment report at pugetsoundnearshore.org (Schlenger et al. 2011).

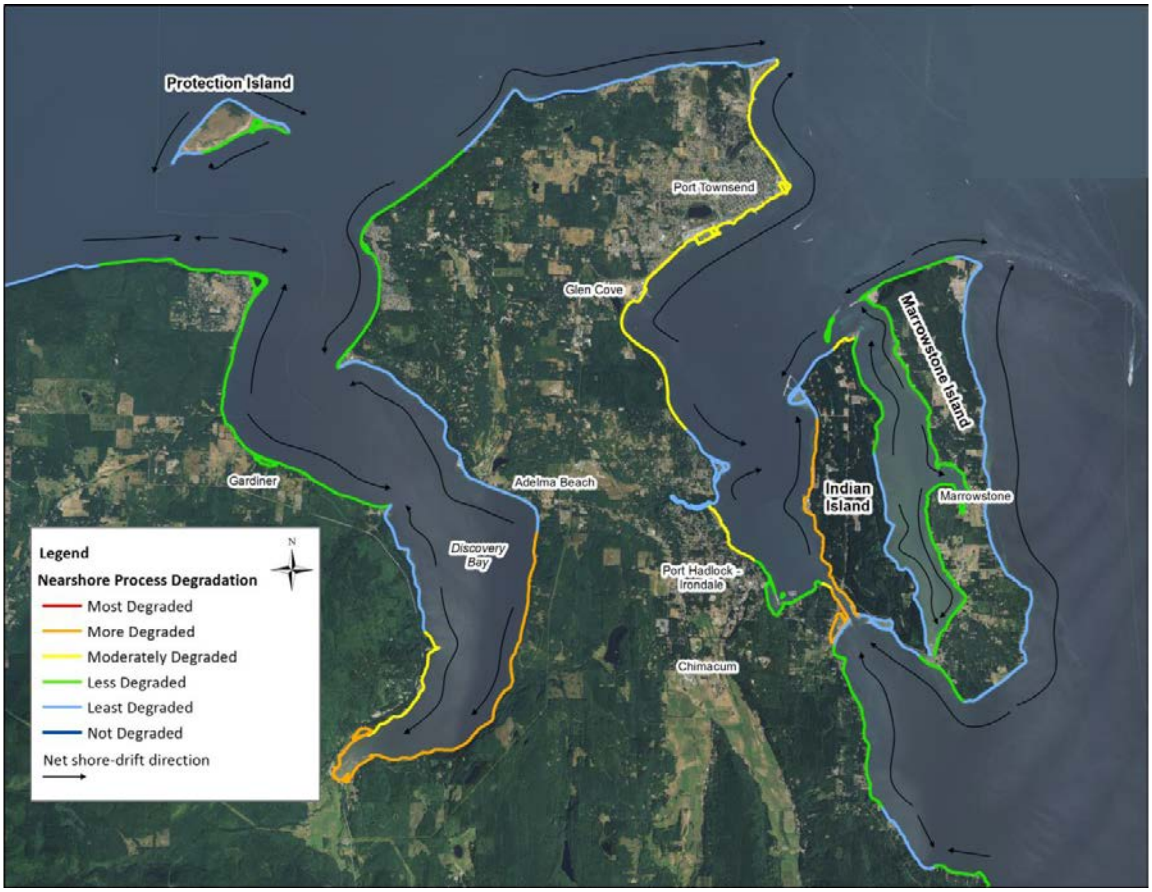


Figure 4-6. Sediment supply degradation in northeast Jefferson County from PSNERP Strategic Needs Assessment process evaluation framework (Schlenger et al. 2011, Simenstad et al. 2011).

Identifying the Problem: Coastal Processes-Based Causes of Erosion

The coastal processes assessment should include a synthesis of the assessment results with specific conclusions relevant to the cause(s) of erosion or mass wasting, beyond that carried out in the site assessment. Site-based causes of erosion, those originating on or immediately adjacent to the subject property, are outlined in the latter part of Chapter 3. Coastal processes-based causes of erosion are generally a product of either the natural range of shoreline dynamics, altered nearshore processes associated with human uses of the nearshore, or some combination of both. In most cases, coastal erosion and landslides are driven by more than one, or a combination of drivers (including site and coastal processes-based causes). Identifying the predominant driver(s) of erosion can help to identify the best management approach(es) or design technique(s). This section summarized ways to identify the dominant type of erosion or mass wasting using data from the coastal processes assessment. In cases where multiple causes exist, several approaches may be necessary to address each cause of erosion.

If possible, recent and historical aerial photographs of the site and adjacent shores should be compiled and reviewed to gain understanding of baseline dynamics and human alterations to nearshore processes. There is a wide range of analysis that can be conducted using aerial photographs; however, the nature of the analysis is typically dictated by the quality of available imagery, the experience of the analyst, and the tools available for use (such as ArcGIS). The most detailed analyses of this nature are done in GIS using high-resolution, vertical-format imagery that is orthorectified or georeferenced with a low measure of error. Considerable literature is available to guide the selection of an appropriate shoreline proxy, though the more landward features can generally be interpreted with greater certainty (Ruggerio et al. 2003). Standard methods apply to this type of analysis with regard to calculating shoreline change rates (Moore 2000, Morton et al. 2004). Standard, static reference points (control points) should be used throughout to assure observations are made for the correct locations. The more time periods (of air photos) that are referenced, the greater the understanding of shoreline dynamics and, potentially, documentation of events that resulted in altered conditions. General shore change trends such as long-term average change rates (or more commonly erosion rates), and if variable, the range of change rates, and the cumulative measured change (shoreline or bluff crest recession) that have occurred at the site should be documented. In addition, the distribution of erosion features such as toe erosion or landslides and accretion areas can be determined.

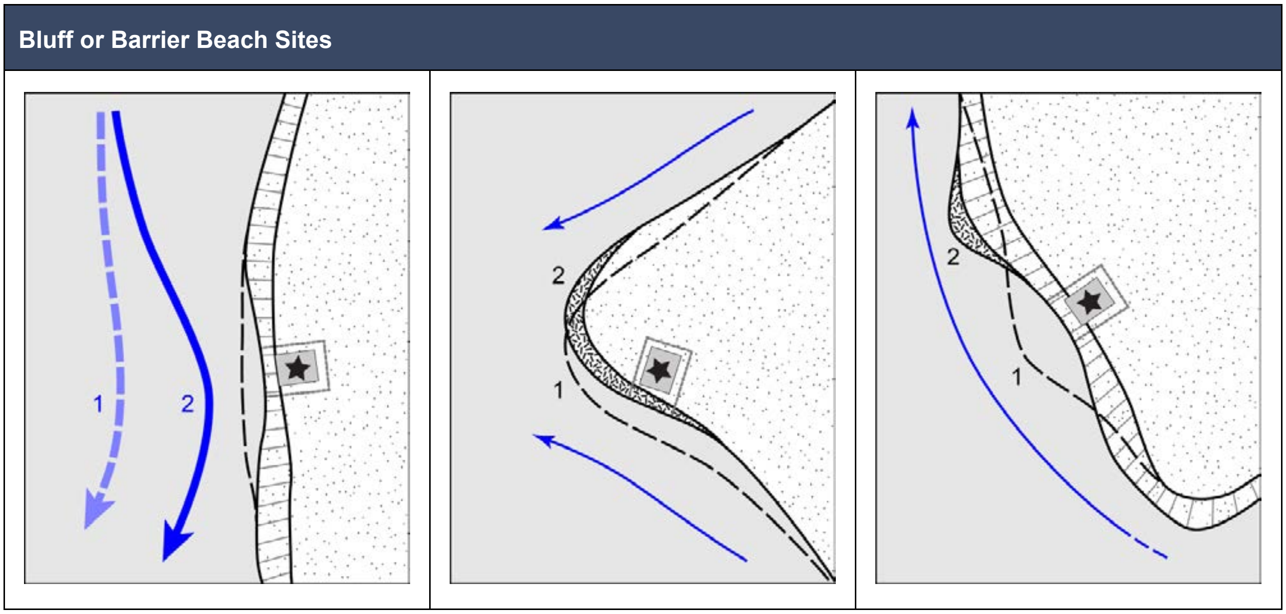
Similar qualitative observations can be made by non-GIS users by simply comparing the vertical format images over time. For qualitative analysis only, oblique imagery is available on the Department of Ecology’s digital coastal atlas from the 1970s, 1990s, early 2000s, and 2006–2007 for most of the Puget Sound region. Photos starting in 2000 offer high resolution views of the entire region.

The following list of questions can be explored to inform baseline dynamics and anthropogenic change to the site. The images shown in Figures 4-7 and 4-8 highlight how these trends may appear in vertical aerial photographs.

Natural trends:

- Has there been a change in the location of a nearby tide channel?
- What overarching trends (erosion, accretion, or relative stability) can be observed within the shoreform (landform) and drift cell that encompasses the subject site? Look for erosion or depositional areas that migrate in the direction of transport.
- Is there a consistent shift in shoreline position without much loss to the shoreform? Such as northward migration of the entire feature? Long-term northward migration of south facing barrier beaches (accretion shoreforms) has been documented in the Puget Sound region (Johannessen 1992).
- Explore the photographs to determine if and when considerable erosion has taken place at the site in recent history. Can erosion potentially be associated with a particular event or perturbation, such as a 100-year storm?
- Are current beach characteristics, such as beach width and LWD presence, similar to adjacent beaches and historical conditions?

- Have there been changes in nearshore bathymetry?
- Have there been changes in shore orientation? Beach erosion and or progradation can lead to changes in shore orientation that can affect how waves approach and affect the shore.
- Are there any anomalous conditions that could result in exacerbated erosion such as strong tidal currents or a local deep-seated landslide?
- Can LiDAR data provide additional insight into processes affecting the drift cell or site, such as the extent of coastal or bluff features or the degree of historical landslides?



Channel migration (star=site):

—Caused by tidal channel or subtidal river channel migrating closer to shore

—Waves and currents exacerbate erosional processes at the site

Northward migration of shoreform:

—South shore recedes as entire spit migrates north

—Caused by predominant southerly waves and net northward sediment transport

Migrating sand wave:

—Caused by a pulse of sediment migrating in the direction of net shore-drift

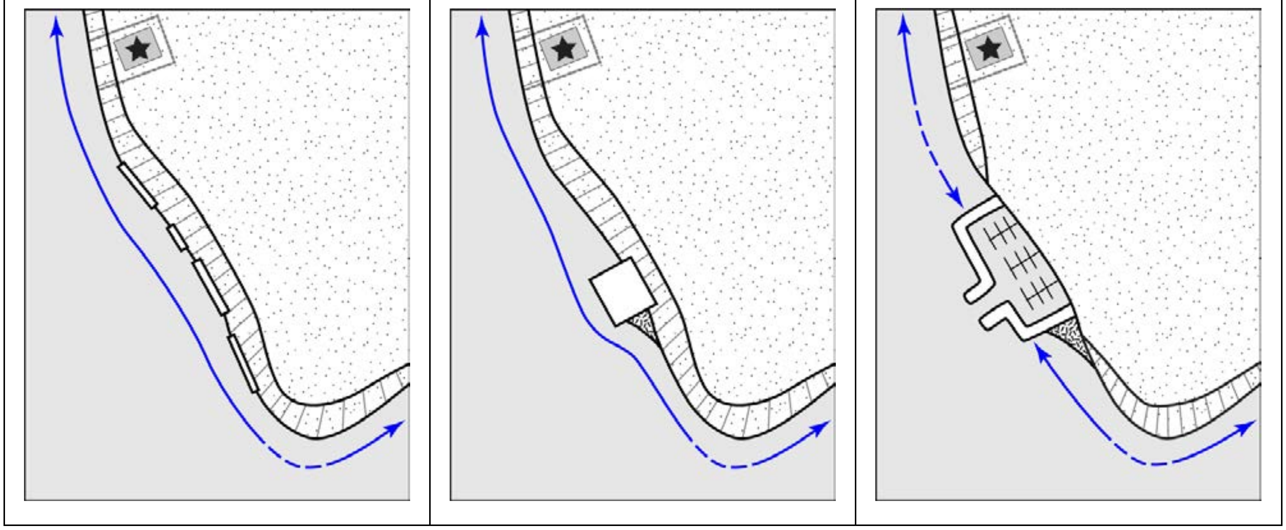
—The bluff toe erodes without the lobe of sediment to buffer wave attack

Figure 4-7. Examples of common natural coastal processes-based causes of erosion or mass wasting.

Anthropogenic trends (Figure 4-8):

- Has change to the site occurred since the installation of a major coastal structure, such as a nearby jetty or breakwater?
- Is there considerable shore armor along feeder bluffs up-drift of the site?
- Are there visible obstructions to sediment transport, such as a groin field, causeway, breakwater, or heavily infringing armored fill area?
- Have there been any changes in boat traffic that could result in amplified wave energy at the site, such as a new marina, ferry terminal, ferry traffic, or port facility?
- Has there been any dredging up-drift of the site?
- Has littoral drift changed through the area since historical conditions due to shoreline developments?

Bluff or Barrier Beach Sites



Sediment supply degraded up-drift of site (star=site):

—Caused by cumulative impacts of numerous hard armor structures at historical feeder bluffs

Littoral drift reduced up-drift of site:

—Caused by fill and structure into the nearshore

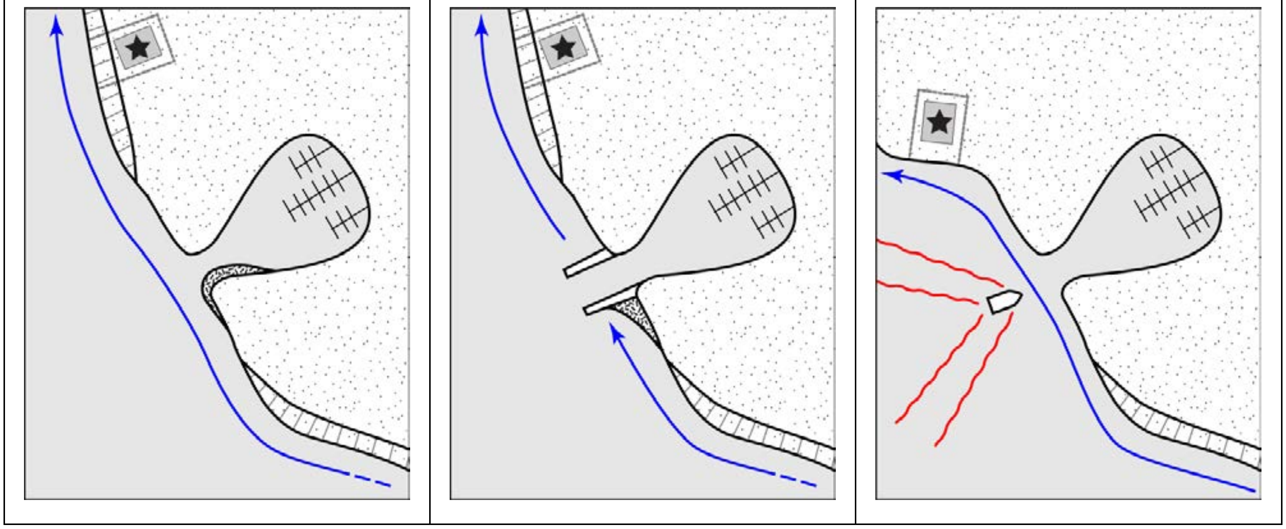
—Not completely blocking littoral drift, but reducing volume

Net shore-drift cell shortened:

—Caused by major nearshore fill completely blocking drift

— Bifurcating historical drift cell and reducing volume of littoral drift

Sites with Inlet or Other Alteration in Drift Up-Drift



Natural inlet widened or dredged within drift cell:

—Littoral drift reduced due to creation of sediment sink (out of natural equilibrium)

Net shore-drift cell shortened:

—Caused by jetties installed up-drift

—Bifurcating historical drift cell and reducing volume of littoral drift

Increased wave energy nearby

—Concentration of boats/wakes near site

—Can be relevant at a low-to-moderate wave energy site

Figure 4-8. Examples of common anthropogenic coastal processes-based causes of erosion or mass wasting.

Climate Change and Sea Level Rise

Implications of climate change, including sea level rise (SLR), should be evaluated for the site and adjacent shores. Evaluating relative sea level rise (RSLR) for the area, the predicted geomorphic response of the shoreforms on the site, and how nearshore processes will likely be altered are of critical importance to understanding long-term dynamics at the site. Identifying a defined planning horizon for the site is a critical first step to estimating future conditions. Implications of climate change and sea level rise should be considered relative to the defined planning horizon. Together these data can provide a foundation from which informed management decisions can be made and additional analysis can be conducted, if necessary.

Relative sea level rise integrates local vertical land movement (uplift or subsidence) with global (eustatic) SLR projections. Because SLR projections are constantly being updated with the advancement of global climate models, only the most recent projections recommended for the State of Washington should be used (currently National Academy of Sciences 2012). Projections are commonly reported using a range of scenarios (low to high or very high). In order to be conservative in assessing all potential areas at risk, the higher magnitude (or the upper extent of the range of) projections should be considered and included.

Once relative RSLR is calculated, the types of threats that are likely to occur at the site (coastal flooding versus erosion hazards), and potential management responses (adaptation versus protection) should be explored. Lower elevation shores are more likely to be affected by coastal flooding and the natural adjustment of the shoreline landward, while high-bank shores will be more vulnerable to landslides and accelerated bluff recession (Table 4-2).

Table 4-2. Shoretype description, response to SLR and climate change, and potential impacts (Shipman 2009).

Shoretype	Description	Geomorphic Response	Potential Impact
Rocky	Bedrock, resistant to erosion	Limited geomorphic response	Low vulnerability, shifts in ecological zonation
Feeder bluff	Steep, erodible slopes	Increased erosion, mass wasting, accelerated bluff retreat	Landslides and erosion, modified habitats, increased sediment delivery to beaches
Barrier beach	Low lying spits and barrier beaches, often with back-barrier wetlands, dunes	Erosion, overwash, barrier migration, breaching, shifting tidal inlets	Erosion, flooding, storm damage, altered backshore habitats, possible encroachment on back barrier wetlands
Estuaries and lagoons	Sheltered estuaries and lagoons, salt marshes, often found landward of barrier beaches	Marsh erosion/accretion, changes in tidal prism, altered inlet dynamics	Marsh/habitat loss, channel erosion, shoreline erosion, sedimentation, changes to wetland configuration
Deltas	Broad, low elevation alluvial features at river mouths	Marsh erosion/accretion, sedimentation changes, altered riverine influence, inundation, salinity intrusion	Increased flood vulnerability, damage to dikes and levees, marsh loss, vegetation shifts, decreased drainage
Artificial	Areas of extensive landfill, usually low elevation, engineered and hardened	Limited geomorphic response	Storm damage, flooding

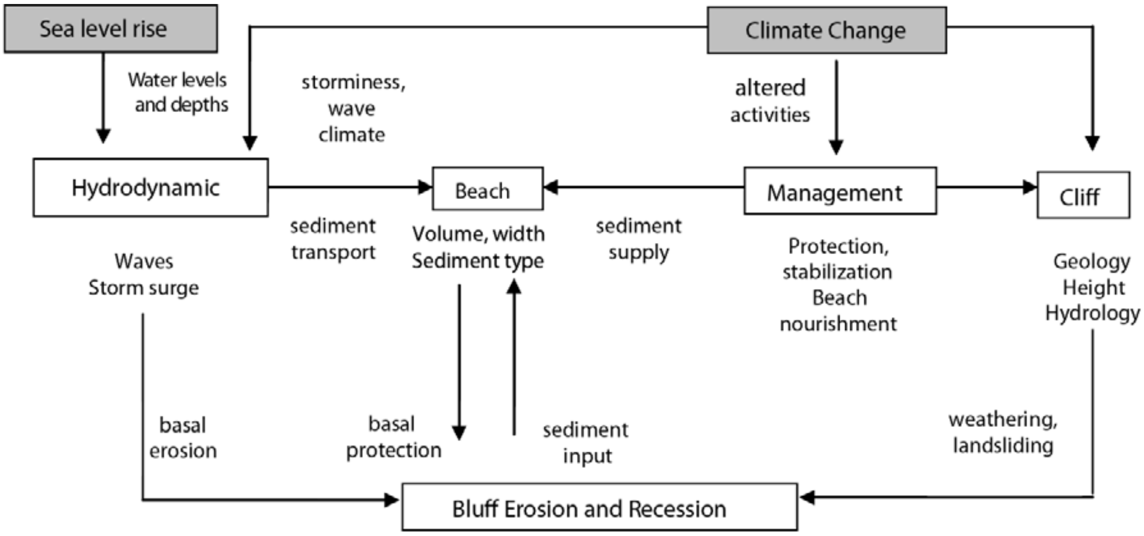


Figure 4-9. Diagram of factors influencing bluff erosion (Bray and Hooke 1997).

Table 4-3. Potential impacts of sea level rise and climate change on nearshore processes (from Clancy et al. 2009).

Process	Anticipated Impacts
Sediment supply and transport	Increased sediment supply from bluff erosion and streams, increased littoral drift rates, likely loss of sediment sources because of new shore protection.
Beach erosion and accretion	Exacerbated erosion along erosional and generally stable shores and likely shifted areas of accretion. Overall landward shift (transgression) of shore features and associated habitats.
Distributary channel migration	Channels may accrete with rising sea levels and have greater tendency for migration in response to altered freshwater input.
Tidal channel formation and maintenance	Tidal channels may accrete and processes may become less predictable in response to altered freshwater input.
Freshwater input	Freshwater input predicted to become more variable, with more flooding (winter-spring) and drought conditions (summer-fall).
Tidal hydrology	Greater inundation and tidal flows into semi-enclosed systems, increased saltwater incursion.
Detritus recruitment and retention	Likely greater detritus recruitment due to overall greater wave energy reaching marine riparian zone. Likely increased storminess and storm surges (including more frequent and intense El Niño storms) and increased input from rivers due to increased peak flows.
Exchange of aquatic organisms	Reduced productivity of threatened salmon stocks due to increased winter flooding, decreased summer and fall stream flows, and elevated warm season and estuary temperatures. Loss of biological diversity/localized extinctions of marine and freshwater species if habitat shifts outpace ability of species to migrate or adapt to changing conditions.
Solar radiation	Altered solar patterns due to hotter summers, colder winters.
Wind and waves	Overall greater wave erosion and potential accretion due to SLR.

Climate and sea level drive the natural range of shoreline dynamics (Figure 4-8, Bray and Hooke 1997). Therefore, as the climate changes and sea levels rise there will be changes to the (baseline) range of conditions as well as the frequency and magnitude of change events. The nearshore processes most likely to be altered as a result of climate change and SLR are shown in Table 4-3. Management responses will introduce additional changes to nearshore systems, particularly in areas where engineering is used to preserve the current position of the shore rather than allowing it to translate (migrate) landward.

Evaluating how climate change will impact shoretypes and nearshore processes (Tables 4-2, 4-3) is an important step in understanding the long-term dynamics at the subject site. However, in addition to shoretype and nearshore processes, several additional variables will contribute to the subject site's response to SLR and other implications of climate change. Data from the site and coastal processes assessment can be used to better understand the likely future position of the shore and how well the subject shore will naturally adjust to these system-wide changes. Intact sediment supply is known to be a critical element of resilience, as sediment is required for beach profiles to translate landward (Pethick 2001). Without ample sediment to support the shoreline translation process, beaches will likely narrow, resulting in inundation and loss of habitat area. Therefore understanding the degree to which sediment sources are intact within the drift cell can also inform the level of resilience of shoreforms. Other variables relevant to shoreform resilience and SLR response include the following:

- Wave climate: Exposure to waves will likely dictate how changes in wave climate will affect the subject site.
- Bathymetry: Broad tide flats, reefs, bedrock promontories and glacial erratics can all cause wave energy to dissipate off-shore and decrease the vulnerability of a given shore to wave attack.
- Upland topography: High resolution topographic data can be paired with RSLR estimates to map inundation at the site.
- Upland/landward geology: Upland geology, particularly stratigraphy, is variable and results in heightened vulnerability to various climate change implications such as increased precipitation and bluff recession.
- Constraints to shoreline translation: Constraints to translation will result in beach narrowing and habitat loss. Anthropogenic constraints such as shore armor or natural constraints such as bedrock geology similarly impede this natural process.
- Armor or other shore modifications: Toe elevation and maximum structure height can inform how the armor will sustain SLR and the potential impact it will have on intertidal habitats. Armor placed at a higher elevation on the beach is likely to sustain for a longer duration, as it is less likely be subject to wave attack. Similarly, lower elevation armor will impact intertidal habitats sooner than higher elevation shore armor. Where armor structure height is low, it may be vulnerable to inundation and is likely not designed to sustain SLR.

The location of existing infrastructure should be linked with projections of physical changes likely to occur at the site. This information will provide valuable insight into the sustainability of different management alternatives. The effort should include all potential features at risk including access roads, homes, accessory dwellings, existing erosion control structures, and critical infrastructure such as septic and utilities. Opportunities to adapt and move at-risk features landward should be explored where possible (see Chapter 6).

Summary

Cumulatively the coastal processes assessment should provide insight into the range of conditions of landscape scale processes, shoretype characteristics, baseline dynamics, and alterations to the nearshore system. These results are used together with data from the site assessment (Chapter 3) to perform an alternatives analysis (Chapter 5) of appropriate management solutions for a given site. The coastal processes assessment should also be used to inform project design (Table 4-1).

A detailed alternatives assessment approach is provided in Chapter 5 that synthesizes these results to screen feasible design techniques and identify appropriate site-specific design techniques. Incorporating several different techniques into a project design often enables the achievement of multiple objectives while limiting adverse impacts and expense to the greatest extent possible.

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Chapter 5. ALTERNATIVES ANALYSIS

Role and Purpose

In this chapter guidance will be provided on how to evaluate and select an appropriate erosion control technique for a specific site. Techniques are not “one-design fits all”. The most appropriate management approach for a given site should ideally:

- Address the causes of erosion
- Be appropriate for the cumulative risk at the site
- Match the natural range of conditions
- Avoid impacts to nearshore ecosystem processes and habitats

In this chapter, the range of management approaches and design techniques will first be outlined, along with lessons learned from the case study assessment (Appendix A) including the range of risk, benefits, and impacts associated with each design technique. The site characteristics (from Chapters 3 and 4) most relevant to the selection of an appropriate approach will be presented together with tools for identifying appropriate alternatives for a given site; alternatives include *Passive Management Techniques* (Chapter 6) and *Design Techniques* (Chapter 7; Figure 5.1). The benefits and impacts associated with the different alternatives will then be described so the potential techniques can be compared and reconciled. The alternative with the greatest total benefit and smallest total impact is recommended for selection.

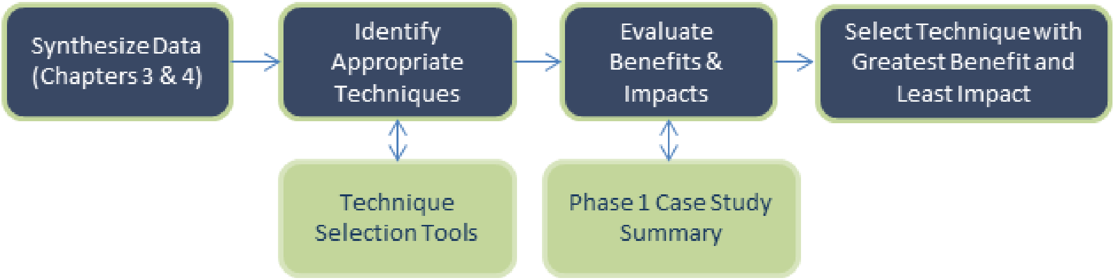

Figure 5-1. Components of the MSDG process for implementing shore protection in the Puget Sound region.

Range of Design Techniques

The broad spectrum of existing shore management approaches can generally be described as encompassing restoration, passive techniques, soft shore protection, and hard armor (Table 5-1). Many different design techniques fall within these general categories but a smaller number are commonly applied on the shores of Puget Sound. Those most often applied in the Puget Sound region are shown in Table 5-2 and Figure 5-2. Refer to Clancy et al. (2009) for guidance on other restoration and protection measures used in the Puget Sound region.

Coastal restoration in the Puget Sound region often includes removal of hard armor, and sometimes fill, to restore the natural shore profile with many anticipated benefits to nearshore ecosystem functions, goods, and services (Clancy et al. 2009). Of the many types of restoration approaches employed in the Puget Sound region, bulkhead removal (Chapter 7.4) is the only marine shore restoration approach addressed in this guidance document. Site specific feasibility and design based on coastal processes, along with continued application of best management practices, are essential to ensure that sites where hard armor is removed remain unarmored in the future. In addition, conservation measures exist to preserve the unarmored condition of Puget Sound shores.

Passive techniques typically preserve the natural condition of the shore and have few to no negative impacts on nearshore ecosystem functions, goods, and services. Passive techniques do not entail complex engineering and include best management practices such as management of surface and groundwater, vegetation management (particularly on bluffs), and relocation. Relocation, also known as managed retreat or realignment, refers to moving coastal infrastructure (roads, houses, buildings, bridges, etc.) inland to allow the shoreline to recede naturally (Chapter 6).

Table 5-1. Range of approaches, design techniques, key elements, and negative impacts to nearshore processes.

Type of Approach	Design Technique	Key Elements	Impacts to Processes
Restoration	Bulkhead removal	Removal of structures to restore the natural beach profile	Improvement
Passive Techniques	Best management practices Vegetation management Relocation	Nonengineered management practices such as planting native vegetation and managing surface and groundwater Preservation/enhancement of natural processes Infrastructure unaffected, relocated, or removed	None
Soft Shore Protection	Beach nourishment Large wood Reslope/revegetation	Preservation of natural processes and coastal dynamics Use of natural materials Slowing rather than eliminating erosion	Low
Hard Armor	Revetments Vertical bulkhead (“seawall”)	Halting natural processes, creating a static shoreline Lost beach area and substrate Attempts to eliminate erosion	Moderate-to-high

Planting native vegetation to manage bank erosion

Large wood used to enhance storm berm

Rock revetment used to prevent bank erosion

Figure 5-2. Examples reflecting a range of management approaches.

Soft shore protection approaches preserve the natural beach and typically rely only on natural materials (at least above grade). Soft shore approaches include projects in which gravel and sand are added to the beach (beach nourishment; Chapter 7.1), large wood (Chapter 7.2) is strategically placed to slow erosion in the backshore, or the bank is regraded and revegetated (Chapter 7.3) to reduce bank erosion (Johannessen 2000). Because soft shore protection projects commonly include beach nourishment, they can benefit areas with decreased sediment supply, such as drift cells with large lengths of armored feeder bluffs.

Hard armor (Chapter 7.5) includes all common variations of rock revetments and vertical bulkheads, which are designed to preclude shoreline migration and bank erosion. Each type of approach has varying degrees of impact with the passive techniques resulting in the fewest impacts and hard armor having the most impacts (Table 5-1). Armor removal has the greatest benefit.

Table 5-2. Description of each design technique covered in Chapter 7.

Design Technique	Description
Beach Nourishment (BN)	Beach nourishment is the addition of sand and gravel to build the beach to mitigate coastal erosion.
Large Wood (LW)	Placement of large wood to retain beach materials and dissipate wave energy (may contain some rock to provide ballast but not in excess of 20% areal density).
Reslope/Revegetation (RE)	Resloping is lowering the slope of the bank to increase stability. Revegetation is planting a bank with native riparian vegetation to create a root network (and ultimately, shrub or tree canopy) that reduces erosion. It can be applied to the existing bank or one which has been resloped. This technique is exclusively applied to the upland (above MHHW and the OHWM).
Bulkhead Removal (BR)	A beach restoration design technique applied along shores where coastal erosion is not substantial or where armor serves solely as a feature of landscaping. The beach may be restored while infrastructure remains unaffected.
Hard Armor-Rock Revetment (RV)	Placement of stationary sloping rock, e.g., “riprap”.
Hard Armor-Vertical Bulkhead (VB)	Vertical face structure constructed of concrete, sheet pile, rock, or wood.

Each of the design techniques can be used alone or in combination, depending on site characteristics and project objectives. For example, bulkhead removal can be used alone for restoration, with or without relocation, or in combination with other techniques (such as beach nourishment) but only along a subject shore where there are no landward structures at risk (Figure 5-4). Similarly, revetments can be used in combination with other techniques, such as beach nourishment. For example, a limited extent of revetment may protect a structure in close proximity to the shore within a larger beach nourishment project area. Large wood projects often include a small volume of beach nourishment.

Figure 5-3. Before (left, 2004) and after construction (right, 2007) at Marine Park in Bellingham, Washington. This project is an example of multiple design techniques employed at one site: bulkhead and partial fill removal, with beach nourishment and a rock drift sill to contain sediment (partially visible in far end of beach), and adjacent revetment maintained to protect railway (on right).

Many developed properties do not have willing landowners or are not appropriate for full restoration (such as bulkhead removal) or enhancement. Other sites may have only limited opportunities for restoration or enhancement. For many of these cases, beneficial actions can still be taken at the site. These actions include application of Best Management Practices (BMPs) such as increasing shoreline vegetation cover, reducing non-point pollution, and increasing awareness of coastal property stewardship. In some cases, landowners are receptive to reducing the amount of armor or moving armor further landward. Where the existing armor is both failing and not necessary, but is also not causing an immediate problem, landowners may decide to simply allow the armor to fall apart over time, or to remove it piece by piece to avoid the expense and disruption of a larger project. All of these actions represent steps along the desired stewardship trajectory. Based on working with shoreline planners and landowners in Port Susan, including multiple evaluation steps (EE Outcomes 2013), an outline of goals and steps was developed for improving stewardship through armor removal and incremental enhancement of processes and ecological function (Figure 5-3).

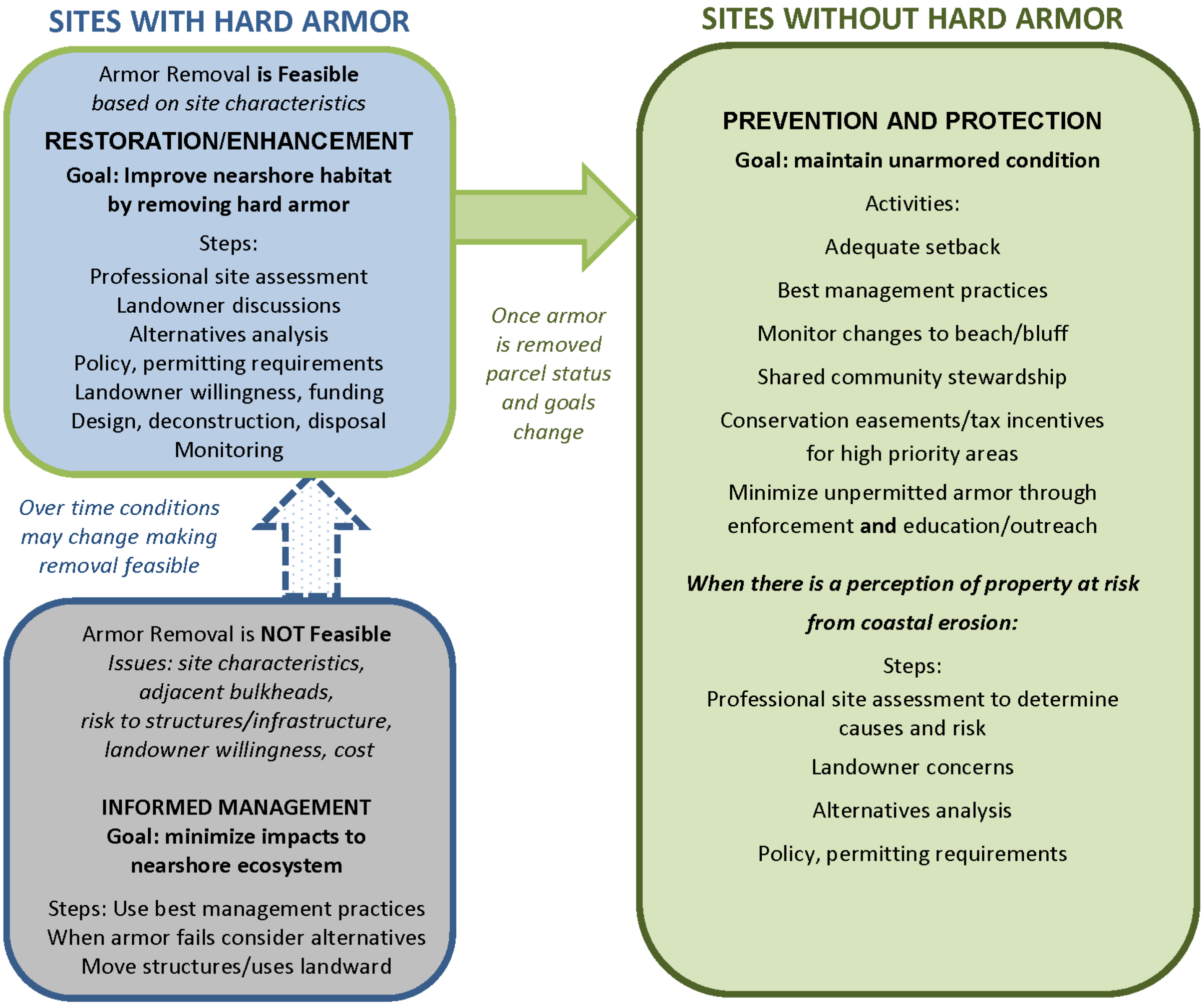

Figure 5-4. The relationship of management approaches as a progressive spectrum with ongoing prevention as the end state goal (EE Outcomes 2013).

Phase 1 Case Study Assessment Results

MSDG began with a case study assessment of 25 previously constructed applications of the 6 major design techniques commonly implemented for erosion control on Puget Sound shores (Table 5-3, Figure 5-5). Revetments and vertical bulkhead projects were later combined into a single technique named “hard armor”, resulting in 5 design technique categories. Detailed field surveys and case study assessments were performed for each project site and adjacent shores to evaluate site characteristics, design specifications, and the relative benefits and impacts relevant to project goals and performance. A successful shoreline design project should integrate the following key elements:

- Use of appropriate design techniques for the site conditions at the landscape (coastal process unit) scale and site-specific (parcel) scale
- Adherence to general design standards
- Provides maximum benefits and minimizes negative impacts

A performance evaluation criterion was developed to measure project success. Methods and full case study documents are all included in Appendix A. Final project performance scores (Table 5-3) were composite measures of numerous benefits and impacts associated with each project.

Table 5-3. Sites assessed as part of the MSDG case study assessment (Appendix A).

Design Technique	Project Name	Year Built	Shore-type	Fetch		Exposure	Risk Score (2 to 64)	Performance Assessment		
				Miles	Class			Benefits Score (0 to 24)	Impacts Score (-24 to 0)	Total Score (-24 to 24)
Beach Nourishment	East Dungeness	2006	AS	36	VH	NE	25	15	-2	15
	East Lummi Island	2004	AS	15.1	VH	ESE	25	21	-1	20
	Marine Park Bellingham	2004	NAD-AR	6.6	H	WNW	15	13	-5	8
	North Beach Orcas Is.	1992	AS	101	VH	N	25	19	-4	15
	Snakelum Point	2002	AS	12.7	H	NW	16	20	-1	19
	Tolmie State Park	1973	AS	6	M	N	6	18	-5	13
Large Wood	Birch Point LWD	2001	FB	24.6	VH	W	28	13	-6	7
	Dabob Bay	2002	AS	13.9	H	SW	16	14	-2	12
	East Eld Inlet	2009	FB	2.6	M	W	20	13	-5	8
	NW Whidbey Is. LW	2008	AS	68	VH	W	25	13	-1	12
	Oak Bay	1999	AS	20	VH	W	30	15	-2	13
Reslope/ Reveg	East Drayton Harbor	2009	NAD-LE	2.4	L	W	4	12	-5	7
	West Lummi Peninsula	2003	TZ	119	VH	WNW	30	13	-3	10
Bulkhead Removal	Birch Point	2001	FB	24.6	VH	W	35	12	-4	8
	Deer Harbor Pool	2008	TZ	2	M	W	8	17	-2	15
	Kopachuck State Park	2005	FB	3.4	M	E	15	18	0	18
	Weyer Point	2006	TZ	5.8	M	E	8	10	0	10
Revetment	Butler Cove	1999	FB	6.4	M	N	35	11	-12	-1
	Lummi View Drive	2001	FB	2.4	M	SW	40	5	-19	-14
	NW Blakely	1980	AS	4.8	M	NW	9	8	-10	-2
	Obstruction Pass	2007	TZ	4.3	M	SE	20	10	-12	-2
Vertical Bulkhead	Samish Island	1998	FB	5	M	NE	25	11	-16	-5
	Skyline Marina	1985	MOD	15	H	S	35	12	-13	-1
	Snyder Point	1990	AS	2.7	L	NW	6	10	-7	3
	Swan Lake	1998	AS	70	VH	W	10	6	-8	-2

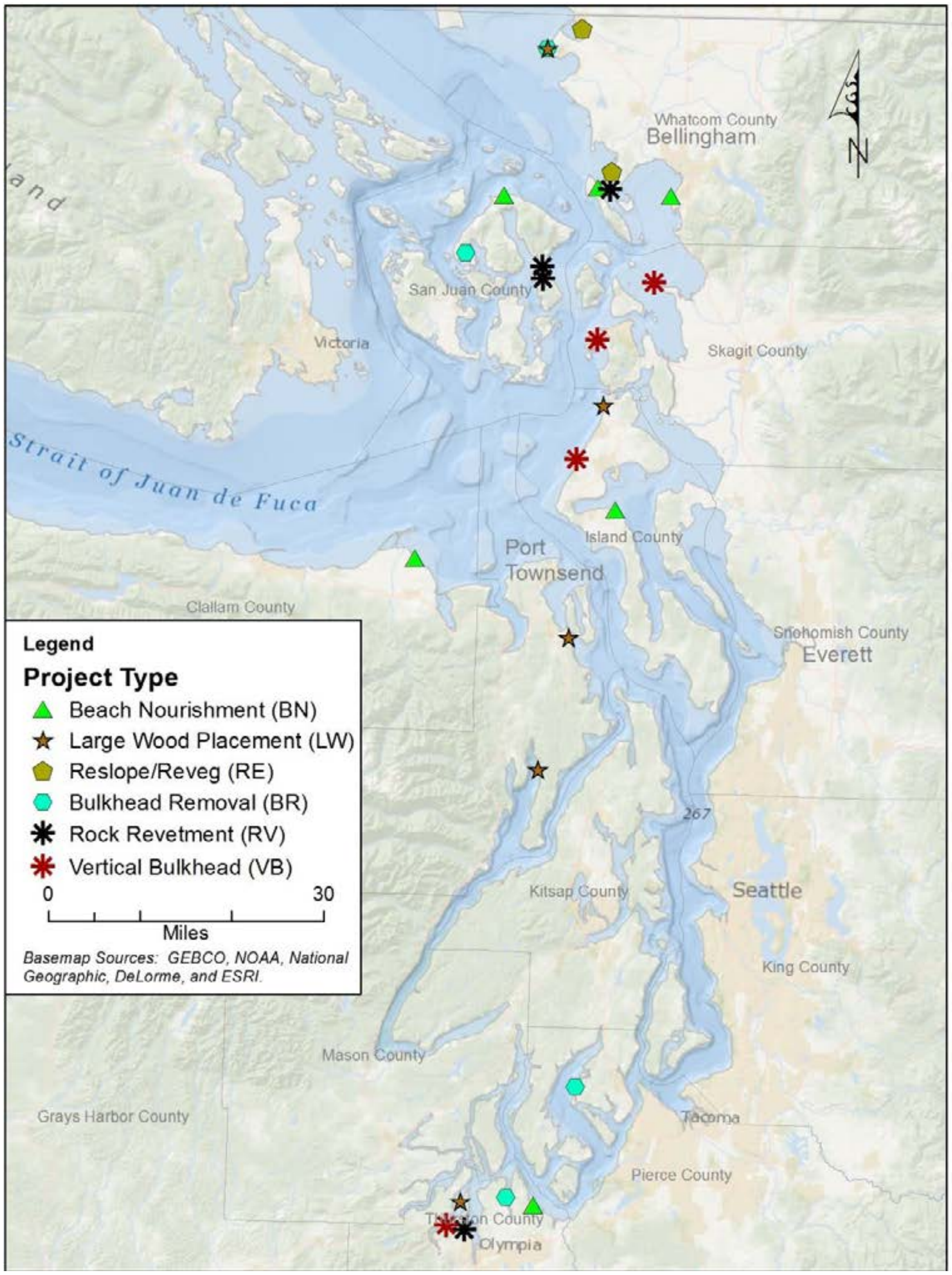

Figure 5-5. Sites assessed as part of the MSDG case study assessment.

Design Techniques, Cumulative Risk, and Effectiveness at Slowing Erosion

The cumulative risk model developed for the MSDG project (described in Chapter 3) was applied to all case study sites. Case study results (Appendix A) showed that revetments were more commonly used on sites with higher cumulative risk scores (Table 5-3, Figure 5-6). In general, hard armor and bulkhead removal projects were applied across the broadest range of risk. Risk associated with bulkhead removal is less relevant when the technique is used in conjunction with relocation of potentially threatened infrastructure. Risk associated with bulkhead removal projects is important when the technique is used alone or when armor is replaced with another erosion control technique. Large wood projects were consistently applied along shores with higher risk than other soft shore approaches.

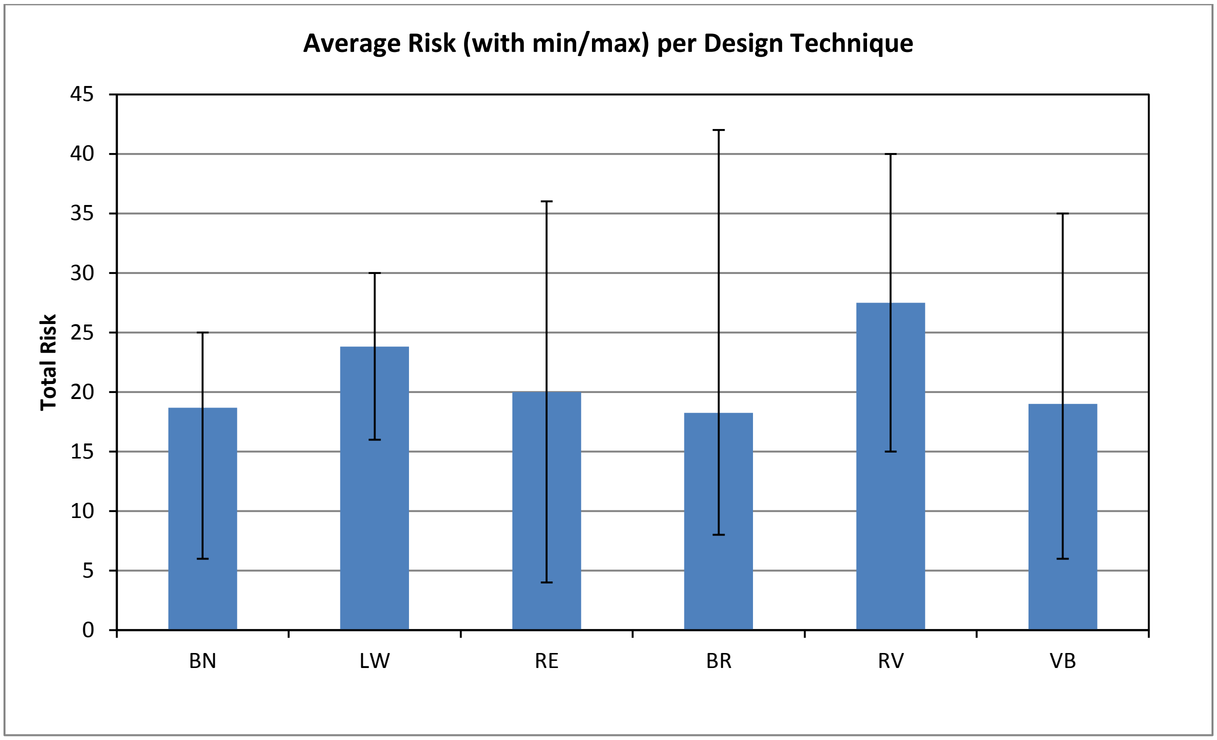

Figure 5-6. Average risk and range of risk from the 25 case study sites, grouped by design technique. BN = beach nourishment, LW = large wood, RE = reslope/revegetation, BR = bulkhead removal, RV = rock revetment, VB = vertical bulkhead.

In addition to cumulative risk (scores), other sources of data, such as data derived from site and coastal processes assessments (Chapters 3 and 4), are recommended for guiding technique selection and design criteria. Project success was evaluated for each case study project by assessing the benefits and impacts documented at the site. One of the most critical criteria contributing to the selection of a design technique is the relative effectiveness of that technique at curbing erosion. In general all design techniques were at least moderately effective at curbing erosion. The most effective techniques at slowing erosion were beach nourishment and hard armor (vertical bulkheads and revetments). The average beach nourishment risk score was lower than those of other design techniques and nourishment was applied on more sites than other techniques (Figure 5-7). Large wood projects exhibited a broader range of effectiveness than beach nourishment, but were also applied along sites with higher average measure of risk (Figures 5-6 and 5-7). Reslope/revegetation projects had a lower range of effectiveness than all other techniques, although this technique was applied at only two case study sites, one of which was a higher risk site. It is likely that this design technique is not appropriate for high risk sites. Bulkhead removal projects were consistently effective at restoring natural processes.

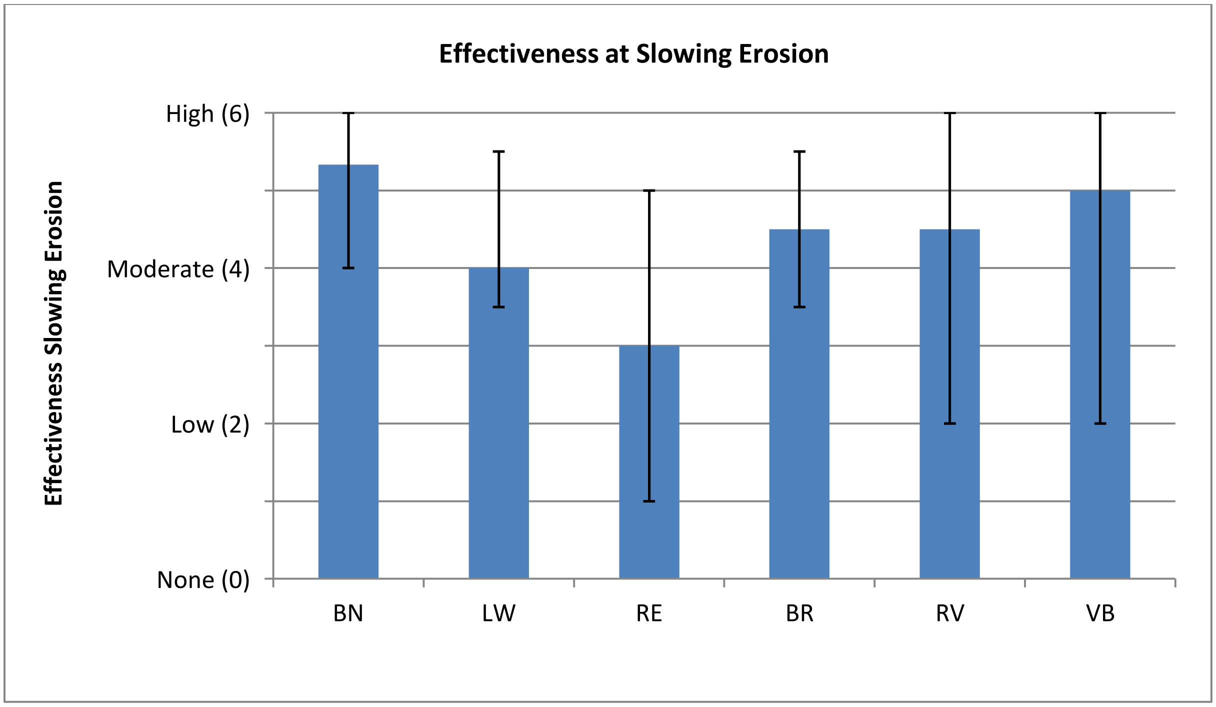

Figure 5-7. Average (and range) of effectiveness at slowing erosion from the 25 case study sites grouped by design technique. BN = beach nourishment, LW = large wood, RE = reslope/revegetation, BR = bulkhead removal, RV = rock revetment, VB = vertical bulkhead. Bulkhead removal was scored based on degree of restoring coastal processes.

Design Technique Benefits and Impacts

A key element of this case study assessment was documenting project benefits and impacts to the nearshore (Appendix A). These data can be used by decision makers to identify feasible alternatives with the fewest impacts and most benefits to the nearshore. The list of potential benefits and negative impacts used for all projects with associated qualifications, scores, and scoring criteria are shown in Table 5-4. The list of potential impacts was compiled from *Puget Sound Shorelines and the Impacts of Armoring—Proceedings of a State of the Science Workshop* (Shipman et al. 2010) and a series of earlier studies and papers.

Benefits were scored positively and impacts negatively. Scoring took place in the field or in the office while reviewing site and design specifications. Scores for the first benefit—effective erosion control—were weighted (doubled) to reflect its inherent importance for most users of this document. Bulkhead removal had a slightly different scoring approach for the effectiveness criterion, because the objective of this technique was to restore erosion and other natural processes. Instead of awarding higher points for stopping or slowing shoreline recession for bulkhead removal, restoration of nearshore processes was the focus. Most scoring applied low-medium-high categories using detailed references to on-the-ground conditions. Table 5-4 shows criteria applied to all sites for all techniques. Additional technique-specific scoring was performed; see detailed methods in Appendix A.

Table 5-4. Benefits and impacts scoring used in the MSDG case study assessment (Appendix A).

Benefit (all projects)	**Scoring Criteria**			
Positive	**None**	**Low (+1)**	**Medium (+2)**	**High (+3)**
Effectively stopped or slowed landward erosion/protected infrastructure *(except bulkhead removal**)*	Erosion	Minimal landward progression or scarping (+2*)	Stopped landward progression with significant overwash, no scarping (+4*)	Stopped landward erosion, minimal overwash and no scarping (+6*)
Sediment volume augmented (from placement or bluff input)	None	Nourishment	Input from feeder bluff allowed	Feeder bluff input and nourishment
Input/exchange of LWD, detritus	Impeded alongshore and cross-shore	Allows either alongshore or cross-shore	Allows both alongshore and cross-shore	Improved input/exchange to alongshore and cross-shore
Backshore vegetation enhanced (composition, area, or both)	none	<3 ft average width enhanced	3–10 ft average width enhanced	>10 ft average width enhanced
Marine riparian vegetation enhanced (composition, area, or both)	none	<6 ft average width enhanced	6–20 ft average width enhanced	>20 ft averaged width enhanced
Low cost and simple installation	>$200/LF	$150–$200/LF	$100–$150/LF	<$100/LF

Impact (all projects)	**Scoring Criteria**			
Negative	**None**	**Low (-1)**	**Medium (-2)**	**High (-3)**
Bury backshore /intertidal area	+ or 0	0–3 ft width	3–7 ft width	>7 ft width
Impound littoral sediment supply	+ or 0	Bank 0–5 ft elevation	Bank 5–30 ft elevation	Bank +30 ft elevation
Coarser/ steeper beach profiles created	+ or 0	Slope <5%	5–15%	>15%
LWD/ organic matter recruitment reduced	+ or 0	Log width reduced 25%	Reduced 25–50%	Reduce >50% or no log zone
End erosion adjacent	+ or 0	One end 0.25–2 ft	One end >2 ft OR both ends 0.25–2 ft	Both ends>2 ft OR one end>4 ft
Required maintenance interval	None or >30 years	15–30 yrs	5–15 yrs	<5 yrs

*Scores for criteria in the first benefit (effectively stopped/slowed landward erosion) are doubled.

**Bulkhead removal scored based on degree of restored erosion processes.

In general, softer solutions provided fewer impacts and more benefits than hard armor (Figure 5-8), while still proving effective at slowing erosion. Also, the impacts of hard armor generally increase over time, as erosion continues to occur waterward of the structure, resulting in exposed armor on the active beach. It is important to remember that projects selected for case studies needed to be in place for at least 3 years, and that most were in place for 5 to 15 years. Therefore this period of performance does not necessarily reflect future performance or performance over many decades. However, the collective lessons learned from these case study assessments can guide the design technique selection process and ideally enhance the likelihood of project success.

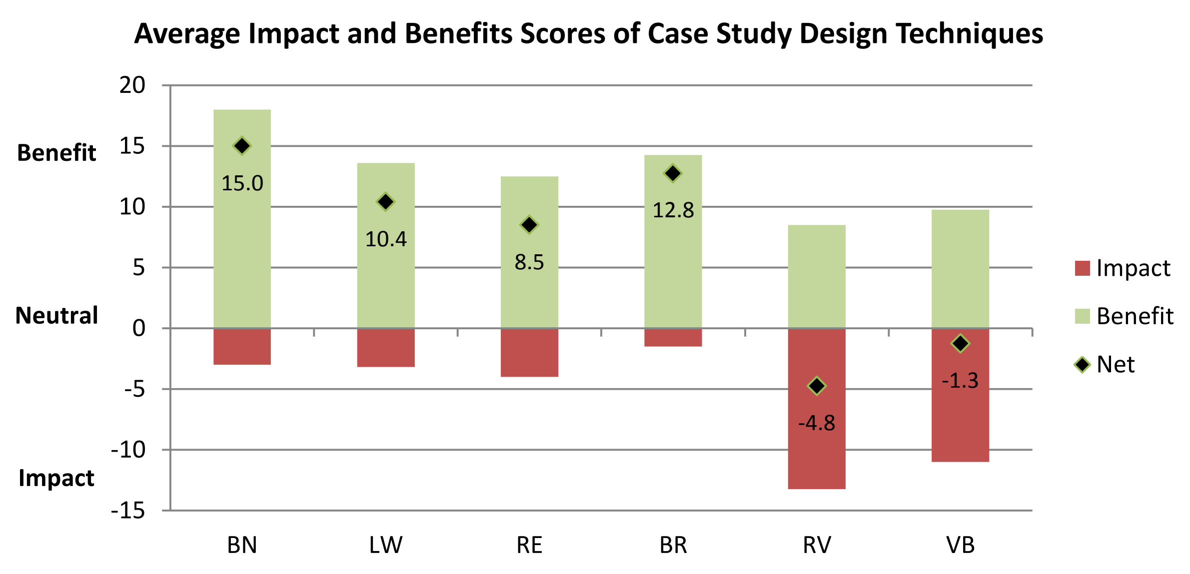

Figure 5-8. Average cumulative impact and benefit scores from case study data for each design technique. BN = beach nourishment, LW = large wood, RE = reslope/revegetation, BR = bulkhead removal, RV = rock revetment, VB = vertical bulkhead.

Case study results highlight benefits associated with softer solutions (Figure 5-8, left side), and in particular the net positive effect of restoration or bulkhead removal, which has the fewest impacts among design techniques. The most impacts were seen at revetment sites, followed by vertical bulkhead sites; this may have been due to subtle design differences or the smaller footprint of vertical bulkheads. Cumulatively revetments also had the least benefits, again slightly fewer than vertical bulkheads. Beach nourishment case study sites on average had the most cumulative benefits. Among the soft shore approaches, reslope/revegetation case study sites on average had fewer benefits than large wood and beach nourishment sites, but the reslope/revegetation sites did not include full removal of debris or extensive planting beyond target areas.

Among the individual benefit scores from case study assessments, considerable variability was displayed among the benefit categories for the different design techniques (Figure 5-9). Beach nourishment had the highest average score and scored higher than most techniques, excluding bulkhead removal, for several benefit categories. All of the design techniques were at least moderately effective at curbing erosion (excluding bulkhead removal for which the effectiveness criterion was effectiveness at restoring natural processes). Bulkhead removal case study sites commonly scored for other benefits including LWD input and storage, cost effectiveness, and increased nearshore sediment volume. Increased LWD recruitment was also a benefit associated with beach nourishment, large wood placement, and reslope/ revegetation sites. Beach nourishment and large wood projects were shown to be most beneficial to backshore vegetation. Costs associated with the case study sites were generally comparable (although cost data were incomplete), with reslope/revegetation projects scoring a little higher.

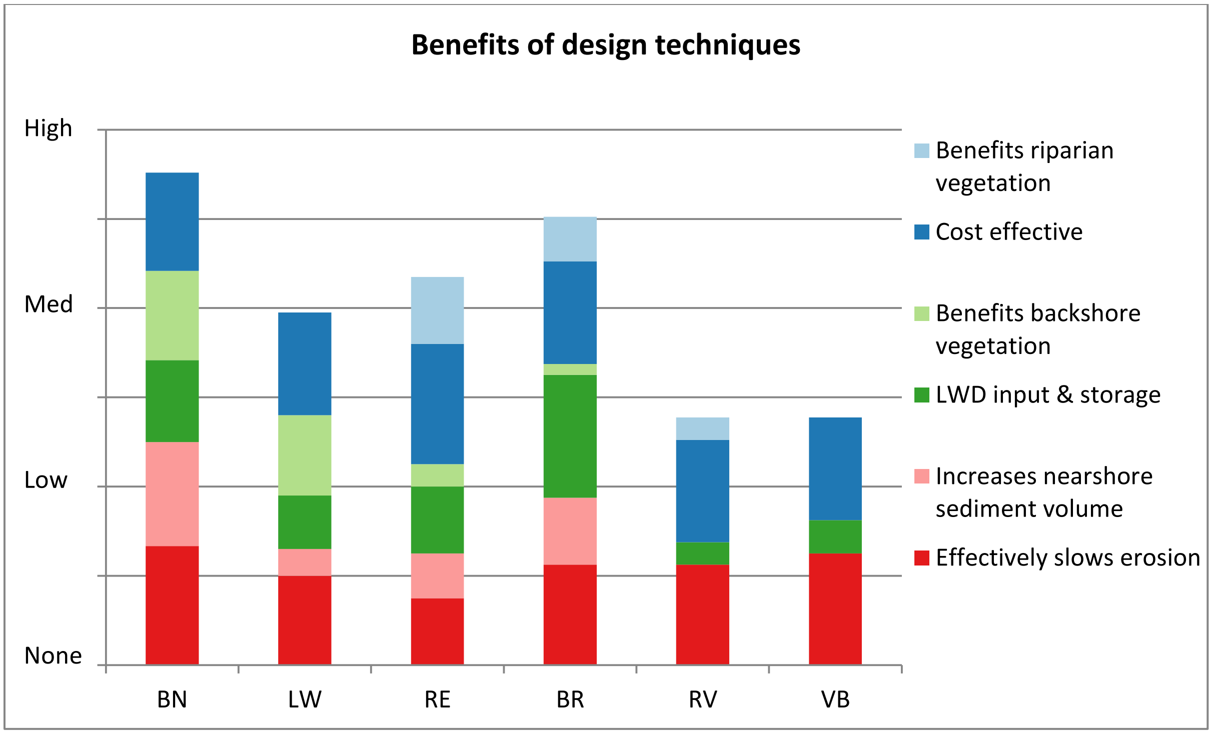

Figure 5-9. Benefits of different design techniques using average of scores of generally 4-6 case study sites per technique. BN = beach nourishment, LW = large wood, RE = reslope/revegetation, BR = bulkhead removal, RV = rock revetment, VB = vertical bulkhead. Bulkhead removal was scored based on degree of restoring coastal erosion processes.

The specific impacts associated with each design technique were also highly variable. As shown in Figure 5-10, cumulatively and across most individual impact scoring criterion, more impacts were observed at hard armor sites than at sites utilizing softer solutions or bulkhead removal. On average, beach nourishment impacts were between none and low; minor impacts were the development of a steeper beach profile and the frequency of maintenance typically required. Large wood had a similar low range of impacts; the greatest was the burial of upper beach area beneath the large wood structure, although large wood is often associated with beneficial micro-climate conditions. The maintenance required for reslope/revegetation projects was the greatest impact associated with that design technique.

The greatest impacts associated with revetment projects were reduced LWD recruitment and buried upper beach area. Similarly, vertical bulkhead sites also had considerable impact due to buried upper beach and additional impacts due to end effects with erosion at the adjacent shore(s) caused by wave refraction. Sediment impoundment and coarser, steeper beaches were also high-scoring impacts of hard armor case study site applications.

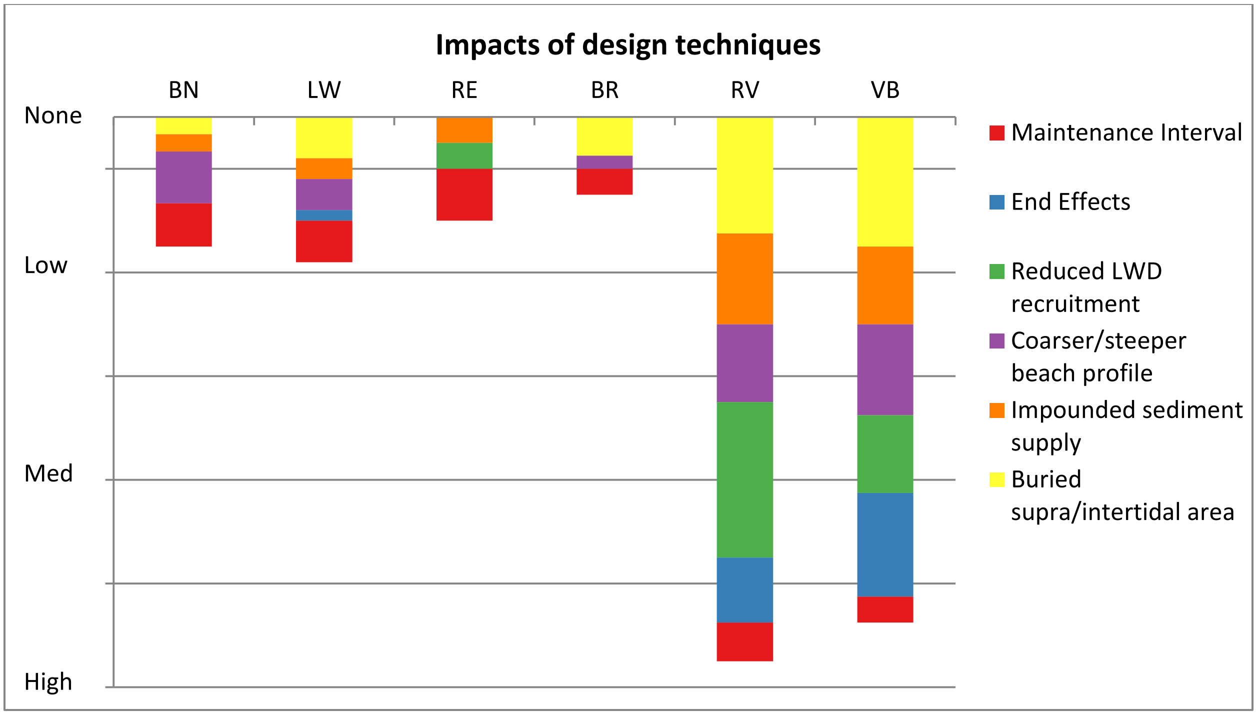

Figure 5-10. Average impacts of different design techniques based on case study data. BN = beach nourishment, LW = large wood, RE = reslope/revegetation, BR = bulkhead removal, RV = rock revetment, VB = vertical bulkhead.

Linking Cause of Erosion with Design Techniques

In addition to being appropriate for site conditions the appropriate design technique(s) should address the causes of erosion identified in the site and coastal processes assessments and incorporate where actions should occur. A synthesis of the critical site characteristics to aid in the selection of appropriate alternatives, including the causes of erosion at the site, and other elements relevant to the forthcoming design process should be provided by the site assessor. Identifying what techniques will address the causes of erosion at the site, and the spatial extent required to reduce erosion, are key elements to minimize impacts to the nearshore, as well as contain project cost. Causes of erosion can range from natural to anthropogenic (those caused by human alterations to the shoreline) and can be categorized as either site-based or coastal process-based.

Site-based causes of erosion are the most common causes of coastal erosion and include passive erosion or storm wave attack, impacts of bulkhead and other coastal structures, vegetation clearing, bluff geology, surface and groundwater management, and many more (see Chapter 3, Figure 3-10, and Table 5-5). **Coastal processes-based causes** of erosion include changes to the drift cell, alterations in sediment supply up-drift of the site, and modified wave climate (Chapter 4 and Figures 4-7 and 4-8). The process of selecting the appropriate technique and the development of the associated design should address each of these types/causes of erosion, and integrate all of the measurements and knowledge gained about the subject site. Detailed design guidance for each technique is provided in Chapter 7 of this document.

Most natural causes of erosion will occur along a broad reach of shore, which can necessitate a design spanning the entire subject site. For example, beach nourishment can be recommended over the entire site to mitigate wave-induced erosion of a barrier beach where there is risk to buildings since the waves affect and erode the shore uniformly. In contrast, anthropogenic drivers of erosion are often more limited in the area of influence.

However, altered sediment supply, transport, and wave processes, are all anthropogenic causes of erosion, which cause more broad scale erosion issues.

Table 5-5. Causes of erosion, source, scale of impact, and appropriate design techniques to mitigate erosion. Technique abbreviations are: BN=beach nourishment, LW=large wood, RE=reslope/revegetation, BR=bulkhead removal, HA=hard armor, R=relocation, BMPs=best management practices.

Cause of Erosion	Natural (N) or Anthropogenic (A)	Site-Based	Coastal Process-Based	Appropriate Design Techniques
Wave attack	N	√		BN, LW, R, HA, RE
Bluff geology	N	√		RE, R, BMPs
Deep seated landslides	N	√		R
Vegetation clearing	A	√		BMPs, RE
Surface and groundwater management	A	√		BMPs, RE
On-site gravel beach gravel mining	A	√		BN
Fill or an artificial shoreline	A	√		R, BR, HA, BN, LW
Decreased sediment supply or transport	A		√	BN, HA, R, BR
Altered wave action	A		√	LW, HA
Boat wakes	A		√	BN, LW, HA

Table 5-5 draws linkages between the causes of erosion and the appropriate design techniques used to manage the erosion. An example of an anthropogenic site-based cause of erosion is a large bulkhead located immediately adjacent to the subject property that infringes on the intertidal beach. The armor causes end-effects, resulting in a moderate amount of erosion adjacent to the structure. Bulkhead removal may not be an option as the adjacent landowners may not be willing. Because the erosion is largely driven by end-effects from the adjacent shore, the treatment area can be limited to that area. If the rest of the site is eroding at a slower rate, then other management options may be appropriate for the remaining area (such as large wood placement with beach nourishment and backshore vegetation plantings).

Widespread loss of sediment supply resulting from armored feeder bluffs is clearly an impact of development but is very difficult to directly address. Opportunities to remove bulkheads from feeder bluffs up-drift of the site should be explored. If not feasible, then sediment input may be mitigated by beach nourishment. The relative benefits of nourishment design should be evaluated and include comparison of bolstering sediment supply on-site, or up-drift of the site. Analysis of site conditions (alignment and sediment transport rates) must then evaluate if the nourishment sediment would be maintained adequately with or without drift sills, and the impacts of both the potential nourishment and sills must also be evaluated. Again, the results of the site assessment and coastal processes assessment need to be integrated into the design process as outlined in Chapter 7, for this and other examples.

Selecting an Appropriate Design Technique

A general process has been outlined for the MSDG to help designers, shoreline managers, and others identify the optimal design technique for a site. This process builds on addressing the causes of erosion discussed above. The process integrates fundamental site characteristics that will determine which design techniques will suit site conditions and also address the causes of erosion at the site. This requires integrating site and coastal processes data including:

- Project length (also referred to as treatment area; typically not entire parcel length)
- Cumulative risk
- Wave energy
- Alignment
- Shoretype
- Available backshore width

Figure 5-11 presents a decision tree that can be used together with site assessment data to identify the appropriate design techniques for use at a given site. Other decision tools such as those produced in the *Coastal Erosion Management Study* (Cox et al. 1994), *Protecting Nearshore Habitat Functions in Puget Sound* (EnviroVision et al. 2010), and *Green Shorelines: Bulkhead Alternatives for a Healthier Lake Washington* (City of Seattle 2012) were referenced in the development of this new tool. Cox et al (1994) was mostly focused on hard armor alternatives (rather than soft shore alternatives) and was developed with minimal design or performance data from Puget Sound. The Green Shorelines document focused only on Lake Washington shores and is therefore not transferable to the wide range of conditions found on the marine shores of the region. The simple decision tree for determining a host of alternatives for Lake Washington shore relies heavily on nearshore and yard slope, and is therefore not appropriate as it does not factor in wave energy, tidal influence, geology, or the range of other site characteristics important to consider for marine shores.

The *Protecting Nearshore* document (EnviroVision et al. 2010) focused on recommendations for reducing impacts from shore armor in the Puget Sound region. This included citing the (draft) Whatcom County SMP language for regulating the development of shore stabilization structures (WCC Section 23.100.13) which required the use of surface water management techniques, followed by soft shore protection. Hard armor was only allowed if demonstrated to be necessary to protect an existing primary structure threatened with substantial damage within 3 years, and where mitigation of impacts would not cause a net loss of shore ecological functions and processes. This approach followed guidance from Ecology and serves to outline the general approach to employ the least impacting alternative for any site.

The first step to selecting an appropriate design technique for a given site is to look for opportunities to employ BMPs (See Chapter 6) at the site (Figure 5-11). Improved surface water and vegetation management can often curb erosion exacerbated by shoreline development. There are often opportunities to address this single driver of erosion alone or in combination with other design techniques. Since mitigating risk to buildings and infrastructure is the primary reason erosion control projects are needed and permitted, cumulative risk is the first variable to influence appropriate design technique selection. Risk is calculated and classified using the model found in Chapter 3 (Table 3-4).

If the site is a high-risk site, then relocation of buildings or other major improvements should be explored to determine if it would be feasible to move the structure landward out of harm’s way. Relocation is the lowest impact and most effective long-term solution for a threatened improvement—although it is not feasible for brick homes or homes constructed of other masonry materials. Where relocation is infeasible, and the threat to the structure is imminent, owners could consider selling the property to a local or regional conservation organization. Cost and inconvenience alone do not make relocation infeasible. Relocation is also appropriate for lower risk sites and should also be considered when resources (e.g. sediment supply or forage fish spawning areas) may be at risk (see Chapter 6). Relocation can also be used in combination with bulkhead removal.

If it is not feasible to relocate the building landward, then the next step is to address the wave energy at the site. If this site has high wave energy, then hard armor may be the only feasible alternative. Armor should always be used along the shortest extent of shoreline possible to protect infrastructure (e.g. only waterward of the home). If the site has low-moderate wave energy, then other alternatives are viable. Feasible alternatives for this scenario apply to both high and moderate risk, non-bluff sites. If the site is not a bluff and it has low energy, then no action is necessarily required at the site. If it has moderate energy, then beach nourishment and large wood placement (or some combination of the two options) are feasible alternatives. If it is a moderate risk, non-bluff site, with high wave energy, additional variables need to be explored, including beach alignment, backshore width and project length. For sites where multiple adjacent parcels are vulnerable to the same risk and site conditions, the project length can expand to include several properties. This can prove beneficial to property owners often resulting in considerable cost savings.

All bluff sites with moderate risk should be assessed to determine if relocation of structures is a feasible alternative. If it is not feasible to relocate structures, then wave energy should be assessed (Table 5-6) to explore other viable options. Bluff sites with moderate risk that cannot relocated structures and have low wave energy are appropriate for a broad range of alternatives including: no action, beach nourishment, large wood placement and reslope/revegetation. Similar sites but with very high wave energy are limited to hard armor installation, while those with high wave energy can feasibly apply beach nourishment with the added installation of drift sills to help maintain nourishment sediment or hard armor. Other alternatives that are appropriate for bluff sites with moderate risk, where relocation is not possible, and wave energy is moderate need to explore beach alignment, backshore width (Table 5-7) and project length to ascertain what design techniques are most appropriate for site conditions. The range of conditions associated with each variable and subsequent recommended alternatives are found in Figure 5-11.

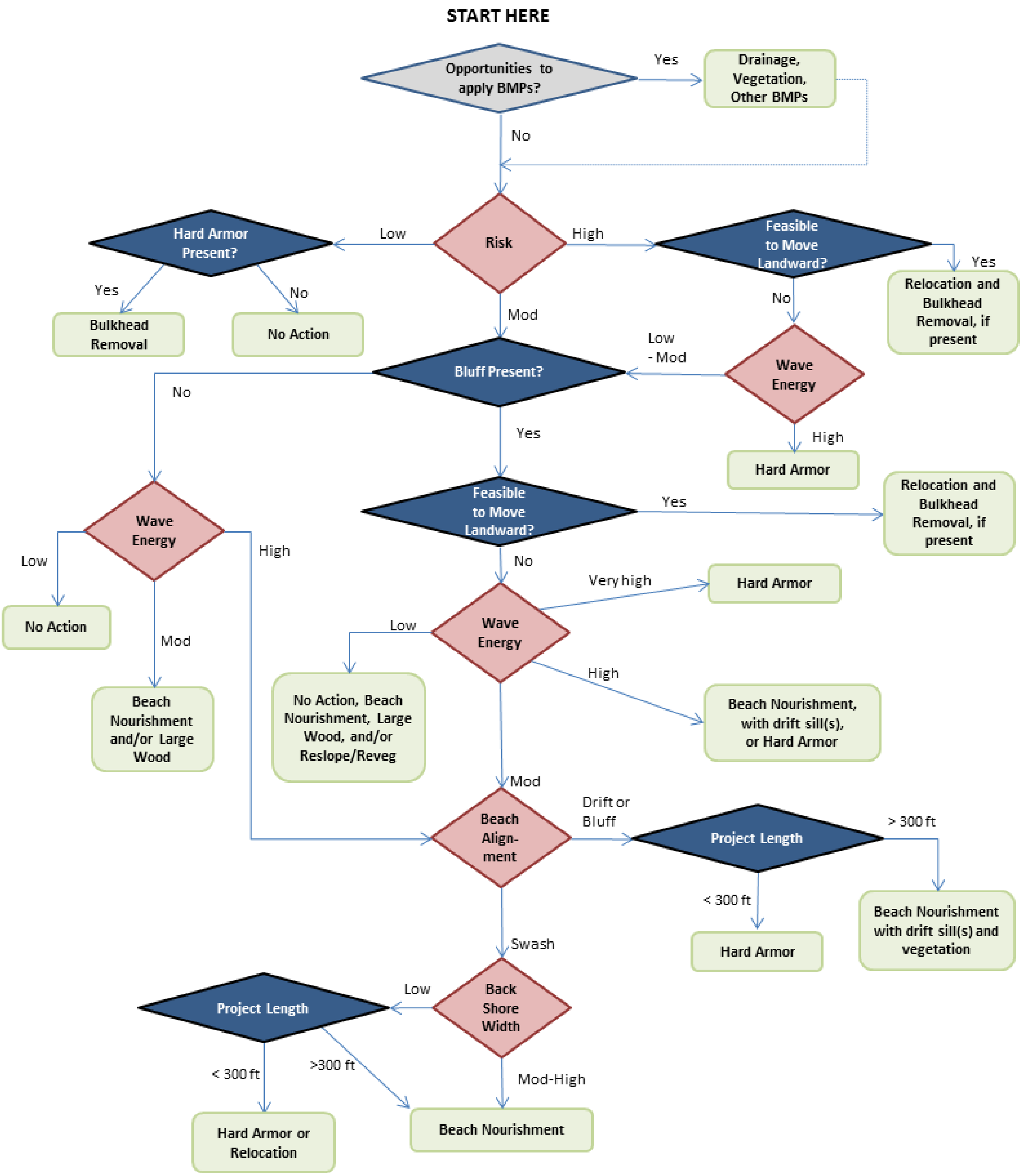

Figure 5-11. Decision tree for identifying appropriate design techniques for a given site. Read top to bottom. Refer to site and coastal processes assessment data, Table 3-4 for risk, Tables 5-6 for wave energy, and 5-7 for backshore width categories.

Table 5-6. Wave energy categories to be used in selecting appropriate design alternatives for site conditions (also in Chapter 3).

Wave Energy	Greatest Fetch*
Low	0–1 miles
Medium	1–5 miles
High	5–15 miles
Very High	15+ miles

*Greatest Fetch = whichever is greater: maximum fetch from southern quadrant (SE to SW) or half the maximum fetch from other aspects

Table 5-7. Backshore width categories measured from MHHW landward in ft to assist with selection of appropriate design alternatives for the site conditions.

Backshore width (ft)	Wave Energy Category		
	Low	Moderate	High and Very High
Low (ft)	<5	5-15	15+
Medium (ft)	5-10	15-25	25+
High (ft)	10-15	25-35	35+

After appropriate design techniques are identified, the benefits and impacts should be weighed before selecting a final design technique(s). After evaluating the options and their benefits and impacts the alterative(s) with the least impacts should be selected. Site assessment data should then be revisited to explore if using multiple approaches could reduce the potential impacts associated with using the chosen approach alone.

Conditions, and particularly risk, are often variable within parcel-boundaries, particularly on large properties. The suitable design technique for the area waterward of the home may not be necessary for the entire shore. For example, on large parcels, where risk is variable, risk may need to be calculated for smaller segments of shore to assure that unnecessarily robust engineering is not applied to low risk areas. If portions of the property are appropriate for lower impact approaches then the spatial extent of armor should be limited to the extent necessary in order to limit potential impacts and mitigation requirements.

The decision tree presented in Figure 5-11 does not always identify a single design technique. Key variables of influence that assist with design technique selection are displayed in Table 5-8. Typically more than one approach is appropriate for site conditions and this additional analysis should be conducted to determine which design technique(s) to select for implementation. This table provides a simpler method for determining the best alternative(s) based on risk, wave energy, shoretype, and backshore width. Table 5-8 is also consistent with the decision tree (Figure 5-11).

Table 5-8. Key variables of influence to selecting the appropriate design technique. See Tables 5-6 and 5-7 for wave energy and backshore width categories.

Risk	Wave Energy	Shoretype	Backshore Width	Appropriate Technique
All	All	All	NA	RELOCATION & BMPs
Low	Low to Very high	All	NA	NO ACTION
Low	Low to Very high	All	Low to High	BULKHEAD REMOVAL*
Low to Moderate	Low to Moderate	All	Moderate to High	LARGE WOOD
Low to Moderate	Low to Moderate (drift aligned)	All**	Low to High	BEACH NOURISHMENT
	Low to Very high (swash aligned)	All**	Moderate to High	
Low to Moderate	Low to Moderate	Bluff	Moderate to High	RESLOPE AND REVEG
High	High or Very high	All	Moderate to High	HARD ARMOR REVETMENT
High	Moderate to Very high	All	Low	HARD ARMOR VERTICAL

*If not armored then NO ACTION.

**Beach nourishment is only appropriately applied at bluff sites when integrated with other measures including backshore vegetation and an evaluation of littoral drift OR on shores with low wave energy.

Impacts and Costs

Impacts

The ideal design technique for a given site will effectively achieve the objectives of the project, while resulting in the fewest impacts and the greatest benefits possible. Each design technique is associated with impacts that range in duration, magnitude, and variety. Impacts associated with a given design technique can be minimized or avoided if the alternative selected is feasible for the site and designed and built appropriately (See Table 5-9). For example, if forage fish spawning is documented or is very likely to occur at the site, then a design alternative should be selected that does not impact upper intertidal spawning habitat. Table 5-9 can be referenced to identify the range of impacts associated with each design alternative.

Table 5-9. Impacts and duration of impact associated with each design technique.

Design Technique	Impact	Range of Duration
Beach nourishment (BN)	Beach disturbance from equipment, materials staging and sediment placement	Temporary
	Burial of current substrate (smothers meso/meiofauna) Commonly coarser substrate is applied Can steepen beach profile Drift sills can temporarily impair sediment transport	Intermediate
	Drift sills bury portion of intertidal beach Degraded salmonid migratory habitat	Permanent
Large wood (LW)	Beach disruption from equipment, materials staging and placement Subgrade excavation disturbance to beach substrate	Temporary
	Anchoring system commonly comprised of non-native materials Logs bury a portion of the intertidal beach	Permanent
Bank Re-slope/ and revegetation (RE)	Beach disruption from equipment access, materials staging and placement Disturbance and upland habitat loss associated with regrading bank Sedimentation associated with vegetation clearing Changes in upland surface water flow	Temporary
	Vegetation takes time to mature and effectively function as erosion control	Intermediate
Bulkhead removal (BR)	Beach disruption from equipment access, materials staging and placement Sedimentation/turbidity associated with removal Disturbance of beach substrate during subgrade excavation	Temporary
Hard Armor: Rock revetment (RV)	Beach disruption from equipment, materials staging and placement Increased turbidity	Temporary
	Precludes sediment input Buries portion of upper beach Degrades salmonid migratory habitat Coarsened sediment composition Can steepen beach profile Precludes LWD input and deposition Riparian vegetation alteration Altered wave action and littoral drift	Permanent
Hard Armor: Vertical bulkhead (VB)	Beach disruption from equipment, materials staging and placement Increased turbidity	Temporary
	Precludes sediment input Buries portion of upper beach Degrades salmonid migratory habitat Coarsened sediment composition Can steepen beach profile Precludes LWD input and deposition Riparian vegetation alteration Altered wave energy and littoral drift	Permanent

Adaptive Capacity, Maintenance Interval, and General Cost

In addition to the adverse impacts and benefits associated with each design technique, several other elements are relevant to design technique selection that may not be initially apparent. For example, some approaches have greater natural adaptive capacity and are likely to sustain a moderate rise in sea level (~1 ft) with little alteration. In contrast, other approaches may be more likely to fail or further impact the beach as shorelines migrate inland (Table 5-10). An example of design technique with high natural adaptive capacity is beach nourishment along a barrier beach, in which the foreshore and backshore naturally migrate landward as sea levels rise. Natural beach profiles with intact sediment supply are assumed to have the most adaptive capacity, also referred to as resilience.

As shown in Figure 5-8, and the Phase 1 case study assessment (Appendix 1), design techniques vary in the benefits provided to nearshore processes as well as maintenance costs and intervals. Although any design technique has a give design lifetime, some techniques may require maintenance more frequently than others in order to continue to be effective. Typically, techniques with shorter maintenance intervals may not cost as much to both implement and maintain as those with longer maintenance intervals. Conversely, techniques with a longer maintenance interval may require a full rebuild rather than maintenance (such as vertical bulkheads).

Table 5-10. Typical (installation) costs and benefits associated with different design techniques. L=Low, M=Moderate, H=High.

Design Technique	Cost	Slows Erosion	Benefits Processes	Adaptive Capacity	Maintenance Cost	Maintenance Interval
Beach nourishment (BN)	M	H	M-H	H	L-M	L-M
Large wood (LW)	L-M	M-H	M	L-M	L	M
Re-slope/ revegetation (RE)	M	M	M	M-H	L	H
Bulkhead removal (BR)	L-M	NA	H	H	None	None
Hard Armor: Rock revetment (RV)	M-H	H	None	None	M	L
Hard Armor: Vertical bulkhead (VB)	M-H	H	None	None	H	L

Mitigating Impacts

The ultimate goal for selecting the appropriate alternative for a given site is to find balance between the project objectives and other factors such that the project avoids or minimizes impacts and maximizes benefits to the greatest extent possible. However, in some cases, the most appropriate design technique results in impacts of considerable magnitude and duration, such that mitigation is required to prevent a net loss. Additional guidance is available on mitigation strategies for habitat loss due to shore armor in EnviroVision et al. (2010).

Where impacts associated with the selected design alternative cannot be minimized or avoided, compensatory mitigation efforts should be identified and integrated into the project design. Mitigation should emphasize on-site and in-kind rehabilitation or replacement of degraded processes, habitat, and ecological function to the greatest extent possible. Many impacts can be avoided or minimized with proper planning and design, however some impacts are unavoidable and are difficult to adequately mitigate. Potential mitigation actions are outlined in Table 5-11, although these are just a few of the many possible mitigation opportunities, which like design techniques, are also site-specific.

When mitigating for hard armor it is important to be mindful that extensive data show that hard armor can produce measureable impacts that extend for many times the length of the structure (Coyle and Dethier 2010). The distance at which these impacts occur is related to the length of the armor. Longer reaches of armor result in more wide-ranging alongshore effects (Coyle and Dethier 2010). Therefore mitigation requirements for shore armor should reflect this association and larger armor projects should require additional mitigation.

Off-site mitigation, such as an in lieu fee program, can be effective if options are very limited at the subject site and the mitigation has proper planning and tracking. For example, off-site armor removal could be adequate compensatory mitigation for installing armor within the same drift cell. If an off-site mitigation opportunity exists that will provide long-lasting benefit to nearshore processes (such as bulkhead removal), then it should be preferred over less beneficial structural enhancement mitigation opportunities located within the drift cell or on-site mitigation opportunities. Beach nourishment can be effective at partially mitigating for armor; however the benefit will be much shorter in duration than the impacts since the lifespan of hard armor is typically 30 years or more. Nourishment cannot effectively mitigate for lost forage fish spawn area due to direct loss via burial. Additionally, mitigation using (re)nourishment would be required every 5 years, indefinitely, resulting in considerable cost and disturbance and, perhaps more importantly, these types of ongoing mitigation requirements are often not adequately tracked or carried out. This type of ongoing mitigation requirement is therefore not recommended.

Table 5-11. Potential mitigation options associated with each design technique.

Design Technique	Potential Mitigation
Beach nourishment (BN)	Backshore vegetation enhancement. If beachface sediment composition is coarser than natural substrate in documented spawning area, substrate suitable for forage fish spawning could be applied to the upper reaches of the beach profile. Backshore vegetation enhancement.
Large wood (LW)	Backshore vegetation enhancement.
Re-slope/ revegetation (RE)	Mitigation not applicable in general. Revegetation if disturbance to vegetation occurs as part of accessing the site. Augment sediment supply.
Bulkhead removal (BR)	Not Applicable. Revegetation if disturbance to vegetation occurs as part of accessing the shore to remove structures.
Hard Armor: Rock revetment (RV) and Vertical bulkhead (VB)	Structure placement as far landward and high on beach profile as possible. Avoid clearing to greatest degree possible of marine riparian and backshore vegetation. Plant all disturbed areas. Nourishment of upper beach if necessary to preclude beach lowering, coarsening if more permanent mitigation is not possible. Augment sediment supply if at a bluff site. Off-site mitigation such as armor removal.

The information and tools provided in this chapter are intended to guide the user to a set of appropriate design techniques for conditions at the site and the larger coastal process unit (or net shore-drift cell), from which the user would select the technique or mix of techniques that adequately addresses the causes of erosion with the fewest impacts to the nearshore. Impacts can often be reduced by limiting the spatial extent of higher impact techniques to only where necessary to protect infrastructure at risk, and implementing lower impact alternatives elsewhere. Supplemental information on maintenance, mitigation, and costs were provided to increase awareness and expectations when designing and implementing the selected design technique.

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Chapter 6. PASSIVE MANAGEMENT TECHNIQUES

Passive Management Techniques are practices that help the shoreline owner manage some types of erosion without using the engineered approaches featured later in Chapter 7. These techniques have fewer impacts to beach processes and habitat, and can be less expensive than highly engineered shore protection techniques. Coastal property owners should consider these techniques when evaluating alternatives for managing erosion on their property. Passive shoreline management techniques include:

- Surface and groundwater management
- Vegetation management
- Relocation of infrastructure

Passive management is thoroughly addressed in several existing documents (identified below) and is outlined here to highlight its place in the suite of alternatives for shore protection.

Surface and Groundwater Management

In the undeveloped, forested condition, up to 40% of rainwater is intercepted by the canopy where it accumulates on the foliage and is transpired or evaporated (Bauer and Mastin 1997). Compared to the forested condition, relatively little reaches the ground, and what does is absorbed by the thick layer of leaf litter and humus. When the forest is cleared for development more water is able to reach the ground. Additional infrastructure to support human uses such as septic drainfields and irrigation systems are also sources of water input. Water management and drainage systems that route runoff into the ground without adequate consideration of soil characteristics may result in slope instability. Figure 6-1 schematically shows these changes to groundwater and the potential increase in bluff slope instability.

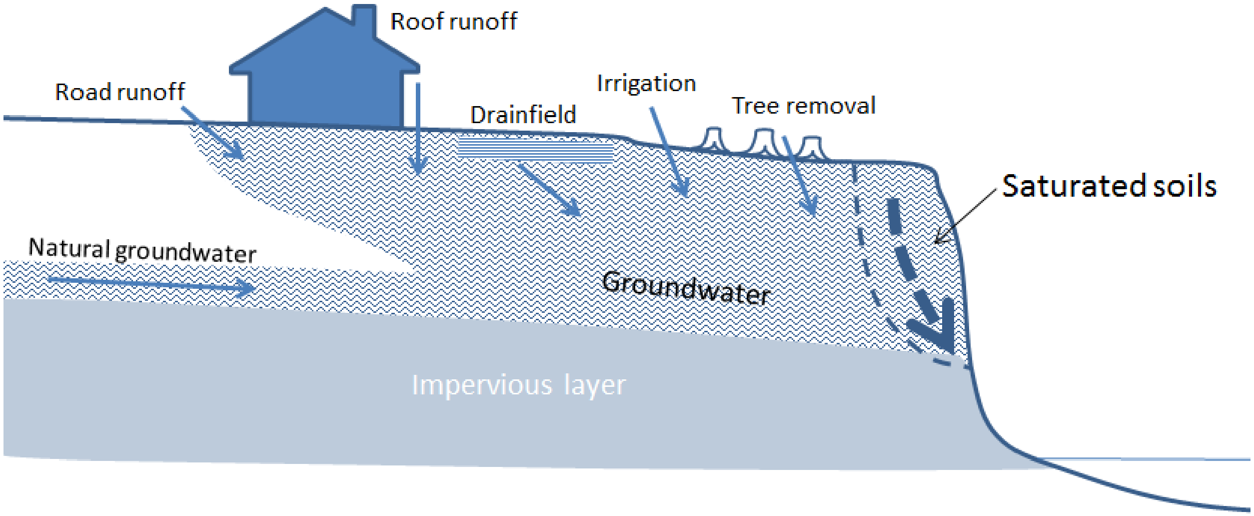

Figure 6-1. Development practices can increase groundwater and saturate bluff soils, increasing the likelihood of slope failure (Redrawn from Marsh 2005).

Runoff from a site acts in two ways to exacerbate erosion of coastal bluffs. Surface water from developed property collects and flows over the soil carrying away particles, forming rills and then gullies. The gullies can undermine portions of the bluff and cause them to shear off or otherwise interfere with a landowner's use of the property. Water that is allowed to seep into the ground near the crest of the bluff helps saturate the soil, increasing pore water pressure and decreasing the strength of the soil structure. This saturated soil can then fail catastrophically in a landslide or slump, especially when there is an impervious layer (clay or compact till) underlying the site, as show in Figure 6-1.

Managing runoff around homes and other structures at the top of bluffs is important for bluff integrity. Because each site is unique, water management will require different combinations of solutions with varying degrees of technical and professional design needs. Best management practices for drainage are clearly explained in Department of Ecology's **Managing Drainage on Coastal Bluffs** (Myers et al. 1995) and Ecology's website (http://www.ecy.wa.gov/programs/sea/pubs/95-107/intro.html) recommends a 3-step approach to managing groundwater:

- Evaluate the property, its geology, and the pattern of water movement
- Identify potential problems that could lead to slope instability and select from the suite of techniques to create a drainage plan that manages them
- Construct the drainage plan and maintain it

Some groundwater is always present, especially above impervious layers. The goal of runoff management is to reduce additional input that is caused by clearing and development to reduce the risk of bluff failure (Myers et. al. 1995). Preventing runoff and drainage from saturating the ground by routing it over a bluff is one way to address slope stability concerns, but this must be done with adequate attention to the outfall structure to prevent erosion problems to the beach or marine riparian zone.

Design and placement of the drainage outfall are important factors in reducing beach erosion. Outfall control structures dissipate the energy of flow at the outlet caused by the velocity and pressure of water rushing downhill from the site. This energy can be considerable when a large quantity of water flows from a high height, such as a 100-foot bluff. There are engineering design methods for outlet control structures in many stormwater design guides, such as WSDOT *Highway Runoff Manual* (Washington State Dept. of Transportation 2011) and the Ecology *Stormwater Management Manual for Western Washington* (Bakeman et al. 2012) and the Federal Highways Administration's *Hydraulic Design of Energy Dissipaters for Culverts and Channels* (Thompson and Kilgore 2006). Some of the alternatives suggested in these manuals are unsuitable for the beaches of Puget Sound, particularly those that have a large footprint at the outlet such as those with extensive rip rap dispersions pads and gabion basket structures. To avoid impacts to the beach and outlet structure should:

- Be located above OHW or below -10 ft MLLW
- Reduce structure footprint and weight
- Spread water flow
- Reduce water velocity

A rule-of-thumb criterion for minimizing the potential for erosion is to reduce the velocity of flow to a point where it will no longer move the size of sediment composing the beach or upland area. Based on the Ishbash equation (Ishbash 1936) the maximum velocity in the outlet flow should not exceed the following for the given grain size:

1 fps - sand (average particle size 0.15 inches)
2 fps - fine gravel (average particle size 0.6 inches)
3 fps - coarse gravel (average particle size 1.4 inches)
4 fps - cobble (average particle size 2.4 inches)

A diffuser tee is a common outlet device used in Puget Sound that can be designed to facilitate upland drainage and reduce beach erosion impacts. Generally they are constructed from high density polyethylene pipe fusion welded into a tee configuration (Figure 6-2). Flow enters the stem of the tee and is forced sideways into the arms, dividing the flow and reducing the energy in the turbulence caused by the impact with the top of the tee. The lateral arms of the tee are perforated with many holes to divide the flow into small streams with limited power to erode the bank and beach. Leaving the ends of the tee open reduces the potential for plugging with debris (leaves and litter), but may result in significant flow and velocity out of the open ends. High velocity discharge may be countered by making the lateral arms longer than the recommended two times the pipe diameter. Some designers have fitted the ends of the arms with caps that prevent flow from pouring out the ends. These caps can be removed for maintenance by using a bolted fitting.

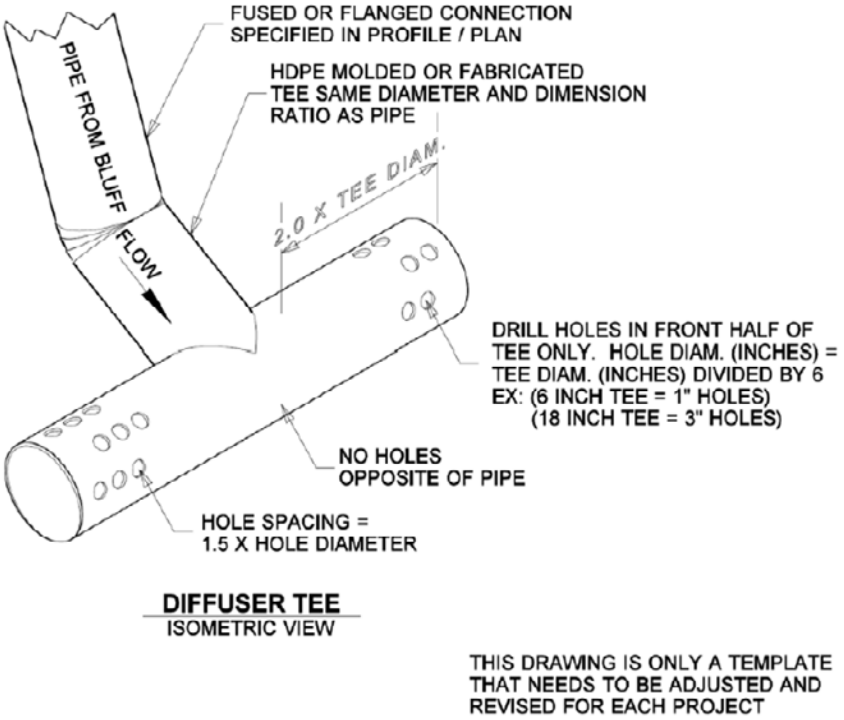

Figure 6-2. Diffuser Tee (WSDOT Stormwater Best Management Practices, Design Manual).

Since stormwater is periodic it is possible to establish a bed of native vegetation for the diffuser tee that uses the root strength to resist erosion. In some instances the tee can be mounted in the backbeach area without any additional erosion protection (Figure 6-3).

The diffuser tee can be mounted on a small bed of coarse crushed gravel or quarry spalls to further reduce the threat of erosion, although this method has environmental impacts that may require mitigation.

Figure 6-3. Diffuser tee mounted at the toe of the slope, upland of OHW, and behind existing drift logs. No rip rap pad was used.

In addition to beach erosion concerns, water quality must also be addressed. There is always a potential for pollutant discharge from any site. It is best to first control any pollutant sources and then treat stormwater for what cannot be controlled. Best management practices can be found in Ecology *Stormwater Management Manual for Western Washington* (Bakeman et al. 2012).

Discharges from small properties (less than 5 acres) do not require stormwater permits, but larger developments may need to get a NPDES (National Pollutant Discharge Elimination System) permit from the Dept. of Ecology. The outfall structure itself will require an HPA (Hydraulic Project Approval) from the Dept. of Fish and Wildlife. Other permits may apply from the local City, County, or Army Corps of Engineers.

Vegetation Management

Appropriate management of existing vegetation on slopes can help reduce the risk of failure. Vegetation intercepts a portion of rain water, preventing it from reaching the ground and eroding the surface. The roots of this vegetation act to bind the soil particles together, increasing its strength and stabilizing the slope. Maintaining the existing vegetation, or planting new native species, preserves these functions. Vegetation management is discussed in Chapter 7, Technique 3, Reslope-Revegetation, although the focus of the technique is on slope recontouring.

The marine riparian (the vegetation that grows immediately adjacent to the beach) provides many benefits in addition to slope stability and landowners should consider revegetating cleared sites. These benefits include the natural beauty of a mature coastal forest, fringing marsh, or salal and sword fern bank. These native plants are the primary producers of the terrestrial nearshore absorbing nutrients from the soil, dropping insects and leaf litter, slowing water movement and supplying large wood to the beach.

The Department of Ecology has a guide for this technique, Vegetation Management: A Guide for Puget Sound Bluff Property Owners (Menashe1993). Management Measure 17: Revegetation in Management Measures for Protecting the Puget Sound Nearshore (Clancy et al. 2009) also discusses this topic.

When site-appropriate vegetation management is incorporated into a development plan it can naturally reduce erosion risk and maintain slope stability. However, the owner and designer should be aware of the distinction between superficial erosion and deep-seated slope instability. Superficial erosion includes rills, gullies and shallow landslides. It takes place on sloped soil surfaces exposed to rainfall and runoff. Vegetation is an effective method to control superficial erosion on sloped surfaces. On the other hand, deep-seated slope instability is due to subsurface stratigraphy, soil saturation or toe erosion. Vegetation can reduce ground water levels, but it cannot eliminate all the risks due to these other factors.

Vegetation Planning and Design

The first step in designing a revegetation strategy is to determine the characteristics of the shore where the work will be done. This includes the type of shore form, stratigraphy, soils, bank height and slope, and then the cause and general rate of erosion occurring (Manashe 1993). This information helps determine whether vegetation can stabilize the site and what degree of disturbance it can tolerate and still provide the functions of a healthy riparian zone.

Landowners are often concerned with trees and how they affect the view. Manashe (1993) discusses in detail the problems with removing, topping and pruning trees. In general, tree root systems aid in soil stabilization. Fallen trees are important to beach ecosystems and should be left on the beach to provide habitat and natural shore protection.

The types and variety of plants that naturally grow along the shores of Puget Sound vary from one place to another. This has to do with the steepness of the banks, the soil types, the ground water and rainfall, the direction the bank faces, the degree of disturbance or development, and where in the natural succession of plants the site is at. Knowing these characteristics will help the owner or designer determine a revegetation plan and the species of plants that are most likely to be successful there. Dept. of Ecology has a website for plants commonly found on Puget Sound shores http://www.ecy.wa.gov/programs/sea/pubs/93-31/app-a.html.

Some tips for a successful project (Clancy et al. 2009) include:

- Conserve and restore the soils
- Protect the existing native vegetation
- Control erosion on disturbed soils while plants establish and grow
- Use good quality plants native to the area
- Select a skilled and knowledgeable contractor.

A properly vegetated slope and adjacent upland can provide considerable stability and also be more natural looking than other heavily engineered solutions. And because it is a more natural approach, it does allow for some amount of erosion to occur and support beach processes. Depending on the quantity and types of plants, this can also be a less costly technique for managing slope stability. Vegetation, however, will not decrease coastal erosion or the instability due to underlying geologic conditions.

Relocation

As a shore management technique, relocation means to move coastal infrastructure inland to allow natural erosion to occur. An example would be moving a house or a road back from an eroding bluff rather than trying to stabilize the bluff. This approach is also referred to as “managed retreat” or “realignment.” Relocation will have fewer impacts to nearshore ecology and processes than armor placement, however it is often costly and used when no other options remain. This is particularly true on feeder bluffs, where eliminating a sediment source by installing a bulkhead has far ranging effects on down-drift property owners and shore habitats. In low bank situations relocation can allow for the formation of a backshore area, let tidal water flood back into a former marsh, or allow sea level to rise unimpeded. Siting infrastructure away from the shoreline during the planning stage of a project is always good practice and reduces the need for relocation.

Managed retreat is often used for coastal roads. In the following series of examples (Figures 6-4 to 6-7), relocation is shown as a practical alternative to protecting the road in place. Note that the roads in these examples are all local roads, not State highways. It is relative rare to move a highway because they are often part of a complex web of other roads, access points, and utility networks.

Figure 6-4. Cook Road located northwest of Port Townsend along the Strait of Juan de Fuca. The realigned road is at the top of the photograph and the abandoned road at the bottom where the corner has been cut away by bluff erosion. The narrow, steep beach and high energy waves cause persistent erosion with no backshore to locate a practical bulkhead. The relocation took place in the 1990s (Dept. of Ecology Digital Coastal Atlas).

Figure 6-5. Lummi View Drive (Whatcom County) was relocated back away from an eroding shoreline about the year 2000. The old road was located on top of the bluff immediately adjacent to the shore. The new road is show above it and approximately parallel (Dept. of Ecology Digital Coastal Atlas).

Figure 6-6. East Pritchard Park access road relocation and bulkhead removal project. Pritchard Park is located on Eagle Harbor, Bainbridge Island. The bulkhead at the toe of the bluff (shore on the right of the photo) below the original access road was removed, destabilizing the bluff. The road was relocated to the left in the photo to restore access to the southeast part of the park.

Figure 6-7. Deer Harbor Road on Orcas Island relocated away from an eroding bluff. The old road alignment was exposed to periodic bluff failure and is shown as a dashed white line. The new alignment runs roughly parallel to the right.

Road relocations are generally carried out by public entities with greater access to planning and engineering support with a responsibility to provide reliable transportation services to the public. Individual structures, on the other hand, are the responsibility of the owner who may have more modest resources. Two examples of structure relocation are shown in Figures 6-8 and 6-9.

Figure 6-8. These two photos are of a section of shore near Dockton Park on Vashon Island. In the left photo, taken in 2001, a structure on the right (indicated by arrow) is protected by a bulkhead that protrudes out into the intertidal mud flat. In the right photo (2006) the structure has been moved back from the shore and the bulkhead removed (Dept. of Ecology Digital Coastal Atlas).

Figure 6-9. The large, deep seated slide on Hammersley Inlet caused the landowner to relocate their house. The slide can be seen in the middle of the photo and extends from the shore to lower edge of the cleared area (top of slide indicated by white dashed line). The foundation of the relocated house is below and to the right of the asphalt cul-du-sac (white arrow) (Dept. of Ecology Digital Coastal Atlas).

A final example shows vertical relocation or retreat where a structure is elevated to allow water to flow beneath it to avoid damaging the structure itself. Vertical relocation reduces the need for shore armor. This is a common technique on river floodplains other areas prone to flooding.

Figure 6-10. A Maury Island home elevated three feet above base flood elevation. Skirting hides the elevated part of the house, indicated by the square vent holes seen on the right side. The owner also replaced a bulkhead with softshore protection that allows for sediment movement and occasional flooding at high tide (photo K. Higgins).

Relocation Planning and Design

Because the type of infrastructure found on a shoreline varies considerably in its size, purpose, geographical setting, and supporting infrastructure, there is no one source for planning and design guidance on relocation. There are many examples of relocation shown in the figures above and in the literature from coastal communities in the United States and elsewhere in the world (NOAA 2007, San Francisco Planning and Urban Research Association 2012, Rankka 2005). The actual engineering design of the relocation project covers a range of disciplines, most of which are outside the scope of these guidelines, such as the civil, coastal and hydraulic engineering. However, the decision to use relocation is within the assessment and design procedures suggested here.

Techniques for removal and relocation are discussed in *Management Measures for Protecting the Puget Sound Nearshore*, (Clancy et. al. 2009). These include,

- Armor Removal or Modification
- Berm or Dike Removal or Modification
- Topography Restoration

Determining whether there is a suitable place to relocate the infrastructure is an important first step in evaluating relocation feasibility. For example, a shoreline home at the base of a bluff may not be able to be moved back away from the shore due to the bluff behind it, but a home at the top of a bluff may have adequate space to be moved back away from the bluff crest. Complex sites may have water and gas lines, drainfields, and access/easement issues that will all need to be thoroughly explored and evaluated before the decision to relocate can be made. Looking beyond existing conditions to projected sea level scenarios may also help determine whether relocation is a suitable approach.

The benefits from relocating infrastructure away from the shoreline may not be immediately apparent, especially when considering cost. Relocation may be a large up-front cost, but the move – if sited properly away from the shore – will be permanent with no new costs necessary to protect the home. Other approaches, such as building a bulkhead, will involve initial costs and periodic maintenance and replacement costs since a typical bulkhead lasts 15 to 40 years (Clancy et al. 2009). The peace of mind and life and safety benefits gained from moving away from an eroding bluff is unquantifiable in standard cost-to-benefit analyses. Equally challenging to include in a cost-benefit analysis is the benefit to habitat from allowing natural erosion to occur. However, proper siting of infrastructure away from the shoreline so that armor is not necessary is one of the best options to increase benefits and reduce impacts to the shoreline.

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Chapter 7. TECHNIQUE 1
BEACH NOURISHMENT

Description

Beach nourishment, also referred to as beach replenishment or beach feeding, is defined as “the natural or artificial supply of sand or gravel to a beach” (Bird 2005). Finkl and Walker (2005) discussed it as:

> The artificial (mechanical) placement of sand along an eroded stretch of coast. Efforts to artificially maintain beaches that are deprived of natural sediment thus attempt to proxy nature and (re)nourish the beach by mechanical placement of sand. The beach sediment is thus replenished by artificial means.

In the Pacific Northwest gravel beach nourishment has been referred to as “constructing a protective berm” by early practitioner Wolf Bauer, who designed the first gravel nourishment projects in Puget Sound in the 1970s (Bauer and Hyde 2010). Beach *re*nourishment typically refers to the resupplying of nourishment material at a previously nourished beach where some of the placed sediment has eroded.

Beach nourishment projects are usually designed to emulate natural processes, although many times the longevity of the nourished beach is enhanced through the use of sediment slightly larger than native sediment or other measures that extend the functional life of the nourished beach. Like natural beaches, nourished beaches are intended to adjust in response to wave action such that the beach geometry often changes both spatially and temporally, appearing to erode and accrete (grow) in different areas over time. The degree of protection to infrastructure is not constant for a deformable shore as it usually is with hard armor (revetment or bulkhead, Cox et al. 1994). Despite this fact, beach nourishment has become a common method of erosion control in the Puget Sound region (Shipman 2002) and has been applied on coasts throughout the country and across the globe (Finkl and Walker 2005).

Many larger Puget Sound projects have included both beach nourishment and hard engineering approaches such as rock revetments. The discussion herein focuses on nourishment projects that are dominated by gravel or gravel and sand nourishment and designed to allow for dynamic processes, although these projects sometimes include other design techniques as well in portions of a site. All those involved in project review must be able to critically examine scaled design drawings (plan view sheets and cross sections) because in some cases hard armor dominates to the degree that the project can no longer be considered soft shore protection (Johannessen 2000). For example, traditional rock revetments covered with sand and gravel have at times been submitted for permitting as beach nourishment or soft shore protection projects.

Application

Beach nourishment is a common technique used for shore protection in many parts of the world. The application of beach nourishment has increased in recent decades as hard armor has become less desirable due to negative habitat impacts, down-drift sediment reduction, and increasing costs (Finkl and Walker 2005). Additionally, the economic and ecologic benefits of beaches have become better understood. In the Puget Sound region, gravel beach nourishment was pioneered by Wolf Bauer (Shipman unpub., Bauer and Hyde 2010). Early Bauer nourishment projects have served as models for landowners and designers since his first public project in Puget Sound in 1972 (Tolmie State Park, described in Appendix A). Some Bauer designs have been criticized for using sediment that was considerably more coarse than natural, but beach nourishment can adapted to satisfy a variety of goals at different scales and site configurations. Design decisions will vary depending on the site and project goals, which can range from erosion control at a high-risk setting to habitat restoration or enhancement.

The beaches of Puget Sound are unique both nationally and globally in their fetch-limited fjordal estuarine environment and mixed sand and gravel sediment composition (see Chapter 1). The crenulated (complex) shore of Puget Sound controls the type of application that is feasible for a given site, and also underscores the need for site-specific designs. The majority of the beach nourishment literature concerns placing sand on open-coast beaches exposed to large, long-period waves. Puget Sound region beaches are dominated by gravel-sized sediment due to repeated glacial ice sheet advances and subsequent deposits (Booth 1994). Gravel is used almost exclusively as the dominant nourishment sediment as gravel tends to be maintained on upper beaches while sand is often transported to the lower beach. Gravel is more resistant to erosion and littoral (longshore) transport than sand (these concepts are explained further in the Effects section below).

Beach nourishment has most often been used in the Puget Sound region to reestablish broad beach profiles that act as buffers against wave attack, and to mitigate erosion of the upper beach and backshore areas. Many beach nourishment projects have focused on creating, or recreating, a relatively high-elevation backshore storm berm to limit the effects of storm waves in this area. The simple augmentation of beach sediment volume, whether in the intertidal or in the backshore alone, provides a wider and/or higher buffer to incident storm waves. Beach nourishment helps offset beach gravel mining (the inverse of nourishment) which has been carried out throughout human history. Beach gravel mining was widespread in Puget Sound through the mid-20th century and depleted many local beaches, although documentation is sparse (Johannessen and MacLennan 2007).

Beach nourishment is not advised where frequent renourishment will be required. This is in order to minimize both maintenance costs and unnecessary impacts from modern gravel mining. Rounded gravel is a limited resource and the availability of gravel has steadily decreased over the decades. Additionally, gravel mining poses its own environmental impacts through site disturbance and potential impacts on surface and groundwater.

As detailed in this chapter, barrier beaches and specifically swash-aligned beaches are best suited for successful beach nourishment projects. Sites appropriate for applying beach nourishment include those that have naturally eroded or have had erosion exacerbated by development, putting buildings or other development at risk. For example, at North Samish Island (Johannessen 2002) the cumulative negative impacts of extensive bulkheading along feeder bluffs and the installation of groins led to substantial loss in beach width and elevation (Canning and Shipman 1995). Gravel beach nourishment was initiated at North Samish Island in 1998 to offset these impacts, and has been successful in protecting houses and maintaining a wider beach suitable for surf smelt spawning for 15 years without renourishment. Nourishment has also been initiated to restore beaches for habitat enhancement (Johannessen and MacLennan 2007).

Effects

Gravel beach nourishment absorbs a large amount of incident wave energy on the beach. Gravel beaches can dissipate up to 90% of the incident wave energy (Diserens and Coates 1993). As explained below, sediment that is slightly coarser than native beach sediment is often used in nourishment designs (Dean 2002) and this can help form a high berm for storm protection (often called a storm berm). This berm dissipates storm wave energy by reducing wave runup through increased friction. Backwash water volume and velocity are also dissipated as the water percolates through the coarse gravel (Finlayson 2006, Komar et al. 2003). The typically steepened beach slope resulting from gravel nourishment can provide additional erosion control in the form of wave reflection. Waves reflect off the beach and collide with incoming waves, which enhances breaking and energy loss from the incoming waves (Komar et al. 2003).

The use of coarse sediment for nourishment can alter the beach habitat somewhat, at least in the initial years after placement. The use of coarser sediment is normally limited in documented forage fish spawning areas. Most of the beaches that have been nourished with coarser sediment, with the exception of some sites in low-wave-energy locations (such as Place Eighteen in Zelo et al. 2000), have naturalized with beach surface sediment closely resembling native sediment conditions within 3 to 5 years after placement (such as the Marine Park and North Beach Orcas Island case study sites in Appendix A).

Beach nourishment projects can provide sediment to down-drift beaches at higher rates than in pre-project conditions by augmenting the littoral transport. This has off-site as well as on-site benefits, including partially mitigating impacts to sediment supply that was degraded due to development.

Beach nourishment projects selected for the case study assessment (Appendix A) were distributed between the Nisqually Reach, the Strait of Juan de Fuca, and Whatcom County. Photos of these sites are shown in Figure 7.1-1 as examples of Puget Sound nourishment projects. Sites assessed for the study covered a wide range of conditions and design approaches, and were installed between 1972 and 2005, with the majority installed between 2002 and 2005. Because there were more beach nourishment projects than projects using other soft shore protection design techniques, most project case studies selected have been in place for 7 to 10 years, allowing assessment of medium-term performance. Table 7.1-1 summarizes conditions at the 6 case study sites. The range of beach nourishment project sites surveyed for preparation of these guidelines is also discussed in Chapter 5, *Alternatives Analysis*.

The relative wave energy (wave climate) is a critical factor in determining the amount of erosion at a site. Larger waves often equate to larger littoral drift rates, and can result in loss of nourishment sediment. Conditions at the six nourishment sites assessed for this study varied considerably, from low to very high wave energy (Table 7.1-1) and with dominant wave fetch ranging from 6 to 101 miles. Fetch exposures also varied, with three generally southern-aspect sites, two generally northern-aspect sites, and one site exposed to very long fetch from the northeast (East Dungeness).

The wide range of erosion processes in play made comparison of the case study sites difficult. For example, the Marine Park site was located in a highly modified reach of shore (termed “artificial” in PSNERP mapping) with a moderately high rate of background erosion in the absence of shore protection. Although it was not possible to determine background erosion rates at most of the Appendix A sites, it is clear that erosion rates were far lower at the more protected sites such as Snakelum Point or Tolmie State Park.

The beach nourishment sites also covered a wide range of project beach lengths, from 50 ft at Snakelum Point to 1,500 ft at the East Dungeness site (Table 7.1-1). Four of the projects were in residential areas, with two at single-family properties and two encompassing multiple properties. The remaining two projects were at public park shores. The longer shore reaches at Marine Park and East Dungeness project sites allowed for nourishment to extend across most of the intertidal. Conversely, the short reaches at the single-family nourishment projects were limited to placement above MHHW.

Table 7.1-1. Case study project summary data for beach nourishment technique. VH=very high (fetch greater than 15 mi), H=high (fetch 5-15 mi), M=moderate (fetch 1-5 miles), L=low (fetch less than 1 mi).

Site Measurements	Project Name					
	East Dungeness	Tolmie State Park	Snakelum Point	Marine Park Bellingham	North Beach Orcas Is.	East Lummi Is.
Total Risk (range: 0–64)	25	6	16	15	25	25
Wave Energy	VH	M	H	H	VH	VH
Placement Approach	Dune/ backshore	Lower intertidal-backshore	Dune/ backshore	Lower intertidal-backshore	Lower intertidal-backshore	MHHW-backshore
Length (ft)	1,500	900	50	300	510	181
Volume (CY)	1,740	6,000	38	2,759	2,500	440
Volume Density (CY/FT)	1.2	6.7	0.8	9.2	4.9	2.4
Toe Elevation (ft MLLW)	6.5	9.5	13	2-4	2	9.25
Local MHHW (ft MLLW)	7.36	13.89	11.4	8.51	8.68	8.77
Berm Elevation (ft MLLW)	12.74	14.5	15.6	13.0	11.0	14.5
Berm El. Ratio (Berm/ MHHW)	1.73	1.04	1.37	1.53	1.27	1.65
Sediment d50 (in)	0.3	1.75	3	1.25	1.25	2.5
Sediment Range (in)	0.1–2.0	-	2–5	0.1–5	0.5–2.5	1.5–4
Year Install	2006	1973	2002	2004	1992	2004
Maintenance (Y/N)	Y	N	N	Y	N	N

Note: East Dungeness berm elevation was dune elevation.

a) East Dungeness, Clallam County; backshore/dune placement

b) East Lummi Island, Whatcom County; MHHW-backshore placement

c) Marine Park, Bellingham; lower intertidal to backshore placement

d) North Beach, Orcas Island; lower intertidal to backshore placement

e) Snakelum Point, Penn Cove, Whidbey Island; MHHW-backshore placement

f) Tolmie State Park, Thurston County; lower intertidal to backshore placement

Figure 7.1-1. Examples of the range of different beach nourishment projects surveyed for this study (Appendix A), with placement approach noted in captions.

Design

The Salish Sea shores are characterized as complex with a high degree of variability and therefore site-specific analysis and design is always required for successful project design. The region has a wide range of beach conditions, wave fetch distances, drift cell lengths, and littoral transport rates which must be considered along with other factors in the development of a final design. The design sequence for nourishment projects would include these elements:

- Determine risk to structures and establish project goals
- Determine general extent and placement approach
- Evaluate design parameters and develop design details

Information from the *Site Assessment* (Chapter 3) and *Coastal Processes Assessment* (Chapter 4), such as determination of risk and characterization of erosion rates, is the foundation for the design process. *Background* erosion refers to coastal erosion that occurring at a site due to natural causation. This is noticeably different from *active* or *structural* erosion, which is caused by negative impacts of engineered structures, typically resulting from altered wave action (see Chapter 1). Beach nourishment is usually initiated at sites where background erosion has persisted. Background erosion rates will be superimposed on a nourished beach (Dean 2002). In reality, post-project erosion rates will be greater than background erosion rates since the beach profile is pushed waterward (Verhagen 1996). Persistent significant background erosion can jeopardize the success of any beach nourishment project (Clancy et al. 2009).

The total erosion rate at a site is the sum of background erosion and active erosion. It is not critical and often not possible to separately quantify these two components of the total erosion rate. However, it is critical to have an understanding of the magnitude of the total erosion rate at a site prior to developing a beach nourishment design. Ideally an erosion rate should be determined over a period of 30 or more years. This is best done through the use of survey or other accurate site measurements that can be compared over time. Historical aerial photographs spanning back to the 1960s or earlier are also a very good way to quantify the erosion rate at a site. Delineating one or several beach features such as the vegetation line, waterward extent of drift logs, bluff toe, or other features from multiple years allows for comparison. Aerial photographs need to be very carefully rectified and georeferenced to remove as much distortion as possible in the photographs prior to comparison (Morton 1991). Erosion rates are best expressed in terms of inches per year (in/yr), with the initial and current data points as far apart in time as possible. However, for sites or shore reaches which have incurred significant modification, it is most useful to compare the end point erosion rate with the erosion rate for the period following the shore modifications.

The beach nourishment design approach should be largely controlled by the scale or shore length of each site, the magnitude of wave energy the site is exposed to, and whether the beach at the site is swash aligned or not. These and other parameters are shown in the generalized design model for the use of beach nourishment for erosion control presented in Figure 7.1-2. This design model is not intended to produce design dimensions or absolute design pathways; instead it is intended to highlight key factors contributing to site feasibility determination (upper portion) and outline key design elements to be evaluated in the design process (lower portion). For these guidelines, analysis was carried out on 6 beach nourishment case study sites in combination with additional regional sites (discussed later in this chapter), and no clear correlates between site conditions and design parameters could be determined. Due to the high degree of variability in conditions in the region, the variety of project goals and objectives, and the lack of clear correlates, a qualitative design analysis process is best suited to beach nourishment projects, and is outlined in this chapter.

The different portions of the general design model (Figure 7.1-2) are outlined here. Risk and wave energy are discussed in Chapter 3, *Site Assessment*. The influence of the dominant wave approach angle on design is explained in the *Site Geometry* section below. Determining the shoretype as mapped by PSNERP is outlined in Chapter 4, *Coastal Processes Assessment*. Project length is discussed in the following section of this chapter. Failing to evaluate all of these parameters when developing a beach nourishment design can result in a design that either does not achieve project objectives or one that requires excessive maintenance. These design parameters are discussed in terms of design development in the following section.

This *Design* section is organized to assist the designer to assess and evaluate key design parameters. The goal is to balance project elements to achieve a functioning and resilient beach, without unnecessary changes or impacts to coastal processes or on- or off-site habitats. This section is organized as follows:

- Placement approach and project length
- Wave energy and volume density
- Site geometry
- Drift sills
- Berm elevation
- Sediment size selection
- Beach habitat considerations
- Site grading

Beach nourishment projects can be suitable for barrier beach or other sites with adequate backshore width, and/or those with sufficiently long project length (generally greater than 300 ft long). Sites which are most favorable are swash-aligned beaches, where the beach faces directly into the predominant wave approach; sites where historical gravel mining occurred are also suitable. Beach nourishment is generally not suitable for rapidly eroding sites. More detail is provided below.

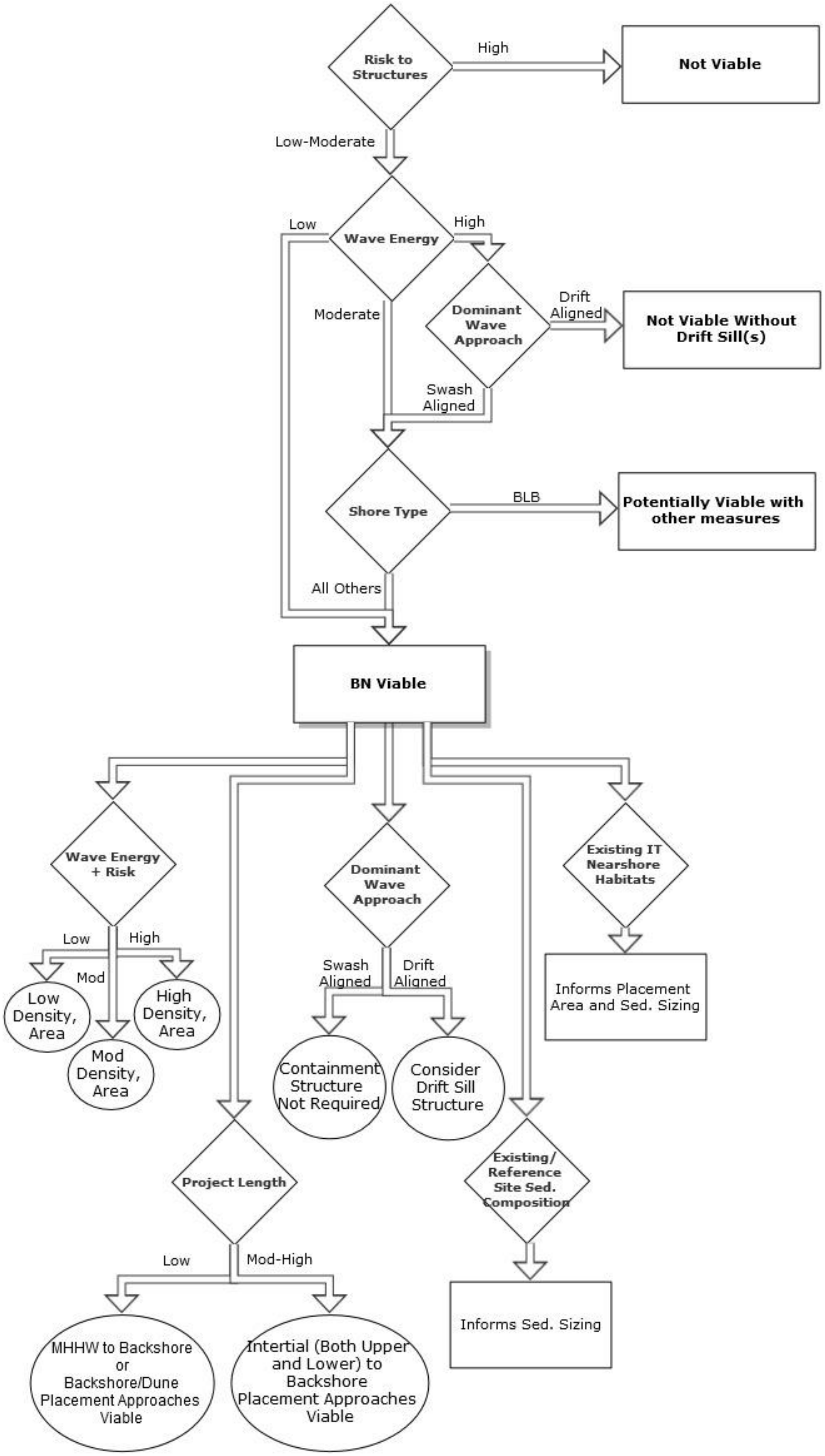

Figure 7.1-2. Design model for the use of beach nourishment for erosion control. Most terms are included in the Glossary at beginning of this document. BN stands for beach nourishment, BLB is bluff-backed beach, IT is intertidal.

Placement Approach and Project Length

The elements of nourishment placement approach, meaning where on the beach profile sediment is placed, and nourishment project length are dependent on each other. Generally longer project lengths allow for a greater choice of approaches in terms of placement width and location on a beach profile. Regional beach nourishment projects typically use gravel applied from the mid-intertidal beach up to and including the backshore area (Shipman 2002). However, other placement approaches have been used and each offers benefits in certain situations.

The term equilibrium profile refers to the generally accepted understanding that a beach with an unchanged sediment size will have a dynamically stable beach profile (Bruun 1988). Following this reasoning, if sediment of the same grain size as the native sediment is placed ungraded on only on a portion of the beach profile, waves will distribute this sediment and adjust the beach back to its original slope. However, the use of coarser sediment will result in steeper profiles, and the creation of a higher berm will also change profile responses. These factors need to be evaluated together for the selection of the project length and placement elevation.

Beach nourishment sediment can be placed over the entire beach profile from the backshore area down to the subtidal, or only on a portion of the beach profile. Placement options consist of the following (Figure 7.1-3), in general order from the broadest cross-shore coverage to the least:

- Entire beach (profile nourishment)
- Lower intertidal to backshore
- Upper intertidal to backshore
- MHHW to backshore
- Backshore/dune
- Bar

Applying beach nourishment sediment over the entire beach profile, **profile nourishment**, allows for less redistribution of nourishment sediment and greater longevity. Profile nourishment allows for nourishing the full width of the beach down to the depth of closure (the greatest depth where wave energy reaches). The depth of closure is not well defined for Puget Sound and is also quite variable depending on the wave climate, but is normally in the range of 8 to 15 ft below MLLW. Complete profile nourishment is rare in Puget Sound due to negative impacts to eelgrass and other submerged aquatic vegetation (SAV) in the subtidal along with subtidal biota. The clear break in slope on most Puget Sound beaches is in the vicinity of MLLW (Johannessen and MacLennan 2007, Finlayson 2006), hence broad nourishment across the beach profile typically means nourishment of the lower intertidal and backshore profile, but not extending offshore across the low tide terrace (lower intertidal to backshore placement, Figure 7.1-3).

The two most common nourishment placement approaches in greater Puget Sound include **lower intertidal to backshore** and **MHHW to backshore** (Figure 7.1-3). Starting nourishment in the lower intertidal is most appropriate for longer length projects, generally longer than approximately 300 ft. This is to ensure that an adequate volume of sediment is placed to unsure that nourishment sediment is not dispersed too quickly. Examples of these approaches are included in the detailed case studies in Appendix A. MHHW to backshore placement performs well at shorter to intermediate length projects. **Upper intertidal to backshore nourishment** can be successfully applied to sites of intermediate to longer length (150–300 ft or more).

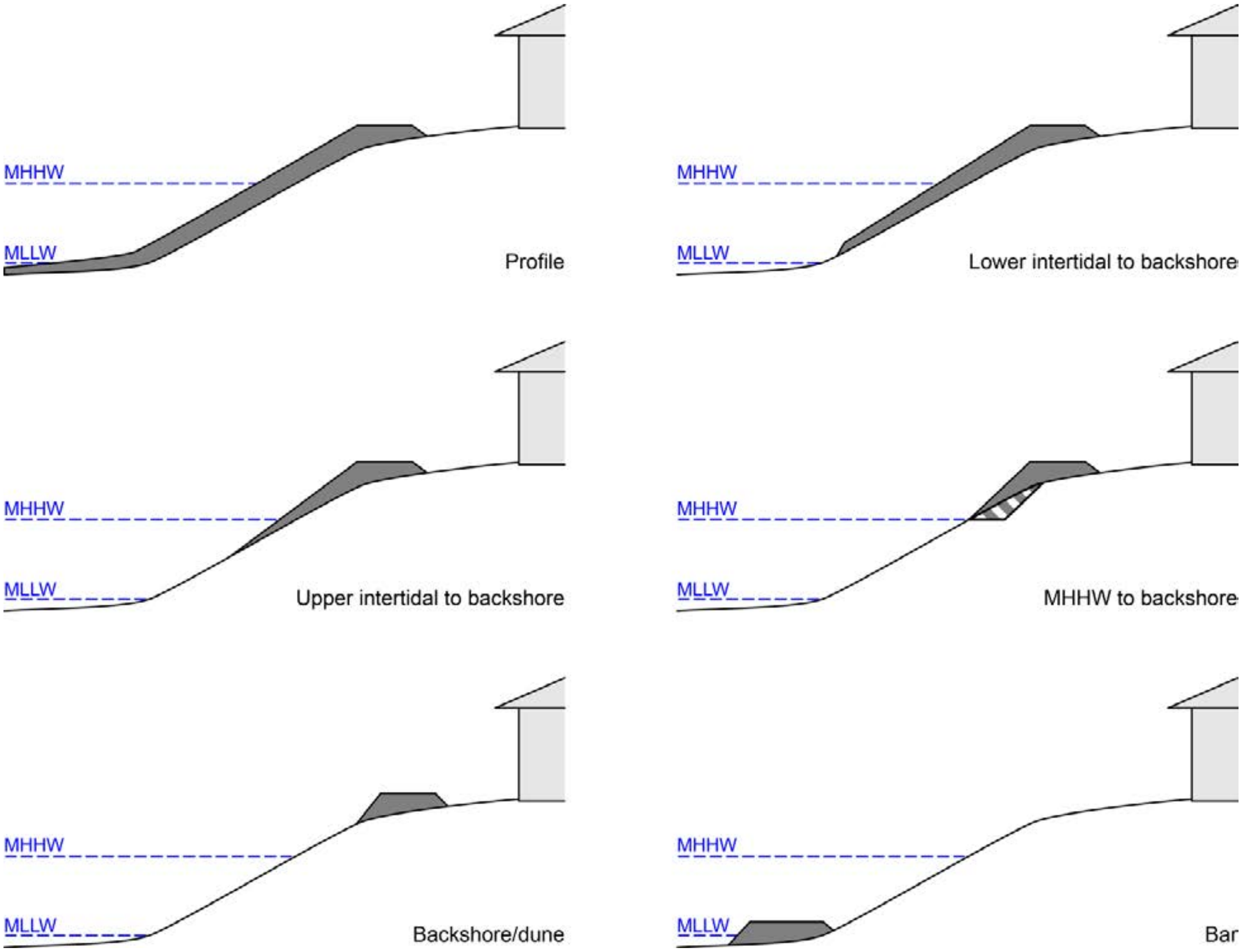

Figure 7.1-3. Beach nourishment placement approaches for Puget Sound application from most extensive in profile to least. Note that the limited-width approaches sometimes have excavation into the beach (as shown by hatching in MHHW to Backshore profile) for keying in the toe of gravel at sites where erosion control is critical.

Backshore/dune placement is generally aimed at increasing the elevation of a small dune and may be separated by some distance from the active beach. This approach focuses on augmenting sediment out of reach of non-storm waves. Backshore/dune placement is well suited for shorter project lengths (generally less than 100–200 ft long) as sediment placed on the intertidal would be lost to littoral drift too rapidly at short project sites. Backshore/dune placement is best suited at barrier beaches where ample space is available. Note that as with all site parameters, it is the full combination of parameters which lead the designer to the final design approach and extent. Other than placement length, the choice of which placement approach to use is related to wave energy and approach angle, and biological considerations, all of which are outlined below.

Excavation prior to beach nourishment is appropriate at some limited-size properties. Excavation is not practical at larger projects or projects with moderate to large volumes of nourishment sediment added, and has generally only been carried out at MHHW to backshore nourishment projects. (Several are detailed in Appendix A.) The reason to complete excavation below the pre-project beach grade is to allow for placement of a thick enough layer of gravel to provide excellent drainage and wave-energy dissipation and erosion control. Excavation in the range of 1.5–2.5 vertical feet has been appropriate for achieving these goals. Where excavation has been carried out, it has typically been to remove fine-grained sediment from the lower portion of the nourishment area. This excavated sediment has been useful for placement along the higher, landward edge of the project area, and has provided excellent substrate for backshore vegetation planting.

Bar nourishment refers to only placing nourishment sediment on the shallow subtidal below the steeper beachface, with the expectation that sediment will be transported onshore to protect the beach. Bar nourishment therefore greatly reduces impact on upper beaches but is not appropriate for many sites due to the presence of SAV at and below MLLW. No installations of bar nourishment are known in the Puget Sound region in recent decades.

Examination of the project length and nourishment volume from Appendix A sites along with other sites from Shipman (unpub.) and CGS files shows that there is a positive relationship between total project length and the total volume, as expected (Figure 7.1-4).

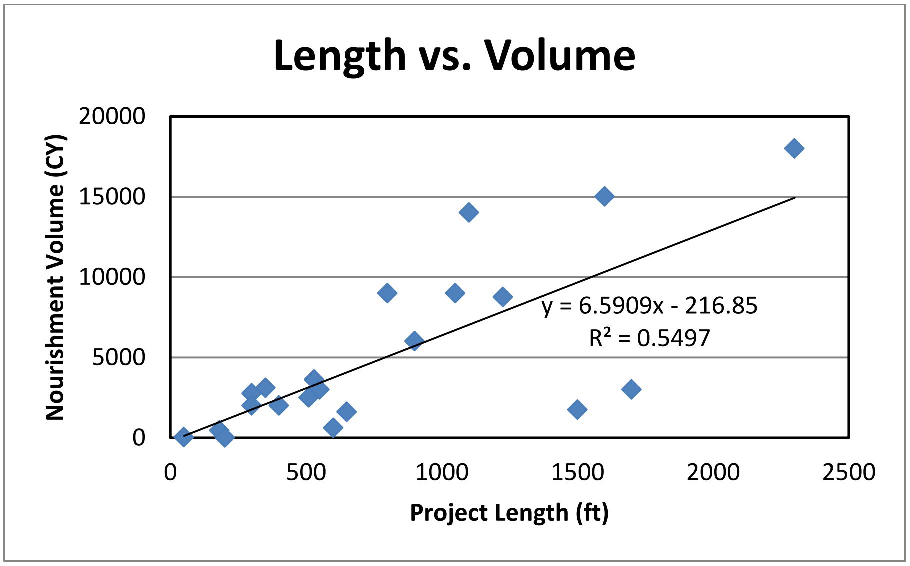

Figure 7.1-4. Plot of beach nourishment volume with project length.

The scale of beach nourishment projects in Puget Sound typically ranges from several thousand feet for larger projects to less than 100 feet for small residential parcels. The project length is highly relevant to the overall approach and performance of nourishment. Shorter nourishment projects, particularly ones that extend into the intertidal, will tend to have relatively greater sediment loss than longer projects due to adjustments which occur at both ends of the placement area dominating a short project length (Dean 2002). Nourishment sediment placed low on the beach in a short project would make the beach out of equilibrium and unstable, potentially requiring more maintenance (renourishment) than is generally acceptable.

Long beach nourishment projects appear to experience greater longevity in retaining nourishment sediment (Leonard et al. 1990). An example is North Beach Orcas Island (Figure 7.1-1 frame d, and in Appendix A), which had nourishment placed above +4.0 ft MLLW along 4 properties for a total length of 510 ft. Although there are multiple factors involved, length was a benefit to relative stability as this very-high-wave-energy project (Table 7.1-1) has not needed maintenance since installation in 1992 and appears to not require maintenance in the foreseeable future. This is due to the long project length and the fact that it is swash aligned (discussed in *Site Geometry* section below). Tolmie State Park is another example of this (Appendix A).

Wave Energy and Volume Density

The relative wave energy (wave climate) experienced at a site is a critical factor in determining the amount of sediment mobilization that may occur. Larger waves usually equate to larger net shore-drift rates (the net, long-term effect of littoral drift). Wave energy relates directly to determining the ideal sediment placement approach, sediment volume density, and grain size. Beach nourishment is typically feasible at low- and moderate-wave-energy sites (defined as less than 1 mile fetch, and 1–5 miles of fetch, respectively; Cox et al. 1994). High-wave-energy sites can also be suitable with the combination of longer project length and swash alignment (Figure 7.1-2). Therefore, consideration of wave climate must be paired with site geometry and alignment (see *Site Geometry* section below).

Sites with relatively high erosion rates (e.g., greater than 3 in/yr) should include a more robust beach nourishment design to partially offset the anticipated erosion. This typically involves a high sediment volume density (such as at Marine Park Bellingham or North Beach Orcas Island, Table 7.1-1). Sites with even higher erosion rates will need renourishment over time, and possibly a significantly coarser sediment size (further discussed below).

The volume density, sediment per unit of shore length (cubic yards per foot - CY/FT), is an important design consideration that is determined by balancing site conditions and required durability with habitat conditions and budget. Nourished beaches often have erosion “hotspots” where one or several areas suffer greater losses than adjacent areas (Dean 2002). If volume density is low, such areas can suffer unacceptable sediment losses such that renourishment is required after a short interval resulting in a reduced perception of project success. Volume density must account for loss of fines if the nourishment sediment is finer than native beach composition. An overfill factor is used to inflate the needed volume to account for the likely loss of fines in the short term (Terich et al. 1994).

Determining an appropriate volume density depends primarily on the wave climate and erosion rates, in combination with constraints, although other factors affect the decision process to a lesser extent. High-wave-energy sites that are not swash aligned generally require high beach nourishment volumes to be successful, and renourishment may be required at some of these sites. Volume densities for the 6 projects described in Appendix A ranged from 0.8 to 9.2 CY/FT, with the small dune/backshore nourishment at Snakelum Point on the low end and Marine Park in Bellingham on the high end (Table 7.1-1). Other documented Puget Sound projects have ranged from 2.5 to 9.0 CY/FT, with (typically shorter) upper beach projects on the low end and longer profile nourishment projects on the high end.

Site Geometry

Site geometry refers to the configuration of the shore surrounding the potential nourishment site. This ranges from linear shores to complex headlands, and pocket beaches. Shoreline configuration and the geometry of the subject site play a critical role in determining the location and degree of future erosion. Charlier and DeMeyer (1995) examined numerous beach nourishment projects and summarized physical parameters that should be considered in any beach nourishment design. Nourishment is most successful at beaches located between headlands (such as pocket beaches), because sediment loss can only take place in a cross-shore direction. Many Washington State nourishment projects were designed using headlands or rock structures to partially mimic pocket beach conditions (Shipman 2002, Shipman in unpub.). Shorelines near tidal inlets tend to be more dynamic and unstable than those along straight coastlines. Similarly, nourishment sites near dynamic spits and river channels would also be expected to be dynamic and potentially unstable.

A *swash aligned* beach is oriented facing the predominant waves at the site, such that the larger wave fronts tend to reach the beach (after the waves are refracted by the shallow bay bottom) parallel to the beachface (Bird 2005). This is typically the case at a pocket beach, and is not uncommon at some accretion shoreforms. However, most spits and bluff-backed beaches in the Puget Sound region are not swash aligned, but rather *drift aligned* (Figure 7.1-5). Along drift aligned shores the dominant waves break at an oblique angle, which generates littoral drift parallel to the shore. Many beaches are intermediate between the two conditions, such that in practical application beaches that are oriented close to the direction of drift generally are considered drift aligned, and those aligned closely with the dominant wave approach swash aligned.

Figure 7.1-5. Examples of swash aligned (left) and drift aligned beaches (right) from the Livingston Bay area of northeast Camano Island. Arrows indicate prevailing wave direction.

Beach nourishment projects are more likely to succeed at swash-aligned beaches because the losses of sediment due to littoral drift are often negligible. These beaches have a greater number of options in terms of specific design elements and often beach nourishment can be successful even where wave energy is high. Examples of this are North Beach on Orcas Island (Appendix A) and nourished pocket beaches. Similarly, beaches which are very close in orientation to swash aligned are favorable for nourishment. Beaches where the refracted waves reach the beachface at a 45-degree angle tend to have the highest littoral transport rates and design development needs to be quite conservative; these drift-aligned beaches are not generally suitable for nourishment where moderately high wave energy is present.

Several proven variations on beach nourishment exist for extending the nourishment project life where the site geometry is not ideal. The methods can supplement the basic rectangular planform of nourishment design by placing additional nourishment sediment at an erosional site. One approach is to simply extend the nourishment area up-drift of the subject property or properties. This approach was termed a *feeder beach* by Wolf Bauer and is sometimes referred to as *advance nourishment*. An example of a feeder beach is shown in Figure 7.1-6 at North Beach on Samish Island. This was a privately-funded nourishment project to rebuild a beach which was largely eroded due to the cumulative impacts of extensive up-drift armor (Shipman 1998, Johannessen 2002).

The direct project area was an 850-ft-long barrier beach fronting multiple houses and cabins (Johannessen 2002, Zelo et al. 2000). The nourishment footprint was extended approximately 90 ft up-drift onto an adjacent property to allow for the placement of additional nourishment volume; the project has not required any maintenance nourishment in over 15 years.

Figure 7.1-6. Example of an up-drift feeder beach, also termed advance nourishment, which was located on property adjacent to the main project area. The site is North Beach Samish Island, during initial placement in January 1999 (Johannessen photo).

A second approach for modifying the basic nourishment planform is placement of additional nourishment volume in a wider reach within the up-drift end of the nourishment area. An example of this was constructed along the west shore of Marchs Point in Skagit County in 2010 (Figure 7.1-7). This project used easily transported sand with fine gravel in a low-wave-energy setting as the project recreated lost surf smelt spawning habitat. Tolmie State Park is another example of advance nourishment (Appendix A).

Drift Sills

A drift sill is a term coined by Wolf Bauer for a low-elevation and relatively short groin (cross-shore structure) constructed at, or minimally above, the nourished beach profile. Drift sills have typically been constructed out of angular rock. These sills generally do not typically extend below the lower intertidal; however, at highly modified, urban sites, they may need to extend down to several feet below MLLW. Drift sills should be avoided at most sites as these groin structures can interrupt littoral transport and cause wave refraction adjacent. Drift sills have been utilized in the Puget Sound region at degraded urban settings where fill has pushed the shore into deeper water and no sources of up-drift sediment exist. They have also been used at drift-aligned beaches with moderate or greater wave energy and limited other options. Examples of sites that required drift sills installed with beach nourishment projects in greater Puget Sound include the drift-aligned North Samish Island site (Johannessen 2002), and the constructed pocket beach at Marine Park in Bellingham (Figure 7.1-8 and Appendix A). Examples of drift-aligned beaches coupled with greatly reduced sediment supply due to up-drift armored bluffs where small drift sills were used are shown in Figure 7.1-9. A newer project with similar conditions which will also have a large rock drift sill will be constructed in 2014 at North Seahurst Park in Burien.

Figure 7.1-7. West Marchs Point, Skagit County, WA. Advance nourishment used a widened lower intertidal to backshore nourishment profile at the up-drift end of a surf smelt spawning habitat enhancement project (Johannessen photo).

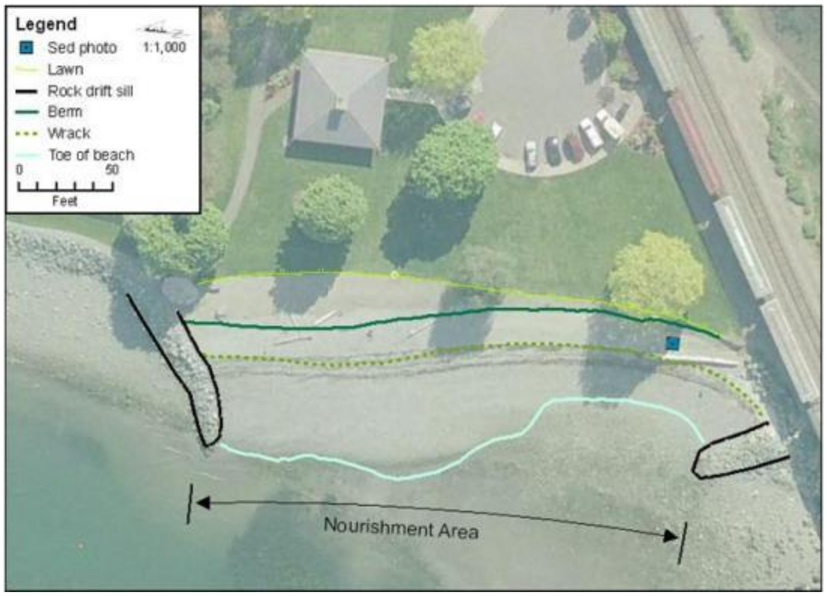

Figure 7.1-8. Marine Park, Bellingham, WA. The nourished beach is confined between drift sills (outlined in black) in this urban shore dominated by railway revetments, fill, and Chuckanut sandstone cliffs.

a) North Beach, Samish Island; single drift sill at down-drift end of 850-ft-long project.

b) Boulevard Park, Bellingham; single larger groin at down-drift end of 280-ft-long beach.

c) North Beach, Orcas Island; western drift sill at end of 510-ft-long project, eastern sill at opposite end (Appendix A).

d) Weaverling Spit, Samish Indian Reservation; 1 of 4 large log drift sills within a 500-ft-long project in a highly degraded net shore-drift cell.

Figure 7.1-9. Examples of drift sill installation at beach nourishment sites. Samish Island is summarized in Zelo et al. (2000) and Gerstel and Brown (2006). North Orcas is in Appendix A.

Rock groins larger than drift sills have been constructed at a limited number of nourishment sites around the region, including Brackett's Landing in Edmonds; Olympic Sculpture Park in Seattle; and Seacrest Park in West Seattle where the sill was incorporated into a large revetment (Figure 7.1-10). The Edmonds groin also provides public access to its end. These structures were designed very conservatively in terms of the application of engineering standards and as a result are quite large. Attempts to minimize the burial of intertidal area should be carried out at all future projects, including those at urbanized shores. The Birch Bay example shown was originally a smaller drift sill structure which was later expanded during maintenance following a major winter storm.

a) Brackett's Landing, Edmonds; terminal groin at end of 480-ft-long beach (revetment and ferry terminal at opposite end).

b) Coasthaven Condominiums, Birch Bay; single drift sill which at a 300-ft-long project which was enlarged years after design and construction during maintenance event.

c) Olympic Sculpture Park, Seattle; 1 of 2 terminal groins (one at each end of 180-ft-long beach) at revetment ends at artificial pocket beach.

d) Seacrest Park, West Seattle; groin built out from existing riprap fill area at down-drift end of 190-ft-long artificial pocket beach.

Figure 7.1-10. Examples of large rock groins installed at beach nourishment sites. Olympic Sculpture Park is summarized in Toft et al. 2012 (J. Johannessen photos).

Berm Elevation

The nourished beach berm should be set at an elevation that will make the beach slightly higher than pre-project conditions for a more robust berm. Berm elevations should be cautiously designed, as elevations that are too low or too high can undermine project success. Where erosion control is the primary project goal, the berm elevation should be set high enough that the constructed berm crest is above the reach of frequent waves but within the reach of storm waves. The berm crest height should be set so that it is inundated every few years or more frequently to help minimize the spread of invasive species in the backshore (such as has occurred at Lincoln Park in Seattle in the past; Macdonald et al. 1994).

The berm elevation should also not be set too high such that cross-shore sediment transport results in the formation of a scarp (steep erosion feature) into an artificially high beachface. An example of a moderate sized scarp is presented in Figure 7.1-11 from North Beach on Orcas Island soon after initial placement. Designing a berm which is lower than optimal can result in frequent overwash and significant onshore translation of the berm crest, as this is the only way the berm can gain elevation. This results in what appears to be significant erosion to casual observers, but does not pose any issues for habitat as the profile adjusts itself.

Figure 7.1-11. Beach scarps formed during storms soon after lower intertidal to backshore nourishment placement at North Orcas Island site (Appendix A), also showing exposed west drift sill in foreground (J. Ellis photo).

Examination of berm elevation and risk data (from Appendix A and from Shipman unpub.) revealed that as risk to infrastructure went up, the elevation of the constructed berm crest (relative to local MHHW) was designed higher than at lower risk sites (Figure 7.1-12). This was presumably to provide additional volume of sediment in the backshore. Setting the berm elevation higher at shorter project sites with development generally does not pose as much chance of invasive species colonization as much longer sites lacking substantial development and use.

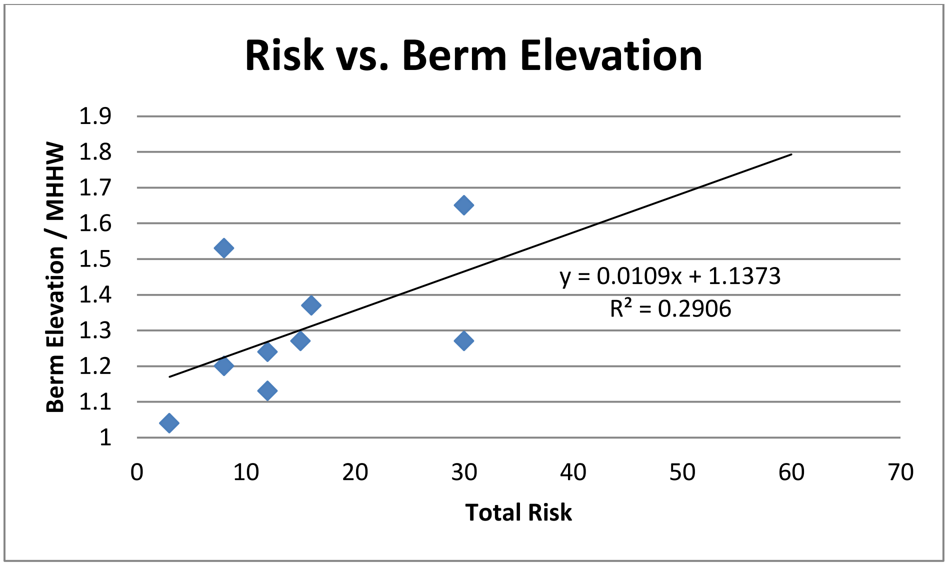

Figure 7.1-12. Plot of cumulative infrastructure risk with relative berm crest elevation.

Wolf Bauer's rule of thumb for setting the berm crest elevation was to start with a berm elevation of 2 feet vertically above local MHHW and then adjust according to the site conditions (Table 7.1-1, Appendix A). Conditions such as high wave energy (greater than 5 miles fetch from the southerly quadrant or for predominant waves, e.g., from the west in the Strait of Juan de Fuca; or 10 miles from other quadrants) or greater potential for storm surge would suggest a need for a slightly higher berm elevation such as 3–4 ft above local MHHW. Conversely, very low wave energy would suggest a slightly lower berm elevation. Note that this principle applies to the active beach berm (which is the more waterward berm on the beach), and not to an elevated storm berm which may be included in a design further landward of the active berm (such as at Snakelum Point or East Lummi Island, where the storm berm was set 4–5 ft higher than local MHHW; Table 7.1-1).

Considering current projections of sea level rise (NAS 2012), using storm berm elevations for the more landward portion of the berm that are higher than what has been done in the past is appropriate for erosion control designs. When designing for erosion control over time, planning for a minimum of 1 ft of sea level rise with a berm 1 ft higher is a minimum design adaptation. If the application is more focused on habitat and beach enhancement, a higher adjustment may not be needed. For major projects with a longer planning horizon, such as 50 years or more, the inclusion of a berm 1.5–2.0 ft higher is appropriate.

Sediment Size Selection

Natural beaches with abundant gravel, such as those in the Puget Sound–Strait of Georgia area and in the United Kingdom, have proven to be a practical form of coastal protection (MAFF 1993). Beach nourishment in the Puget Sound region typically consists of the placement of select size(s) of rounded gravel on the upper beach. The intent is to slow, not necessarily to halt beach erosion (Shipman 2002, Johannessen 2002). Sediment size selection is a critical design parameter in terms of effects to longevity of sediment and habitats. The term *sediment compatibility* refers to the how the nourishment sediment would perform based primarily on grain size as compared to native sediment (Dean 2002).

Coarse nourishment sediment usually erodes more slowly than finer sediment, therefore sediment selected for beach nourishment is recommended to be at least as texturally coarse as the original beach material (Dean 2002). Some practitioners have recommended a mean grain diameter of at least 1.5 times that of the original sediment in quantities sufficient to establish the ultimate slope compatible with the wave climate, although not necessarily at a restoration project site. Terich et al. (1994), advising on Puget Sound nourishment design, stated "As a general rule, the replacement sediment should be slightly coarser than the original beach sediment. This should be accomplished within the aesthetics of the replacement sediment and the availability of a source of supply."

Sand nourishment projects that only nourish the dune area or the upper foreshore tend to experience relatively rapid erosion following placement (Bruun 1988). Sand nourishment sediment placed in the intertidal should be expected to lose substantial volumes, as sand is often transported down to the lower foreshore and subaqueous portions of the profile, and potentially alongshore (Bruun 1988, Finkl and Walker 2005). An example of a project with very short sediment longevity was Wolf Bauer's first beach nourishment project on a pocket beach on northwest San Juan Island in the 1960s. Sand was placed in the upper intertidal and backshore, and only lasted several years before the majority of the sediment was displaced to much lower elevations (Bauer pers. com. 1998). Intertidal sand nourishment should only be performed where sandy beaches naturally exist and there is adequate cross-shore room for a low slope beach. An exception is where very low cost sandy substrate is available (e.g., through beneficial reuse of dredged sand). Sandy dredged sediment can be placed for beach enhancement, as it was at Jetty Island near Everett. Nourished sandy beaches of this type will erode faster than natural beaches. Sandy sediment can also be used for short-term augmentation of a coarse-grained beach for habitat reasons (such as at Lummi Shore Road near Bellingham, discussed below).

Gravel tends to remain high on the intertidal and supratidal beach profile, minimizing loss to the adjacent subtidal area (Houghton et al. 1999), and tends to form a relatively steep beach profile, with slopes of 5:1 to 10:1 (horizontal:vertical) (Van-Hijum 1974) or steeper. Therefore, the equilibrium profile of a gravel beach is considerably steeper than that of a sand beach. Up to a certain size, gravel is normally transported onshore. Indeed, nourishment projects monitored in Appendix A and prior work (Johannessen 2002, Shipman 2002, Houghton et al. 1999) have shown virtually no loss of gravel offshore.

Most Puget Sound beach nourishment projects have relied primarily on rounded gravel larger than 0.75-inch diameter or larger. Five of the 6 projects surveyed (Appendix A) used pebble to cobble (greater than 2.5-inch median diameter). The East Dungeness project had a mix of coarse sand with medium pebble, atypical for most nourishment projects in the region. One project (Marine Park) used mostly 0.5- to 2-inch sediment, but also contained a much wider mix of sediment sizes, mainly to aid in recruiting additional fine gravel and coarse sand for habitat improvement and recreational benefits. Cobble was included in the Marine Park nourishment sediment mix to allow for a portion of the cobble to bolster the toe of the beachface in this erosional area. A percentage of cobble was also included in the Seahurst Park beach projects, and made up almost all of the sediment at Seacrest Park in West Seattle.

Ideally gravel should be washed clean of fines, which is typically completed at the gravel pit. Intertidal projects in embayments with extensive eelgrass beds should use washed gravel to minimize turbidity. However, often “oversize” gravel (greater than 2 inches in diameter) is not available washed and the use of unsorted bank-run (unsorted) sediment does not allow for washing. For projects above MHHW and those away from low energy embayments, it is generally acceptable to use unwashed gravel. Wave action at upper beach projects typically only occurs during storms when ambient turbidity is high. Many areas often experience high natural turbidity due to natural sediment resuspension, river flow, and landslides.

Gravel used for regional nourishment must be rounded in order to resemble natural beach gravel and to allow for good drainage, as well as for habitat reasons. Gravel particle shape has been shown to be important for sediment transport and sorting (Houghton et al. 1999). Generally, discs tend to be transported onshore and spherical clasts are more easily entrained and roll down the beachface. However, Puget Sound gravel pits do not typically have the percentages of flat and elongated particles that some other regions have. For durability of gravel, gravel with 10% or more elongated or fractured particles should be avoided. The only reasonable exception to this is in areas with bedrock where natural beach gravel contains a substantial percentage of angular particles.

It is important to understand that the force of the waves moving a given gravel size up the beach must exceed the forces of gravity and backwash moving it down the beachface. These conditions are different for each site and the specified nourishment sediment must be tailored to a given situation. Gravel particles that are too large typically end up at the toe of the high-tide beach. A good example of this occurred in Birch Bay in Whatcom County, where renourishment of oversize cobble in the 3- to 8-inch range resulted in the larger clasts moving downslope to the toe of the high tide beach (Figure 7.1-13). This sediment was not the size specified in the earlier design by Bauer. Bauer had warned against up-sizing nourishment sediment based on the false assumption that larger substrate makes for a more successful project in terms of gravel stability. His reasons included instability on the upper beach where wave energy is greatest and infringement on the low-tide terrace by nonnative sediment.

Figure 7.1-13. Large cobble (3–8 in) added to the upper beachface during nourishment was sorted by waves to the toe of the high-tide beach and over the low-tide terrace, altering habitats and making wading difficult at this popular recreational beach on central Birch Bay Drive, Whatcom County, 2002 (J. Johannessen photo).

Weighing all of the processes and issues discussed in this section, it is possible to provide general guidance on appropriate gravel sizes for nourishment at erosion control projects. This applies to most of the sites which have received beach nourishment in Puget Sound, but is not appropriate for nourishment designed for habitat enhancement only, or for truly restoring natural processes, which should instead be based on recreating historical substrate size (and other parameters). Examination of Table 7.1-1 and other project data (Shipman unpub., CGS unpub.) reveals that the majority of successful intertidal nourishment projects contained rounded gravel with the general range of 0.5–2.5 inches or similar. Backshore-only nourishment (above MHHW) typically utilizes a slightly coarser sediment mix than intertidal and backshore nourishment designs. Refer to Table 7.1-2 for guidance on appropriate gravel nourishment sediment sizes, with the caveat that all nourishment design elements are site-specific and site conditions and individual project objectives must be incorporated into selection. Also refer to the *Beach Habitat Considerations* section immediately below.

Table 7.1-2. General ranges of appropriate gravel sizes for beach nourishment for erosion control in Puget Sound. Note sediment size selection is controlled by many interrelated processes and issues and each site requires design analysis.

Wave Energy Class (Fetch)	Intertidal Nourishment (median diameter, in inches)	Backshore Nourishment Only (median diameter, in inches)
Low (<1 mi)	0.25–0.75	0.25–1.0
Moderate (1–5 mi)	0.25–1.5	0.5–2.0
High (5–15 mi)	0.5–2.0	1.5–3.0
Very High (>15 mi)	0.75–3.0	2.0–5.0

Beach Habitat Considerations

A limited number of nourishment projects have been carried out with the goal of habitat enhancement, and not for erosion control (Figures 7.1-7 and 7.1-14). One large project was designed for mitigation of the impacts from a new rock revetment constructed along approximately 1.5 miles of the north shore of Bellingham Bay for defense of the rebuilt Lummi Shore Road. The space for relocation of the road away from the unstable and eroded bluff shore was limited in some areas, and the US Army Corps of Engineers designed and built a substantial rock revetment that extended from +8 to +18 ft MLLW. In order to offset the loss of feeder bluff function and burial of the upper beach, a beach nourishment program was designed to routinely replenish the beach with sediment (Johannessen and Dillon 1998). In the short term, this resulted in more suitable surf smelt spawning habitat and surf smelt spawning than before the project (Figure 7.1-14). However, this is not sustainable over decades in a high erosion area such as this. Nourishment was not continued beyond the first five years, and in subsequent years the amount of potential spawning habitat appeared to have been significantly reduced.

Figure 7.1-14. Lummi Shore Road on Bellingham Bay, Lummi Reservation at the same location in the central reach. Prior to revetment construction (top, 1998) and after (bottom, 2000). After revetment was built beach nourishment was applied for mitigation. However, without continued nourishment, the beach is much coarser in 2014 (J. Johannessen photos).

Habitats such as surf smelt spawning substrate have been successfully recreated in beach nourishment projects through the use of fine gravel (Johannessen 2002). Where intertidal habitat includes current and/or historical forage fish spawning, or the desire exists to recreate this habitat, the use of multiple layers of beach nourishment has been carried out. The general approach has been to place a coarse gravel layer in the lower intertidal to backshore, providing additional resistance to erosion when needed, with a fine gravel layer above. The fine gravel needs to be sized small enough to keep sand from settling through the gravel. Examples include North Samish Island (discussed in Zelo et al. 2000 and Gerstel and Brown 2006; design developed by Bauer and Johannessen) and Seahurst Park south and north (Hummel et al. 2005). At Samish Island, potential forage fish spawning habitat was recreated after several years of natural onshore transport of sand from the broad, sandy low-tide terrace. This also occurred at Seahurst Park south but to a more limited extent, as well as at Marine Park in Bellingham.

Another large habitat enhancement project completed was the Mount Baker Terminal beach project just east of the Town of Mukilteo in 2005 (Pentec 2011). This was a 1,100-foot-long reach of beach waterward of the BNSF railway and revetment which was also designed with several different layers of different sediment sizes (Figure 7.1-15). This beach project was completed as mitigation for adjacent development with the goal of habitat enhancement in an area of limited beaches. Five years after the project, the western, up-drift end of the beach was found to have lowered and coarsened, with deposition in the eastern, down-drift end of the beach (Pentec 2011). This enhancement project is an example of the large volume of sediment required to create a broad beach in front of the 120-year-old railway revetment. The Mount Baker Terminal beach had the highest known volume density of documented projects in the Sound, at 12.7 CY/FT.

Site Grading

Differing standards for the degree of grading of nourishment sediment surface apply to sites with different uses and wave energies. A simple way to differentiate sites is that residential and park project sites should receive more careful grading than habitat restoration or habitat enhancement sites. Residential and park settings often require more thorough (and expensive) grading in terms of spreading sediment to within specific low to moderate tolerances from the design. This may not involve much work for small sites; however, for larger park or similar public settings there is often no acceptable alternative to completing consistent site grading. Typical grading standards for this type of site should be plus or minus approximately 0.3 ft.

Beach nourishment projects that are carried out solely for habitat restoration or enhancement can often have much looser grading standards, particularly when placing sediment in the intertidal or within reach of normal waves. This can mean placing a specified volume of sediment in one or more general locations with minimal or in some cases almost no grading at all. Typical grading standards for low- to moderate-wave-energy restoration or enhancement sites can be on the order of plus or minus one foot. However, in moderate- to high-energy sites, seasonal storms can complete the grading up to the reach of waves without any effort or expense on the part of the project proponent. In these conditions, implementation can be planned for months with higher storm occurrence, such as October through mid-March. With these conditions met, it is perfectly reasonable to place sediment in elongated piles in the intertidal without grading. For example, the project at Lummi Shore Road in Whatcom County involved mitigation for revetment impacts to sediment supply at a highly utilized surf smelt spawning beach through the placement of ungraded beach nourishment sediment in early February for a several years (Figure 7.1-16). Within 10 days of the early February nourishment, the sediment was well distributed and graded alongshore and cross-shore.

Figure 7.1-15. Before (top, pre-2005) and after (bottom, late 2005) beach nourishment for mitigation at approximately same location, Mukilteo, WA (Port of Everett photos).

Completing reasonable grading above the normal reach of waves, typically above MHHW plus 2-3 ft, is important at all sites. Large irregularities or low points left in the backshore after a project is complete can last for years, particularly at low energy sites. Low elevation areas can cause localized erosion or damage as high water storm waves can penetrate further inland than in other portions of a site.

Figure 7.1-16. Beach nourishment placement with almost no grading at Lummi Shore Road, Whatcom County, WA, during early February 1999 placement (above) and 10 days later in same location showing effectiveness of allowing winter waves to accomplish grading (remaining sediment in foreground is atop revetment extension (J. Johannessen photos).

Cost

Implementation expenses for a beach nourishment project include primary elements such as design, permitting, contractor mobilization, site preparation/debris removal, sediment purchase, sediment delivery, and grading; and secondary elements such as drift sills, planting, and installation of basic amenities. Due to the higher number of beach nourishment projects in Puget Sound and the slightly better level of documentation relative to other design techniques, reasonable information can be provided on relative construction costs. Known construction costs for beach nourishment projects had a wide range that depended on the project scope as well as general ownership and use. Projects on public lands were generally significantly more expensive than those on private lands, due to a generally higher design and construction standard, as well as the cost of working around public infrastructure. Known construction costs were adjusted to 2012 dollars by using information from the US Bureau of Labor Statistics (using the CPIU). Cost for larger projects—both those surveyed in this study and a limited number of others on public lands with documented project costs—ranged from $810/ft at Marine Park Bellingham to approximately $1,092/ft at Seacrest Park in West Seattle to $1,232/ft at Seahurst Park South (Table 7.1-2). The Mount Baker terminal project, which was constructed as mitigation for an industrial project, had the highest cost per foot for the eight sites with data at approximately $1,820/ft.

Construction costs for small projects at private sites typically involved lower costs. Documented construction costs for the residential projects surveyed in this study ranged from $50 to $178/ft adjusted to 2012 dollars. The East Lummi Island project had the lowest cost, with a low to moderate nourishment density of 2.4 CY/ft and minimal transportation costs for gravel. The North Orcas Island project was quite low cost for its volume density as it had a good amount of design and permit work donated. Also, this project saved money by giving the gravel pit many months to produce the desired gravel blend when they had down time and by giving the grading contractor extra time to perform their portion of the work.

Table 7.1-3. Beach nourishment construction costs for projects with adequate data (Sources: CGS unpub., Shipman unpub., Hummel et al. 2005, Pentec 2011).

Project Name	Project Length (ft)	Year Installed	Density (CY/ft)	Cost 2012 Dollars	Cost Per ft-2012 Dollars	Cost Per CY-2012 Dollars
East Dungeness	1,500	2006	1.2	267,632	178	154
Snakelum Point	50	2002	0.8	8,551	171	225
Marine Park Bellingham	300	2004	10	243,085	810	88
North Beach Orcas Is.	510	1992	4.9	75,277	148	30
East Lummi Island	181	2004	2.4	9,116	50	21
Seacrest Park	1200	1988	-	873,350	1,092	-
Seahurst Park-South	1,050	2005	7.5	1,293,156	1,232	165
Mount Baker Terminal	1,100	2005	12.7	1,998,514	1,817	143
Blakely Is.-Driftwood Bch	650	1999	2.5	110,249	170	68

Monitoring

Monitoring is an important element of beach nourishment projects. Monitoring determines a project's success from an erosion control standpoint as well as an ecological one. Monitoring can also determine if and when maintenance is required. It is common practice to monitor larger projects on an annual basis. Conducting project monitoring immediately after major winter storms provides time-sensitive information as to the extent of changes and potential management concerns.

Monitoring often consists of beach profile measurements that can be accurately and consistently repeated over time. A higher standard of monitoring includes full beach topography, which is often only incrementally more work in the field and much more useful in that sediment volume change can be calculated. Erosion and accretion areas can also be accurately delineated and quantified through comparison of different topographic surfaces over time. Profiles and/or beach topography should extend from the landward extent of backshore areas down to a minimum of 0 ft MLLW, preferably to approximately -5 ft MLLW (using waders at low tide). Other parameters that are useful to map and monitor include the waterward vegetation line, drift log zone position, elevations of the storm berm and active berm crest, potential and utilized forage fish spawning areas, and the inner margin of eelgrass beds. Beach sediment should be characterized from several distinct and consistently monitored elevations along selected beach profiles. This should include the upper intertidal within potential forage fish spawning elevations.

Monitoring at smaller beach nourishment projects ideally would include all of the above discussed topics, but is often more limited due to lesser budgets and fewer concerns. Recommended minimum monitoring includes annual and post storm photographs from fixed photo points covering the entire project area, augmented by less-frequent quantitative data. Measuring beach profiles and characterizing beach sediment along profiles is recommended every two years. Additional information regarding project monitoring elements and protocols is described in Chapter 8 *Monitoring*.

Maintenance

The primary maintenance element for beach nourishment is the need for renourishment. With beach nourishment, “renourishment should occur as needed,” as stated by Terich et al. (1994). However, designers such as Wolf Bauer and others following his general approach have worked hard to avoid the need for frequent renourishment. Bauer’s intent was to have initial nourishment projects last on the order of 20–30 years without the need for renourishment. This was the trajectory of a number of projects such as Tolmie State Park (Appendix A), Golden Gardens in Seattle, and Driftwood Beach on Blakely Island in San Juan County. This is in contrast to the much more frequent renourishment required at many sand beaches on the US East Coast (Leonard et al. 1990), which are exposed to greater wave energy and have much finer sediment.

When renourishment is required at a Puget Sound area project, it is often limited to adding a small volume of gravel to one end of the project area. Typically, renourishment projects consist of less than 20% of the original placement volume, require limited work, and in most cases require only simple placement on the upper beach with limited grading. At the Marine Park site, one of the older projects that have had renourishment, renourishment volume was less than 10% of the original volume.

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Chapter 7. TECHNIQUE 2
LARGE WOOD

Description

Large wood placement designs typically consist of large tree trunks with and without rootwads that are designed to add structure and complexity in order to diminish wave induced erosion of the landward shore. Large wood placement can be used in combination with beach nourishment or vegetation to raise the elevation of the backshore for the same purpose. Large wood was naturally and historically much more common on Puget Sound shores than it is at present (Maser and Sedell 1994). Logs of all sizes, typically with rootwads, were more prevalent Puget Sound wide historically, and in very high densities in river estuaries. The need to place large wood in the nearshore for increased habitat complexity and other structural functions is justified by the reduction of large wood over time in Puget Sound nearshore environments, both from direct removal and reduced recruitment (Maser and Sedell 1994, MacLennan 2005).

Large wood can be placed singly or in groups, with or without rootwads, partially buried and/or anchored, or simply placed on top of the beach substrate, to produce the scale and function required for each application. It is important to understand when contemplating or designing a large wood project that there is a continuum between soft shore protection projects using anchored logs strategically and a rigid log bulkhead which represents a type of hard armor. This and other topics are discussed in this chapter.

The strategic placement of large wood can be designed to achieve the following objectives: enhance shoreform structure, reduce shoreline erosion rates, and enhance marine riparian ecotone, aquatic productivity, and/or habitat complexity. Wood placement can provide erosion control functions by enhancing the elevation of the storm berm, thereby increasing wave energy absorption and structure of the upper beach. Large wood placement often occurs in conjunction with other design elements such as small volumes of beach nourishment (backshore only), vegetation, and strategic boulder placement. Most large wood placement projects include some form of anchoring, burial, or both.

While the placement of large wood is a structural management technique, if designed and installed properly it can mimic the natural process of wood recruitment to the beach or salt marsh that might otherwise take many years to occur naturally in a restoring system (in the absence of a major event that alters the natural development trajectory of the system). Large wood placement designs can be tailored to trap additional large wood and sediment, resulting in increased habitat complexity and biological processes like the germination of certain plants, microclimates for beach fauna, and attachment substrate for sessile invertebrates and boring organisms. Large wood placement can also be used to reduce shoreline erosion and replicate historical processes beneficial to many organisms, including salmonids.

This technique does not include the design of large rigid log structures, such as crib walls or designs that resemble log bulkheads. These topics are discussed in engineering documents addressing traditional engineering approaches included in Chapter 7.5, *Hard Armor*. Design guidance is also not included for large wood placed exclusively for recreational value (such as a place to sit on the beach), or logs placed in dense arrangements below mean high water with the intent of largely obstructing wave energy.

Application

Large wood placement can be applied on most Puget Sound geomorphic shoretypes, excluding rocky shores. Success has been more frequently observed along shores with low elevation backshores (“no bank” sites) such as barrier beaches, low to no bank pocket beaches, and within embayments. Fewer successful installations have been documented in deltaic environments and along bluff-backed beaches, although such projects could be successful if wood were present there naturally. Large wood placement projects are most suitable for sites with low to moderate wave energy; however case studies documented project success on sites with high and very high exposure categories (See Appendix A). Large wood is not the optimal technique for sites with high background erosion rates and primary structures in close proximity. Because this technique is likely to slow rather than halt erosion entirely, it is best suited for sites in which baseline conditions (wave energy, erosion, and risk) are more moderate. Large wood project sites also require adequate backshore width for the construction of the design feature itself.

The response time of a large wood installation depends on the specific objectives and the scale of engineering associated with the installation; however most applications will provide an immediate response. The lifetime of a large wood project is likely to be greater when baseline conditions (mentioned above) are relatively moderate. Assuming that design is well aligned with the site characteristics, large wood installations can allow for a more natural range of shoreline dynamics, particularly when compared with bulkhead installations.

Many existing shore protection structures (e.g., bulkheads) on Puget Sound were constructed decades ago and are or will soon be reaching the end of their design lifetime. Where feasible, bulkheads and other hard armor could be replaced with soft shore protection that incorporates large wood placement. The deposition and retention of large wood can also be increased through enhanced vegetation in the backshore or beach nourishment. This is consistent with state Shoreline Management Act policies that require the use of alternatives to hard armor where technically feasible and encourage property owners to demonstrate the need for armor when no other alternatives are deemed practical. Large wood installation projects, where suitable, provide an avenue for private landowners to comply with regulatory framework and slow erosion on their properties. Planting additional vegetation in backshore and bluff areas will eventually provide on and off site benefits in that fallen trees can provide wood that can be recruited to the beach. Where applied along public shores, large wood placement can offer opportunities for educating the public about beach processes and habitats—particularly the role of large woody debris in the nearshore—through signage, volunteer monitoring, and demonstration value (Clancy et al. 2009).

Effects

The added structure and elevation of a large wood enhanced storm berm can reduce wave-induced erosion, promote deposition of fine sediment in areas with wind-blown sand (aeolian sediment transport), and facilitate increased species richness in backshore vegetation. Winds transport and deposit fine sediment on the leeward side of large wood in some exposed areas in the region, such as along the shores of the Strait of Juan de Fuca. The accretion of fine sediment enhances beach microtopography such as storm berms or depressions in salt marshes. Buried large wood is a natural and historical structural element of Pacific Northwest beaches and can also function as substrate for backshore and riparian vegetation resulting in increased species richness (Guttman 2009, MacLennan 2005). Large wood on beaches is also associated with increased invertebrate abundance and biomass (Tonnes 2008) that serve as food for a number of nearshore species, including salmonids. Large wood on beaches produces microclimate effects, such as increased soil moisture and temperature (Tonnes 2008), with known benefits to surf smelt (*Hypomesus pretiosus*) embryo survival (Rice 2006). Barrier beaches are often associated with larger quantities of large wood due to the depositional nature of the shoreform. Figure 7.2-1 shows a barrier beach with moderate amounts of naturally-deposited large wood, which is one of a number of natural models for large wood installation.

Figure 7.2-1. Barrier beach in developed area with abundant, natural large wood on northeast Whidbey Island (J. Johannessen photo).

The effects of a large wood placement project are dependent upon site characteristics and specific design elements. The typical objective of a large wood placement project is to slow erosion. If designed appropriately, the large wood pieces should be a component of a natural storm berm that serves to absorb wave energy, particularly during storms that occur at high water. Results of case study analyses showed that most large wood placement projects (four out of five; Appendix A) were effective at mitigating erosion with very few to no negative impacts to nearshore processes and habitats. The only case study site that demonstrated a low level of effectiveness was along a bluff backed beach with high wave energy (Birch Point). This combination of shoretype and wave energy does not fit the current recommended site characteristics for large wood installation projects.

Research from other geographic areas, such as New Zealand, has included documenting the role of large wood on relatively high energy gravel-dominated beaches. At these sites large wood is deposited during high wave events and usually positioned at the top of the storm berm (Kennedy and Woods 2012). Large wood acts to trap sediment at the uppermost limit of wave swash and hinders the inland penetration of waves during storm events. As a result, the beach height in the New Zealand study area was on average 1.6 to 3.3 ft higher on beaches with woody debris and the beachface was almost twice as steep as beach profiles without large wood. During intervening calm periods waves rework sediment at lower elevations on the beachface. Kennedy and Woods (2012) concluded that large wood on gravelly beaches appears to act as a buffer to waves during storm events, while remaining inactive during intervening calm periods. Similar research on the effects of LWD on dune development in British Columbia has shown that LWD can trap appreciable amounts of windblown sand in the backshore, enhance sand storage capacity, foredune development and stabilization thereby buffering against increasing storminess and gradual sea-level rise in the region (Jordan et al. 2013, Heathfield and Walker 2011).

Because large wood placement projects typically form a discontinuous log placement area that slows rather than halts erosion sediment supply, sediment transport and (cross-shore) large wood recruitment are largely preserved. Case study results (Appendix A) show that most large wood is placed above MHHW, which avoids the burial of upper intertidal spawning areas. Most case study sites had a low level of sediment (nourishment) incorporated into the design to further enhance the elevation of the storm berm. A slightly steeper beach profile and coarser sediment composition were documented at the case study sites in which gravel beach nourishment was a design element.

Geochemical processes can also be directly affected by large wood placement as large wood is a major component of the carbon nutrient cycle, and can serve as substrate for nitrogen-fixing vegetation (Hood 2007). This management measure can also benefit migrating fish that forage upon prey items residing on or around large wood. An example is juvenile salmonids that feed on amphipods and insects that originate from high intertidal habitats (Cornu et al. 2007, Toft et al. 2004, Sobocinski 2003, Williams and Thom 2001). Large wood placement can also benefit other wildlife as the wood provides habitat for nesting, foraging, and feeding for a number of bird species found in the Puget Sound region (Brennan 2007).

Design

Large wood placements are not as well understood as beach nourishment, hard armor, or other techniques described in these guidelines. The interaction of logs with waves and determining the forces acting on logs by waves in particular are examples of this.

This section describes elements of feasibility for installing large wood and the specific design elements unique to large wood placement projects including: the specific location within the beach profile that the large wood will be placed (elevation and orientation), large wood size and type to be used, whether it is placed atop the current beach grade or buried (and to what depth if buried), and the type of anchoring mechanism, if anchoring is necessary. This guidance is divided into the following sections:

- Feasibility assessment
- Large wood placement elevation
- Large wood placement orientation
- Large wood characteristics
- Anchoring
- Cost

Large wood projects can be well suited for barrier beaches, pocket beaches, and transport zones with low to moderate wave energy and erosion rates, where risk to infrastructure is not high. Beach nourishment and vegetation planting can augment large wood projects, particularly at sites with moderate wave energy or moderate erosion. Common design errors to be avoided are placing logs too low on the beach profile, the use of anchor systems that are completely rigid and do not allow logs to move, and not embedding logs into the beach substrate. The topics are covered in the following sections.

Feasibility Assessment

The first step in developing a large wood placement design is to clearly identify the project objectives and the design elements required to achieve the identified goals. Any constraints that could present solid boundaries to the design area should be outlined early in the process, such as property boundaries or infrastructure. If the project will include additional design elements such as beach nourishment, this should be clearly established early in the design process. As with all projects, the available budget will influence the range of engineering elements that are possible. Lack of site access for construction can also limit project feasibility. For example, if design materials cannot be trucked to the site, then barge access should be investigated—otherwise large wood installation may not be feasible. These preliminary steps will provide a framework which the project design must work within.

The subject site should be evaluated to determine if the conditions for large wood placement are appropriate and identify any potential constraints that could limit project success. The determination of feasibility for a large wood placement project relies on several site characteristics that will also inform design. The most critical site characteristics relevant to feasibility and design include the combined effects of shoretype, wave energy, existing berm elevation, beach substrate density, and existing large wood (Table 7.2-1).

Table 7.2-1. Site characteristics and associated design considerations for large wood projects.

Site Characteristic	Associated Design Consideration
Shoretype	Barrier beaches, pocket beaches, and embayment shores are generally feasible. Bluff backed beaches with low exposure are also potentially feasible depending on drivers of erosion.
Wave energy	Not suitable for high wave energy unless on a barrier beach or pocket beach. Large wood density, size, placement in beach profile, and need for anchoring are considerations.
Existing berm elevation	Large wood placement on beach profile and whether beach nourishment should be included.
Beach substrate thickness and underlying deposit strength and density	Determines type of anchoring mechanism. Different anchor styles are suited for different substrates.
Existing large wood supply	Large wood can be placed to trap natural drift logs if in moderate abundance, or for an enhanced berm only.

Favorable general site characteristics of successful large wood projects include:

- Barrier beaches, pocket beaches, transport zones
- Low to moderate wave energy
- Low to moderate background erosion rates
- Moderate to high setback distance (low risk)
- Low to moderate infrastructure risk
- Enough room in the backshore for log placement

In addition to the site characteristics listed above, a feasibility assessment for large wood placement projects should include a thorough understanding of local coastal processes, the existing erosion rate (if an objective is to reduce erosion rates), the presence of critical habitats, the anticipated wave runup, and the presence of additional stressors such as altered sediment supply or substantial vessel wake. Understanding the larger net shore-drift system (see Chapter 4, *Coastal Processes Assessment*) includes the current condition of nearshore processes relative to historical conditions for sediment supply, sediment transport, and large wood recruitment and storage.

At the site-scale, measuring the maximum fetch is a critical first step in the feasibility and design process. The maximum measured fetch can provide insight into the wave regime at the site. The higher the wave energy, the higher on the beach profile the large wood should be placed. This is important to the design because adequate space is required to place the large wood, especially if multiple large wood pieces are included in the design.

Wave runup could be calculated if wind data are available, but if considerable large wood occurs naturally at the site the landward limit of large wood can also be indicative of the highest tidal inundation and wave runup.

Examining adjacent unmodified sites can also inform feasibility and design, particularly if the subject property has incurred modifications to the natural topography of the backshore. The substrate composition of the upper beach and backshore should be noted along with the density of the substrate specifically in the backshore. The natural elevation of the storm berm and the extent of large wood deposits (vertically and horizontally) along adjacent shores should be assessed and compared to the subject property. It should be noted if large wood appears to be in transport or deposited regularly. The dune or backshore vegetation assemblages and conditions should also be assessed, particularly if vegetation plantings will be included as part of the design.

Large wood placement projects are not well suited for all sites in the Puget Sound region and compromises must be made if site characteristics push the limits of feasibility. Each parameter informs the placement of large wood and the selection of the best anchoring mechanism for the individual site. The design model/decision framework presented in Figure7.2-2 should be used as a guide in this process.

The following list offers an example of the necessary synthesis of parameters relevant to designing a successful large wood placement project:

- If the wave energy at the site is moderate, then the infrastructure must be adequately setback.
- Large wood placement should be placed above normal tidal elevations but within the maximum extent of wave runup (if possible).
- If the site is a barrier beach that is rapidly eroding due to a drastic reduction in littoral sediment supply, then the site should also have low risk to infrastructure and the designer should consider enhancing the storm berm via beach nourishment.
- If the berm is in a low elevation eroded state, the site could benefit from additional upper beach elevation and enhancement to the storm berm via beach nourishment.
- If the site has a high existing natural supply of large wood, logs placement could be oriented to trap (natural) drift logs.
- The large wood pieces should be partially buried and anchored to assure that they are immovable if inundated in the future.
- Vegetation plantings should occur adjacent to and landward of the large wood. The finer the substrate, the more species are likely to volunteer.

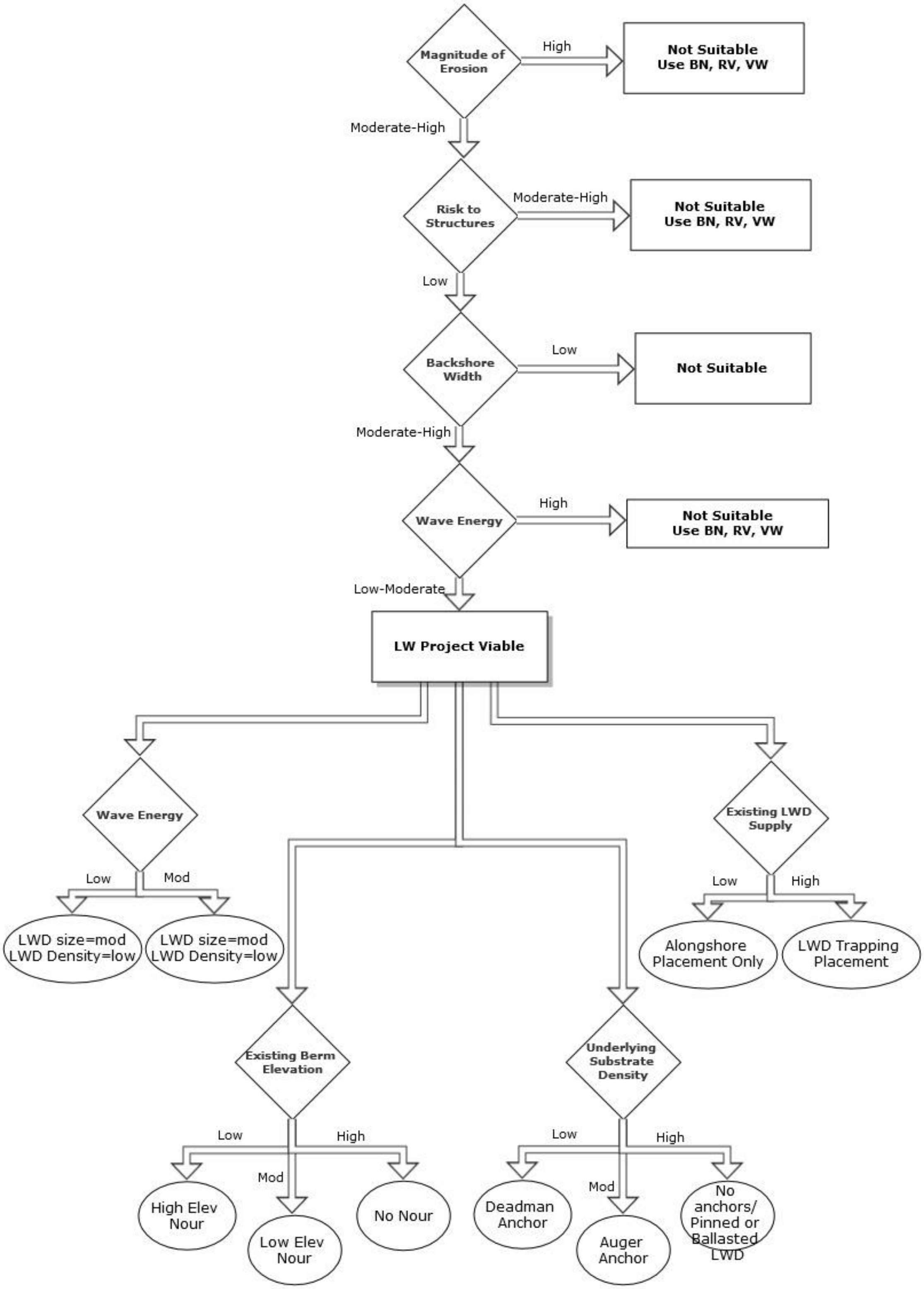


Figure 7.2-2. Design model for large wood projects.

Large Wood Placement Elevation

One of the most critical design criteria for project success is the elevation where the large wood is placed. Logs are typically placed several vertical feet above local MHHW. Large wood placement should mimic the upper limits and elevation of naturally deposited large wood along local reference sites. In areas where no large wood is found on the beach from which to reference, historical air photos can provide insight. In addition, other indicators or documentation of maximum wave runup should guide large wood placement elevations. Sites with higher wave energy will have greater wave runup and the large wood should be placed higher and further landward. The landward limit of appropriate large wood placement is commonly defined by the presence of upland vegetation or infrastructure. Examples of log installation for erosion control are shown in Figure 7.2-3. All examples in this figure show logs which were placed within the natural elevations of large wood deposition. Frame d in Figure 7.2-3 shows logs anchored within the zone of natural log deposition but immediately fronting a large high-value building.

If large wood is placed too low on the beach profile it can result in beach scour beneath the logs and anchor systems may not be able to withstand the combined forces of waves and buoyancy. With the exception of low energy sites, large wood should never be installed at or below MHHW—unless risk to a nearby building or other structure is high and analysis can support this unusual application. Beach scour can occur around logs placed in the intertidal with sediment removed from below and waterward of the logs. Logs have been anchored in the intertidal in the Puget Sound region, and some examples are shown in Figure 7.2-4. Logs placed at or below MHHW become buoyant during high water events and therefore require robust anchor system design and installation.

One site with a 6 mile southwest fetch was visited briefly in preparation of the MSDG where logs were anchored in the intertidal (Bloomquist site in Zelo et al. 2000, Figure 7.2-3 frame c). Beach erosion did not appear to have occurred at this site when observed in 2012 and the project has fared quite well, perhaps as beach erosion was not occurring at this site. Another site with anchored logs in the intertidal in Suquamish has reportedly experienced scour around the logs (Waldbilling pers. com. 2013).

A large wood project which was carried out by the Navy on Indian Island in Jefferson County included anchored logs along with other erosion control measures. The logs were anchored above and below MHHW, waterward of preexisting dunegrass. The 1997 installation also included vegetated geogrids, fill, vegetation, and other measures landward of MHHW, to protect an old landfill from erosion, as summarized in Zelo et al. (Indian Island project, 2000). Subsequent to that report, consultants for the Navy determined that these logs were causing more harm than good to the beach through increased scour and not enough erosion protection for the west end of the landfill. In 2003, 6 years after installation, the Navy removed the logs and constructed a rock revetment at this location.

a) Backshore linear logs, minor nourishment for backshore erosion control (Oak Bay)

b) Complex log pattern to trap logs (NW Whidbey)

c) Backshore placement at east end Hood Canal bridge

d) Logs interlocking with dune (East Dungeness)

e) Anchored and placed high on the beach for erosion control immediately adjacent to the Northwest Maritime Center in Port Townsend.

f) Minimizing end erosion at the ends of bulkheads and transitioning into a soft shore protection project.

Figure 7.2-3. Examples of backshore log installations for different intents at erosion control sites in the Puget Sound region.Arrows point at anchored logs where not obvious. Case study sites indicated in parenthesis; see Appendix A (photos J. Johannessen).

a) Lofall, Hood Canal (Zelo et al. 2000); mid-intertidal and upper beach, mostly shore parallel, anchored logs fronting residence.

b) Suquamish Indian Reservation; mid-intertidal to upper beach anchored logs with bank and backshore retaining wall fronting large building.

c) Kitsap Memorial State Park, Hood Canal (mid-intertidal and upper beach cross-shore anchored logs down-drift of bulkhead.)

d) Swinomish Indian Reservation LaConner; shore-parallel upper intertidal anchored logs fronting dredge spoils at low energy site with wakes.

Figure 7.2-4. Anchored logs placed in the intertidal for erosion control (photos (a) and (d) J. Johannessen; photos (b) and (c) H. Shipman).

Large Wood Placement Orientation

Large wood orientation is also an important element of large wood placement. In most cases large wood pieces are aligned parallel to the shoreline (Figure 7.2-3 frames a, d-f), but in some cases pieces may be oriented cross-shore to facilitate beach access or to trap additional large wood pieces in transport (similar to the key piece of a fluvial log jam, as in Figure 7.2-3 frames b and c and Figure 7.2-4 frames b and c). Cross-shore orientation can be effective if the project site is within a drift cell with a moderate to high volume of natural drift logs in transport. The limited number of projects that attempted to trap natural drift logs used the approach of offsetting the log end facing the predominant wave approach (up-drift) at a 30 to 40 degree angle waterward from the trend of the shore, with that log end elevated up to several feet above the beach level to provide the trapping mechanism. To be effective at trapping natural drift logs, this typically requires that approximately one third of the length of the opposite log end be placed below grade to be stable.

Key large wood pieces and all pieces placed within reach of waves should be partially buried in order to prevent gaps from scouring beneath the logs in most or all conditions. Key pieces should be oriented to pin other pieces in place. These larger pieces should be oriented towards the dominant wave direction in order to act effectively as traps for large wood in transport. Large logs can be placed singly or in groups to produce the scale and function required for each application.

Determining the appropriate amount and location of rigidly anchored logs to allow for the continuation of natural coastal processes is important if the goal is to avoid the negative impacts associated with hard armor structures. A general way to evaluate what constitutes a soft shore project design is to consider if some flexibility is retained in order to allow for natural coastal processes to occur. Another way to evaluate whether or not a project is a soft shore design is to determine whether the percentage of the project site area that is composed of relatively rigid elements, such as well anchored logs, is small, such as 20% or less. In addition, placement of large diameter logs should not be used for creation of dry land. On some Puget Sound projects, logs were placed and stacked almost two high and very close end to end and secured in a way to allow for filling of gravel landward of the logs and establishment of lawn (Figure 7.2-5). The figure shows logs which were placed further waterward than the design specified and with a greater volume of gravel fill used than designed or permitted. This underscores the need for permit agencies to follow up and view projects in the field after completion in order to determine if they were constructed to design and ensure adequate enforcement of regulations.

Figure 7.2-5. Example of inappropriate large wood project on south Whidbey Island which was constructed with fixed, stacked logs placed lower and more vertically than designed or permitted, here retaining fill gravel and creating usually dry land where beach existed prior.

Logs have sometimes been used as a transition feature from a bulkhead to a more natural shore. In these applications logs have been used to try to reduce the effects of end erosion in the area immediately adjacent to the end of a bulkhead, as in Figure 7.2-3 frame f. The intent is to provide an enhanced upper beach or backshore area where wave refraction from the end of the bulkhead is most pronounced. These installations can transition from higher to lower elevation and material density moving away from the bulkhead.

Large Wood Characteristics

Large wood size is also an important design element. Large wood should be of a size that can remain functional in the application for a substantial period of time. Larger pieces will degrade more slowly than smaller pieces. Log diameters in the case studies ranged from 19 to 34 inches, with an average of 23 inches. Generally, larger logs are preferred. Large logs with intact rootwads are optimal because, if partially buried, the complexity and width of the rootwad helps to anchor the log in place. Logs with branches still attached or logs with bends or other irregularities can be advantageous to use in beach applications. These complex shapes can help catch and retain additional logs. Large wood with rootwads or other complex shapes also function better as traps for fine sediment and organic material (including additional wood) as compared to logs that are more cylindrical in shape. Logs can be delivered to a site in a dump truck, on a flatbed, or by barge.

Selecting appropriate species of logs is important, as the wood of many species rots much quicker than several of the native species. Whenever much effort is put into a project, such as if anchors are used, Douglas fir and western red cedar logs should be used to increase longevity of the logs in these moist and salty environments. Western red cedar is the most rot resistant and should be used when possible. Larger and more complex placements that require high strength logs should use Douglas fir where possible. Deciduous woods will not last as long in or near the marine environment, but they can be used for restoration or enhancement depending on the application. Logs treated with chemicals such as creosote should never be used. Creosote leaches into the water and settles into the sediment, where it gets into the food chain and threatens the health of fish, wildlife, and humans (Holman et. al 2007).

Anchoring

Large wood placement for erosion control on a beach that is actively eroding should be anchored in place. Erosion control projects where wave energy is low may not need anchors. If large wood is simply to be reintroduced to the local system for habitat, anchoring is not needed. Anchor systems add cost and complexity of implementation, and can introduce elements that are undesirable. These elements include metal hardware which can become exposed or separated from the original anchors, resulting in aesthetic impacts and safety hazards to people.

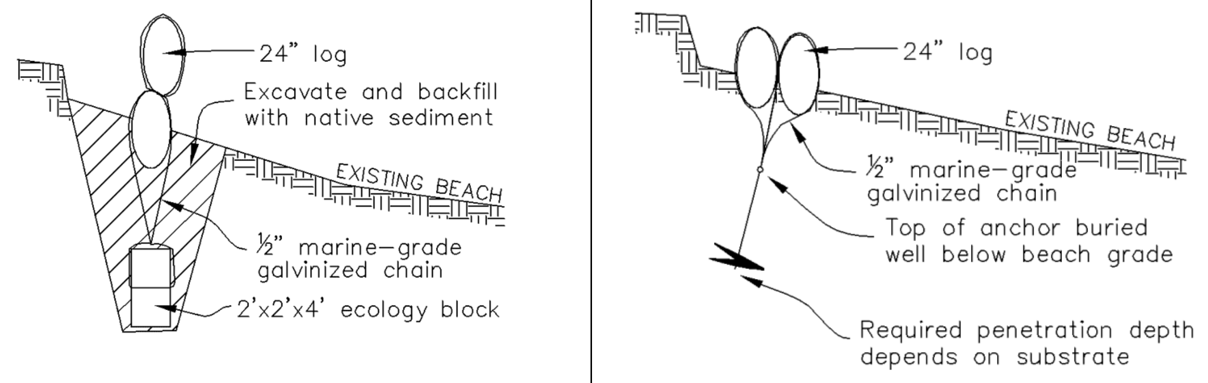
Calculating forces exerted by waves on logs in the nearshore is a very difficult exercise with a large number of variable and many assumptions are required. The number of variables is significantly greater than in stream applications as waves of varying wavelengths come from different angles at varying water levels. Major assumptions include the water level, wave height and period, beach elevation during storms, and breaking strength of logs and anchoring materials. Attempts to quantify wave forces on logs in Puget Sound have been made for some projects, although no published results are known. Wave forces on logs during high water storm conditions are large. Quantitative methods for sizing anchor systems are not included in these guidelines. Qualitative information is provided; refer to Cramer et al. (2012) for additional information on anchoring. The location of placed logs and design of appropriate anchoring devices is therefore critical to retain logs in desired positions.

A variety of anchoring mechanisms have been employed in large wood placement projects in the Puget Sound region. Large wood pieces are most often attached to buried anchors for additional stability in high wave events, but the durability of some anchoring methods and hardware, such as various qualities of stainless steel cable, may be lower than expected. Small anchors such as Manta Ray or duckbill anchors have been used, but the long-term reliability of these is not clear (Figure 7.2-6). The surface area of the anchors and resistance to movement need to be considered based on the anticipated forces of breaking waves and the different soil conditions in which anchors are placed. For sandy or sandy fine gravel beach or glacial/non-glacial deposit substrates, small anchors may not be sufficient. Additionally it is not possible to drive auger or earth anchors into some dense soils. Rock ballast has been used in some beach applications either alone or in combination with deadman or other buried anchors (see Figure 7.2-3 frames b and e and Figure 7.2-6 for isolated boulder placement).

Generally better longevity has been achieved using marine-grade galvanized chain as compared to stainless steel or galvanized cable. Unless the highest quality stainless steel is obtained, durability of stainless steel in the marine environment has been less than the several decades or more desired. The diameter of chain or cable is also a key factor for the breaking strength. Moderately high energy sites should not reply on bolts exclusively or anything short of wrapping around a log, as logs have become separated from anchors due to insufficient hardware.

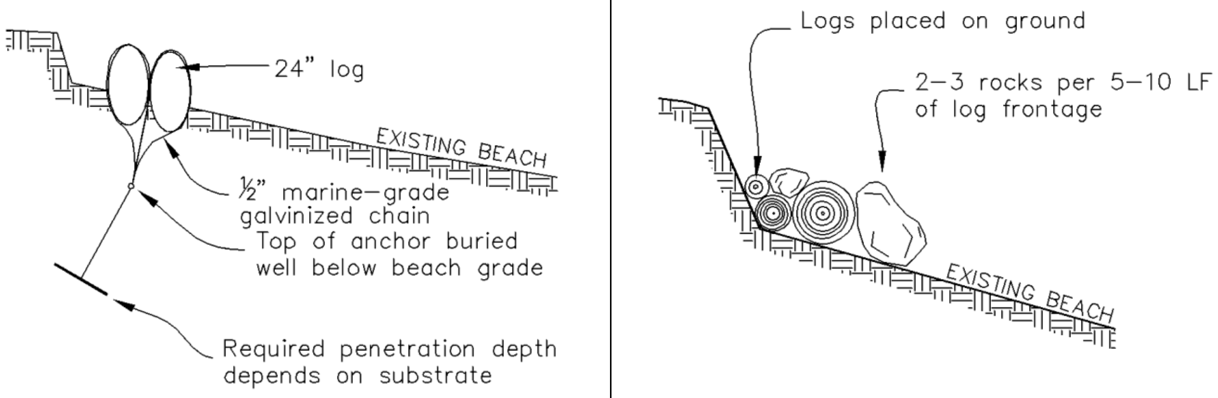
Buried deadman anchors such as large concrete blocks placed well below an existing grade offer a reliable and economic approach (Appendix A). Disturbance when installing these larger anchors can be greater than with auger anchors (Figure 7.2-6, as pointed out by Gerstel and Brown 2006), but it appears that this disturbance is extremely short in duration as natural change can be substantial in most beach environments. Anchoring techniques or installation methods that did not follow recommendations here have led to the loss of anchored logs in several projects. One example at the Northwest Maritime Center in Port Townsend experienced the separation of large logs from anchors, only to later discover that upon excavation, the contractor had used a much cheaper form of anchor system than the design called for. This resulted in the need to excavate anchors and replace the anchors and some attachments. The original log placement at Tacoma Narrows Park used rigid metal posts for anchors (as discussed in Gerstel and Brown 2006), with erosion resulting in the logs being suspended in the air.

Other anchoring designs used in the region have been used where excavation or below gravel penetration was not allowed due to the presence of cultural resources which could not be disturbed. Several approaches to attaching concrete weights to the bottom of logs have been used in these situations (Figure 7.2-6). Project designers should take steps to prevent risk of damage to infrastructure if anchors and cables partially release or create focused, repetitive impacts in the event of partial scour and mobilization. For this reason, logs should never be anchored to the face of a bulkhead or similar structure, or in close proximity, except perhaps in very low energy environments.



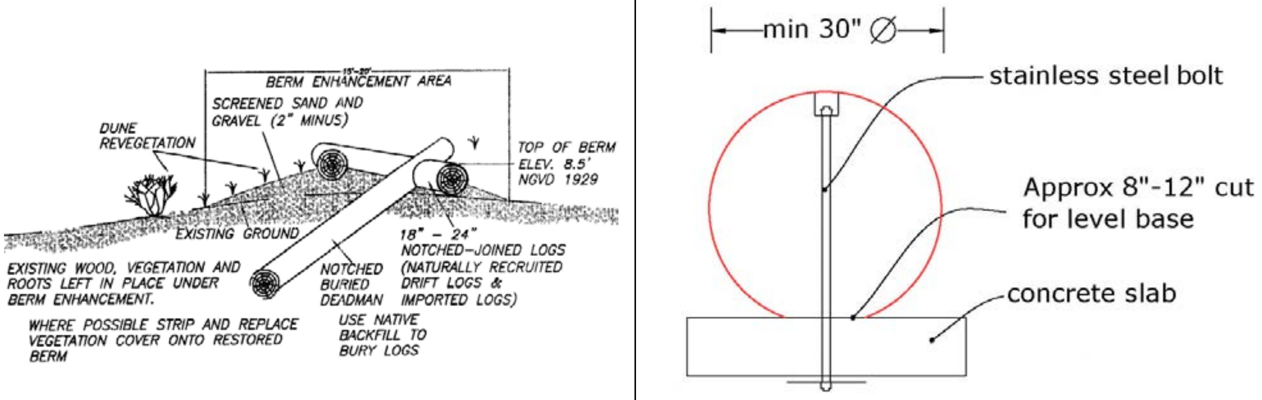
a) Pre-case concrete deadman anchor with center hole (lock block or ecology block)

b) Auger type



c) Earth anchor

d) Pinned in place with rock



e) Interlocking in a dune (no anchors)

f) Concrete ballasted log

Figure 7.2-6. Example of different anchoring approaches and hardware used in Puget Sound projects. Credits: a–c, f) Coastal Geologic Services; d) Warren Demetrick; e) Four Seasons Engineering.

Cost

Cost for installation of large wood projects varies widely. However large wood installation projects are on the lower end of the range for the various design techniques discussed in this document. The primary considerations for cost of a given project are:

- Size and number of imported logs
- Difficulty of access for equipment and materials
- If additional measures are included beyond log placement

Most projects require importing logs to achieve project durability and desired function. This typically involves larger diameter cedar or Douglas fir logs, as discussed in the above sections. In most cases, this size and quality of logs is not available on site. Therefore, logs must be sourced from commercial suppliers and transported to the property. Obviously projects that require fewer logs will be considerably cheaper than projects with dense log placement.

The ease or difficulty of accessing the site will influence the cost of implementation. Sites that can be accessed with a dump truck or long-haul truck relatively close to the beach will typically have lower costs than sites that are difficult to move equipment or logs across. Sites that require barge access typically have the highest cost, unless the project is of great length and the economy of scale is cost-effective for mobilizing the barge and tug. This is usually not the case most for residential applications unless the project area includes several contiguous properties.

The major factor affecting the cost is the materials and labor required for constructing beach nourishment, restoration, or other associated treatments. The mounting costs of purchasing beach nourishment sediment and the cost of placement are key issues, should nourishment be included. Refer to chapters 7.1 and 7.3 for more details on the beach nourishment and vegetation.

Monitoring

Physical monitoring of large wood placement should include topographic mapping or surveying conducted prior to and following wood installation as part of a baseline survey. Subsequent annual monitoring should be carried out in the same season and should aim to measure changes in log locations or elevation, beach or berm topography, sediment composition, position of ordinary high water mark, vegetation assemblages, etc.

For smaller projects and in the absence of topographic mapping, simple measures from reference locations to logs can be valuable. For example, one could measure the distance from the top of a large wood piece to the beach grade. Photographs taken seasonally with the same perspective and clear reference points can also be very helpful for observing change across the years. Specifically, monitoring data and photos should be reviewed to document loss of elevation of the storm berm, movement of logs, scour anywhere around the project, overtopping, and/or failure of anchoring mechanisms. Repairs and maintenance should be conducted if any of the aforementioned conditions are observed. More information on monitoring elements and protocols is described in Chapter 8, *Monitoring*.

Maintenance

High water events could result in mobilization or loss of unanchored logs and contrasting conditions from what the large wood placement project was designed to create. Monitoring large wood projects will identify when maintenance is required and is therefore critical to insuring these projects endure the changing conditions associated with climate change. Maintenance for large wood project can consist of reattaching logs or adding additional beach nourishment sediment. Increased storm frequency, magnitude and occurrence of high water events (associated with *El Niño* conditions as well as storm surges) are all anticipated as a result of climate change.

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Chapter 7. TECHNIQUE 3
RESLOPE-REVEGETATION

Description

Bank or bluff resloping (or recontouring) and revegetating (RE) consists of reducing or lowering the gradient of the slope in order to increase its stability and subsequently planting at the site, preferably with native riparian vegetation. Resloping can be considered as an approach to mitigating slope instability where toe erosion, or more commonly, upland causes result in an oversteepened, unstable upper bluff face. Where erosion is occurring solely due to wave attack, resloping is likely not the appropriate solution.

Resloping generally involves grading the upper portion of a steep slope or bank to “lay back” and “unload” the crest or headscarp. In some cases, it may involve the full length of the slope, such as at the West Lummi Peninsula site pictured in Figure 7.3-1. The addition of vegetation reduces surface erosion by intercepting precipitation and inhibiting surface water runoff, creating a root network to reduce erodibility of surface soils, and improving soil cohesion throughout the rooting zone as larger plants and trees become established. Vegetation also improves soil drainage through aeration and evapotranspiration. Planting can be applied to an existing bank or one which has been resloped.

Conventionally, slope stabilization by resloping has an engineered structure component such as gabion walls, crib walls, soil nailing assemblies, or other soil-retaining structures. Because the objective of this document is to provide more natural alternatives for bluff stabilization, design concepts that include such structures are not included. Gray and Leiser (1989), Macdonald and Witek (1994), and other reference volumes listed in these guidelines (as well as more technical engineering publications) offer concepts and designs with engineered structures that might be suitable for higher risk and problematic sites.

In some cases, resloping is combined with beach nourishment (Technique 1), placement of large wood (Technique 2), or other treatment options presented in these guidelines, specifically to address potentially destabilizing slope toe erosion from wave attack.

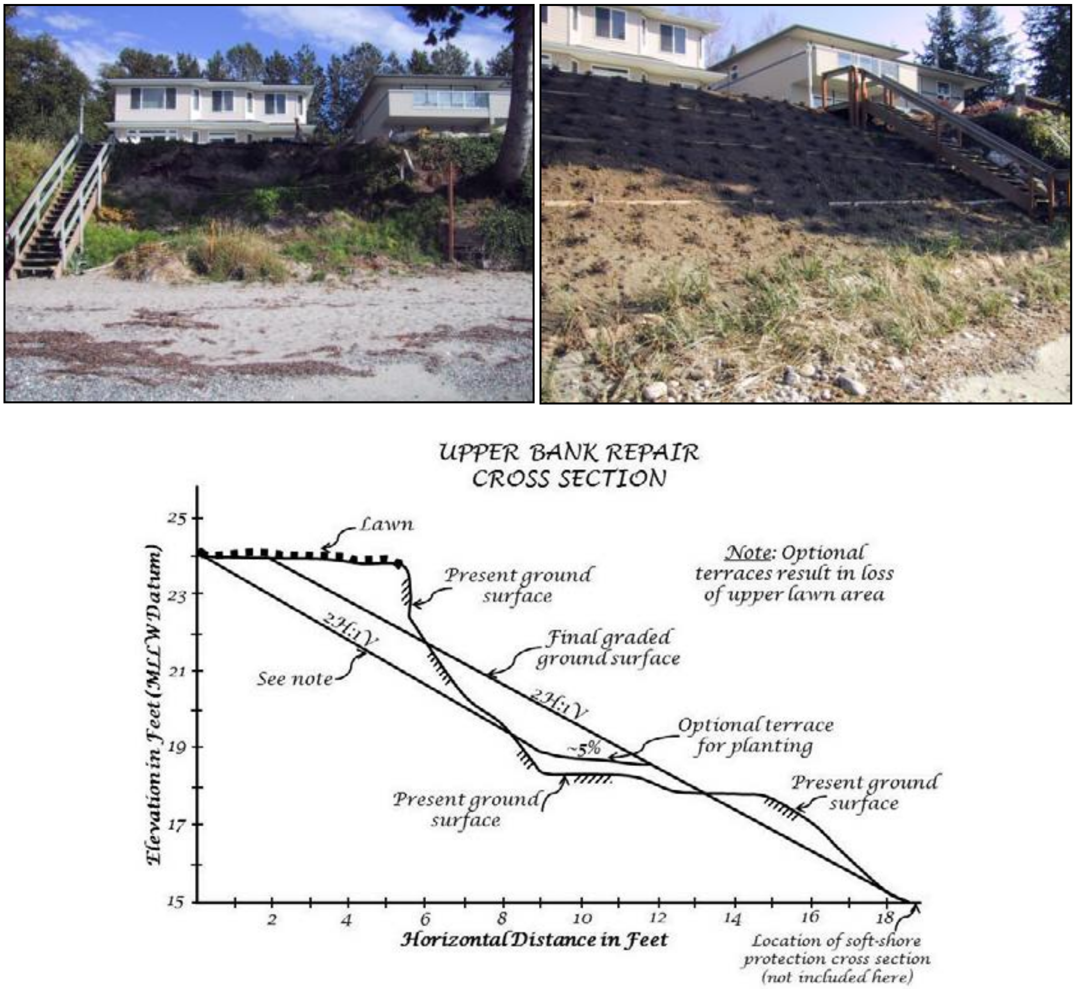

Figure 7.3-1. Example of reslope revegetation project in the Puget Sound. The two photos show before (top left) and after (top right) reslope and revegetation treatment of a medium-high bank site in northern Puget Sound. Treatment was initiated as a result of a soil slump that left the upper portion of the bluff oversteepened and unstable, and the deposited sediment at the toe. The sketched cross-section shows the post-slump profile of the slope and the design plan for regrading. In this case, because slumping was attributed to wave impacts at the toe, the entire slope was regraded to about 30° and planted with kinnikinnick (Arctostaphylos uva-ursi), dunegrass (Leymus mollis), and several other species. Modified from Western Geotechnical Consultants, Inc.

Application

Changing the gradient of a slope, which generally implies lowering it, is a common technique of slope stabilization, often applied where a steep or near-vertical bluff is either a cause or a consequence of mass wasting. A steep bluff face may reflect the characteristics of the sediment it exposes, such as dense till, or may indicate active and retrogressive erosion of softer material. Lowering or reducing the gradient of a slope makes it more stable by reducing the driving forces inherent in a bluff face that exceeds the angle of repose of the sediment in which it has formed. Resloping is generally applied to the upper portions of a slope, but can also be successfully applied to the entire slope (Fig. 7.3-1). Figure 7.3-2 shows another example of a successful resloping project (not included as a case study in this document).

Figure 7.3-2. These three photos are of a site on Eld Inlet, South Puget Sound, where coarse unconsolidated sediment overlies denser sand, silt, and gravel. The top photo shows the differential rate of erosion between the two geologic units prior to treatment, the effects of groundwater perching on the lower unit, and the greater stability of the lower unit except for some surface rilling on the steep face. In the lower right photo, a natural-fiber geotextile is visible fastened to the slope to reduce the potential for surface soil erosion until vegetation is established. Additional challenges at the site included burrowing mountain beavers in the sloughed sediment at the base of the bluff, springs discharging along burrows, and mortality and poor "pruning" caused by the beavers. According to the property owners, slope crest retreat prior to the planting appeared subsequent to increased development upslope and an associated increase in stormwater runoff. In this case, toe erosion is not an issue (bottom two photos by Ben Alexander).

In developing the appropriate design for resloping, it is imperative to first identify the cause or causes of the instability. Upland processes involving surface or stormwater runoff are often the cause of erosion and slope failure (see chapters 3 and 6). Inappropriate management of surface water or excess recharge of groundwater (such as recharging perched aquifers via poorly placed retention, irrigation, or infiltration systems) can cause slope failure when pore-water pressures build within the slope. Without proper site management, upland impervious surfaces such as roofs, driveways, and patios, and other water conveyances such as dry wells, gutter down spouts, etc., can concentrate and direct water to vulnerable and sensitive slopes.

The best solution for a given drainage issue may be the construction of one or a combination of drainage features as simple as a lined stream channel, or as complex as curtain drains, catch basins, open and closed ditches, French drains, dry wells (where appropriate), etc. Any of these must be designed and located with care, as each may be the best approach at one site and the worst at another. More information about the management of runoff can be found in Chapter 6, Passive Techniques, and in the references cited in that chapter.

Changing the configuration of a coastal bluff slope, with or without additional engineered structures, has impacts and possibly unintended consequences to adjacent properties or nearby shores. However, it can be a reasonable slope-stabilizing treatment in cases where cost or permitting restrictions limit mitigation options. As always, an assessment by a qualified professional should first determine whether modifications in upland drainage management could address the problems, or whether additional earthmoving action is needed. Subsequent vegetation of the regraded portions of the slope, and possibly other remaining portions of the slope, should be done when planting conditions (seasonal precipitation, plant availability, soil moisture content, access, and other relevant site conditions) allow.

There is no standard process for property owners to follow in the case of an emergency situation with catastrophic coastal bluff changes. In this case, property owners are encouraged to contact state and local officials immediately to arrange consultation.

At high bank sites, recent landslides leaving steep unstable slopes or cliffs can present a significant hazard to residents and risks to structures. Reducing the gradient of the headscarp may be a viable emergency action. However, landowners should be made aware that the remaining steep lower portions of the bluff may still pose a hazard.

Subsequent to resloping, planting with native vegetation can reduce the potential for erosion and shallow landsliding by contributing to soil strength through root systems. Root systems do little to mitigate failures occurring below the rooting depth of most plants; however, suitable vegetation can partially mitigate the potential for deep-seated failures through precipitation interception and evapotranspiration processes (Macdonald and Witek 1994, Myers et al. 1995).

Effects

Two reslope and revegetation projects (West Lummi Peninsula and East Drayton Harbor) were evaluated for this study and are presented as case studies in Appendix A. A third project included in this study (Weyer Point), but evaluated as a bulkhead-removal rather than a reslope/revegetation treatment, involved a short section of resloping and revegetating where a vertical concrete bulkhead was removed. Collectively, these project sites highlight the challenges of developing appropriate design plans and assuring successful project performance in geologically contrasting settings.

Geologic and hydrologic conditions should dictate the ultimate configuration of any slope modifications; therefore, such conditions must be carefully characterized and taken into account for each individual site design. Because upland land is lost in the process of resloping, benefits, in the way of long-term slope stabilization, and impacts, in the way of reducing the distance between structures at risk and the edge of the slope, need to be considered for each project where resloping is an option. To a lesser degree, the likelihood of successfully establishing native vegetation must also weigh in. Risk to structures must be given additional consideration if the project site lies within a reach where overall objectives include establishing connectivity of a sediment source to the beach.

The West Lummi Peninsula site (Fig. 7.3-1, Appendix A) involved a designed reduction of the entire bluff slope gradient with subsequent vegetation planting. The objective of the project design to mitigate the effects of a recent earth slump and resultant retrogression (or retreat) of the slope crest resulted in a reduction in the potential for sediment input into the beach environment. In this case, without the addition of plants, coarse gravel on the upper beach face, and a large shore-parallel log, continued erosion of the slope toe, with or without resloping, would likely reactivate slope failures and sediment input.

Vegetation can be a potential contributor of LWD and detritus to the beach environment if allowed to topple and move naturally downslope and onto the beach. In the case studies presented in Appendix A, there appeared to be only limited large wood available or larger trees planted as part of the treatment. The formation of a functioning marine riparian zone therefore seems unlikely in the short to medium term and producing large wood did not appear to be an objective of these projects. This illustrates the importance of considering the long-term goals of vegetation management and the desired contributions it will make. If project goals include restoration of a natural backshore with associated vegetation, then beach nourishment might be a suitable complimentary treatment to maintain the appropriate beach elevation. The role of vegetation, particularly shrubs and trees, serves to increase the strength of soil and sediment through apparent root cohesion, soil moisture depletion, and precipitation interception. Along with these benefits to soil and slope stability, vegetation contributes to water quality; provides wildlife habitat, habitat structure, and large wood; creates shade; delivers nutrients to the beach at low tide and to marine waters at high-tide; produces fish prey; creates microclimates; contributes to human health and safety; and enhances aesthetics (Brennan and Culverwell 2004, Brennan 2007).

Resloping is a viable technique for slope stabilization where enhancing or preserving sediment input to the shore environment is not a short- to medium-term objective for the site, and where structure setback is adequate to allow for the necessary and appropriate relocation of the slope crest without creating additional risks to structures.

Design

Slope Grading

The designed and constructed slope gradient must be based on the results of a thorough site assessment (Chapter 3) to determine the cause or causes of slope instability. Where erosion of the slope toe is the trigger for transferring instability upslope, other treatments such as large wood and beach nourishment might be considered. However, slope instability is often caused by upslope land-use practices such as concentrated surface run-off, excessive groundwater recharge (from irrigation, septic systems, concentrated or inappropriate water infiltration), or yard waste disposal. For this reason, resloping is more commonly applied to the upper portions of a bluff or bank than to the full slope length or just the lower slope sections. Figure 7.3-3 shows the process by which this treatment method can be selected.

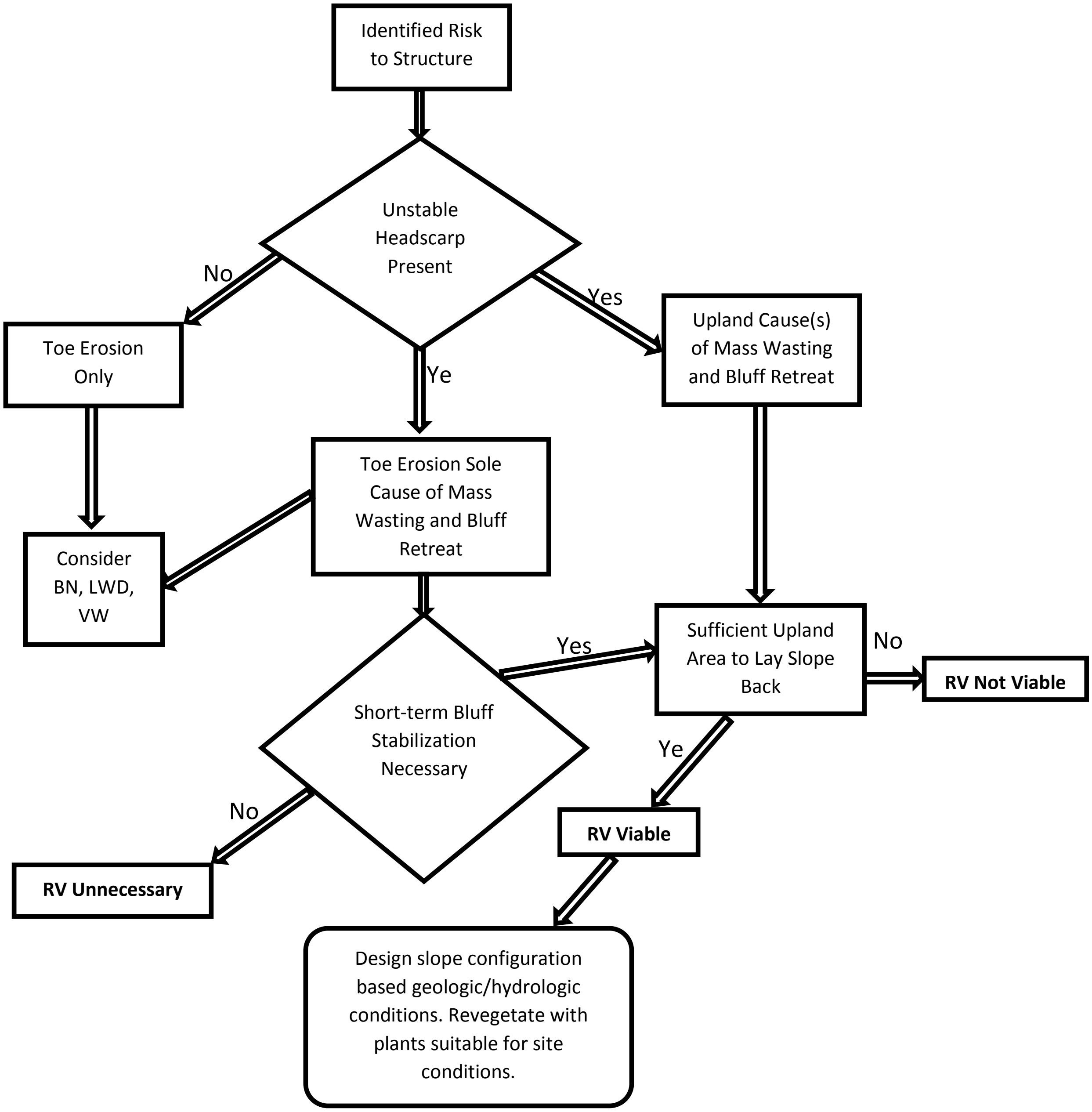

Figure 7.3-3. Design model for selecting Reslope/Revegetation technique.

Slopes can be graded to a variety of different configurations that might be uniform or compound (i.e., terraces or steps). In certain conditions, a compound slope configuration can reduce the footprint of the project while improving stability and reducing the potential for surface erosion. It can also provide more favorable and stable conditions for plants to be established. The selected design configuration may be driven by aesthetics or shoreline access infrastructure, but must consider controlling geologic conditions such as stratigraphy, variable soil/sediment strength properties, and groundwater conditions. Orientation of geologic bedding has an effect on stability and groundwater movement, as does the permeability and porosity of different substrates, collectively creating a predisposition for certain units or layers to be weaker than others.

More competent geologic units are those with greater cohesion and angle of internal friction, particularly when made up of well-graded (or poorly sorted) sediment. This means that sediment grain size is not homogenous. Furthermore, sediment strength is improved if it specifically includes a component of silt and clay; and even more so if it has been compacted through glacial loading, as in the case of lodgment till. Till naturally holds a steeper slope face and can be graded to steeper slope angles than weaker units of poorly graded (well-sorted) and less-compacted sediment. Clean sand would be an example of the latter (Figure 7.3-4).

Where less competent sediments overlie compacted sediments (for example recessional outwash sand overlying advance outwash deposits or till), a stepped or “compound” grading approach can be applied, with the upper unit being graded to a shallower slope angle than the lower (Figure 7.3-4).

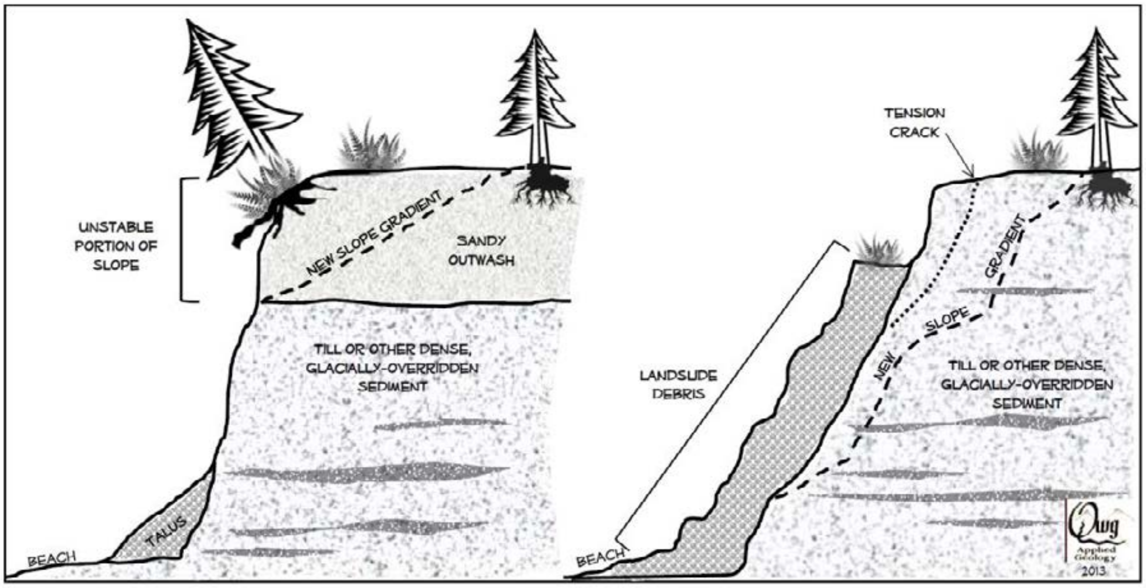

Figure 7.3-4. Two different possible slope configurations in different geologic settings showing resloping (left) and benching (right). Long dashed line in each drawing shows slope gradient created through project treatment.

Although the created slope angle at which soil or sediment will be stable (angle of repose) is important in design considerations, most project managers will admit that resloping is carried out somewhat subjectively or intuitively. More often than not, slopes are regraded without the benefit or application of sediment gradation and strength data, and therefore not designed quantitatively for a particular sediment type, but rather, driven by site conditions such as residential structure setback and equipment operating room, earthmoving and equipment costs, equipment access, safety concerns, surface treatment and planting plans, and other project logistics.

Clearly there are challenges in determining the appropriate angle to which a slope should be regraded. A denser substrate might maintain a stable steeper gradient and thereby limit the area being disturbed; however, topsoil, mulch, and plantings are harder to stabilize and establish on steeper slopes. Conversely, stabilizing less-consolidated sediments requires gentler slopes. These result in more site area being disturbed, but provide more stability for topsoil, mulch, and plantings. For this reason, project objectives may be achieved by necessarily synchronizing and compromising on various project aspects and criteria, and not necessarily by designing exactly to engineering specifications for material properties.

As an example, a slope in clean sand would need to be graded to less than 33° to be stable unless vegetation was established quickly and for the long term. Similarly, till or other dense, generally fine-grained sediment might be stable at near vertical slope angles as long as surface erosion was not a concern. In all cases, the suitability of the geologic material in supporting healthy plant growth must factor into the design.

In excavating the upper limits of a slope or scarp, the transition to adjacent unmodified slopes should be rounded and smoothed. This avoids creating a slope configuration that could propagate instability by leaving an oversteepened face, or concentrating surface or groundwater.

Vegetation

Because grading work generally leaves exposed sediment that is subject to erosion, subsequent planting is an important component of this stabilizing treatment. Vegetation improves soil cohesion, improves soil drainage through aeration and evapotranspiration, and reduces surface erosion through precipitation interception and inhibition of surface water runoff. The planting configuration should be based on the slope gradient, nature of the sediment (or substrate), type of erosion being addressed, and plant species being installed. Native plants are strongly encouraged.

Numerous techniques and plant species exist for vegetation installations, including but not limited to contour wattling, brush layering, fascines (bundles of sprouting sticks such as willow), live willow staking, brush matting, direct seeding, hydroseeding, cuttings, and transplants. The propagation and planting technique used should depend on site conditions, plant availability, season planted, and suitability of the plant for the site. Again, native plants appropriate for site conditions are strongly encouraged.

The following provides an example of one planting technique; installation of fascines:

> Dig a shallow trench that follows the contour at the toe of the slope. The trench should be deep enough to bury ¾ of the fascine below the soil surface. When digging the trench, place soil on the upslope. Any soil that is not replaced into the trench during installation will end up there through the course of gravity and surface runoff. If more than a single fascine is needed to run the length of the trench, overlap the fascines enough to eliminate gaps. Use stakes to anchor the fascines at intervals of 3-4 feet. Use standard, untreated wooden stakes or live stakes, 2-3 feet in length, and pound the stakes into the soil immediately down slope and angled slightly away from the fascine. For extra stability, pound tapered wood stakes through the middle of the fascine at a 45° angle to the slope, staggered between the down slope stakes. Finally, shovel the soil back over the top of the fascine and into the trench, and stomp it down well to work the soil through the fascine. Following backfilling, only the very top (10-15%) of the fascine should be visible. (From http://www.soundnativeplants.com/sites/default/files/uploads/PDF/Fascine_installation.pdf)

In the case of steep slopes, shallow-rooted plants such as grasses may be inappropriate (Figure 7.3-5), and deeper-rooting species might require special techniques to stabilize the soils until root systems can expand and enhance soil stability. It should be mentioned that root systems do little to mitigate failures occurring below the rooting depth of plants; however, vegetation can mitigate the potential for deep-seated failures through precipitation interception and evapotranspiration processes (Macdonald and Witek 1994; Myers et. al. 1995).

Because surface erosion is a common cause of bluff instability, plants can be installed in a variety of ways to repair erosion gullies, small debris flow headwalls, and other erosion features (Figure 7.3-6). As always, successful solutions require that the cause of the erosion be determined first, and addressed directly if possible.

Figure 7.3-5. The slope shown above in unconsolidated sediments was too steep and the roots of the grasses planted too shallow to hold up without some combination of deep-rooted vegetation, contour brush layering, stepped slope contouring, and temporary geotextile or other engineered structure (preferably including vegetation).

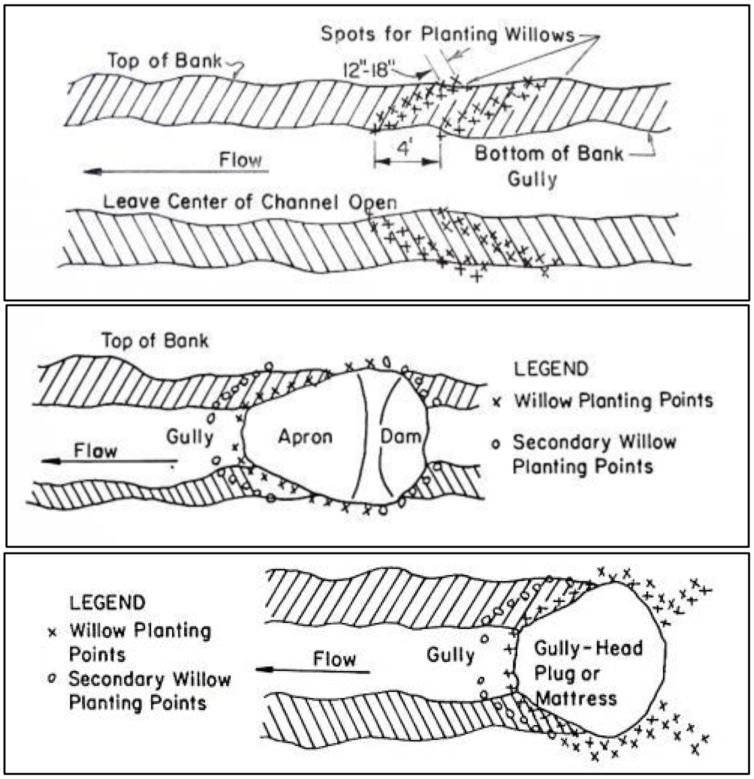

Figure 7.3-6. Three examples, in plan view, of different planting arrangements used to mitigate lateral and headward erosion of gullies formed by surface runoff. The top diagram shows one method used to stabilize channel banks where flow has removed sediment from the channel; the middle diagram shows a method used to stabilize channel banks as well as the up- and down-stream flanks of a damming sediment deposit; and the bottom diagram shows a method of stabilizing the headwall area of a gully. Source: Gray and Leiser (1989).

For stabilizing dune or beach sands such as those accumulating at the base of a sloughing bluff or backshore area, one of the most effective native plants is American dunegrass, also called dune wildrye (*Leymus mollis)*, which is discussed further earlier in this chapter in Technique 1, *Beach Nourishment*. It permeates sand easily and spreads vigorously via roots and rhizomes. American dunegrass is the native species that grows in backshore areas in the range of salt spray and occasional salt water inundation. Other similar grasses such as American beachgrass (*Ammophila breviligulata*; native to the American Atlantic coast), or European beachgrass or marram grass (*Ammophila arenaria*) have proven too aggressive and are now classified as exotic invasive species. For this reason, these should never be used.

In slope and upland areas, to bridge the time between establishing early low-growing plants and larger trees, smaller native trees such as alder, shore pine, vine maple, service berry, cascara, and hazelnut are good choices as they establish relatively quickly on disturbed sites. For longer-term stabilization objectives, Western redcedar, Douglas-fir, and Pacific madrone provide shade, moisture retention, evapotranspiration, and once established, a well-developed root system that contributes to soil cohesion.

Many other native plant species serve well to anchor soils against wind and water erosion, retain moisture or evapotranspire, produce organic detritus, reduce rainwater impact, etc. Table 7.3-1 provides a summary of plant applications and some recommended species.

For additional plant lists, appropriate site conditions, potential benefits, and long-term management, also see Menashe (1993, 2004), Cramer (2012), (particularly chapter 5), Guttman (in press), and on-line fact sheets posted by Sound Native Plants (http://soundnativeplants.com/information-sheets).

Because vegetation alone cannot be expected to mitigate all slope stability concerns, it is critical to plan for appropriate setback of any residential structures, as well as to thoughtfully consider drainage and surface- and groundwater management for a site. These considerations will also need to be factored into the long-term maintenance costs.

Table 7.3-1. Biotechnical slope protection—application and performance (modified from McDonald and Witek 1994; Myers 1993).

Type of Application	Method of Application	Appropriate Use	Role of Vegetation/ Stabilization Mechanism	Some Sample Recommended Species
Conventional plantings including those for long-term contributions to soil cohesion and eventual large wood for beaches	Grass seeding Transplants	Control of surficial rainfall and wind erosion Minimization of frost effects Slow bluff retreat rate	Binds and restrains soil particles Filters soil from runoff Intercepts raindrops Maintains infiltration Changes thermal character of ground surface	Red alder willow Douglas-fir Northern black cottonwood Red osier dogwood Twinberry Ninebark Cascara Salal Salmonberry Snowberry Douglas spirea Vine maple Red-flowering currant
Woody plants used as surface-soil reinforcement and as rainfall barriers to soil movement	Live staking Contour-wattling Brush layering Reed trench terracing Brush mats	Control of surficial rainfall erosion (rilling and gullying) Control of shallow (translational) mass movement	Same as above, but also reinforces soil and resists downslope movement of earth masses by buttressing and soil arching	Pacific and other willows Red osier dogwood Vine maple Ninebark Cascara Salmonberry Snowberry Salal Douglas spirea Red-flowering currant Twinberry
Woody plants grown in interstices of low, porous structures such as retaining walls, or on benches of tiered structures	Vegetated revetments (riprap, grids gabions, blocks) Vegetated retaining walls (open cribs, gabions, stepped-back walls, welded wire walls)	Control of shallow mass movement and resistance to low-moderate earth forces Improvement of appearance and performance of structures	Reinforces and indurates soil or fill behind structure into monolithic mass	Pacific and other willows Red osier dogwood Vine maple Ninebark Cascara Salmonberry Snowberry Salal Douglas spirea Red-flowering currant Twinberry

Materials Required

Resloping implies removal from or relocation at a site of materials such as soils, sediment, or unwanted fill. If the material is determined to be suitable, it might be placed on the beach; particularly particularly if it consists of sediment rather than soil or fill. A different suite of materials may be required to be added and include topsoil, mulch, and plants. If the slope gradient allows, topsoil (4-6 in.) and then mulch (10-12 in.) are usually applied to the regraded area.

If possible, topsoil should be scraped off and stockpiled before resloping, then reapplied after. Plants may be acquired from the site, neighboring sites, or commercial nurseries specializing in native plants. Irrigation systems and a water source may be required for the first year, but project design should limit the need after that.

Geotextiles, preferably of a natural biodegradable type, may be needed to get plants established on less hospitable sites.

If deemed necessary during initial site evaluation, erosion of the slope toe may require a component of treatment presented in other sections of these guidelines. This may include rock or large wood placement, or beach nourishment.

Soil Erosion Control Fabric

To ensure that plants become well established, it is important to keep topsoil from being eroded during the initial period following slope regrading. Immediately following grading, it is common to incorporate some type of geotextile as a soil stabilizer until roots take hold. A geotextile is any permeable textile fabric used with soil, sediment, or rock to increase stability and decrease erosion. It is designed to allow water to flow through it, either freely or at some slowed rate, while holding substrate in place. Geotextiles can be natural or synthetic; woven, knitted, or nonwoven (Figure 7.3-7). Different site conditions and performance criteria require different fabric composition and construction. Woven geotextile (similar to burlap), is particularly suitable where high soil-strength properties are needed, but where filtration requirements are less critical.

Figure 7.3-7. Examples of natural (left) and synthetic (right) geotextiles. Additional geotextile fabrics incorporate a combination of natural and synthetic fibers. Generally, natural-fiber fabrics deteriorate more rapidly than synthetic, and may be an appropriate choice where soil instability is a short-term issue and additional stabilization is only needed until plants are established. (Source: Wikipedia public domain; http://upload.wikimedia.org/wikipedia/commons/c/c8/Geotextile-GSI.JPG)

Depending on the objectives of the project, a geotextile may be selected for its properties to:

- Separate differing layers of soil to maintain design thickness.
- Filter, allowing water to move through the soil while retaining upstream soil particles. For example, this may prevent soils from migrating into drainage aggregate or pipes.
- Drain less-permeable soils by creating a lining on or through which to carry water.
- Reinforce soils by producing a composite system that improves strength and deformation properties over those of unreinforced soil.
- Control erosion by intercepting rainfall impact and surface water runoff.

Depending on the intended function of the fabric and nature of the soil and sediment, a geotextile may not be necessary, or a temporary natural fabric might be useful for the very fact that it will degrade in the first few years, contributing natural mulch to the soil. Geotextile fabrics should be secured with wooden pins rather than metal so the pins do not outlast the fabric. Some examples of natural fibers used in geotextiles include jute, coconut, flax, and hemp.

For more challenging sites where severe erosion is likely, a wide variety of longer-lived synthetic or blend fabrics are available and may be necessary. Synthetic geotextiles are petrochemical-based, and may persist long after their intended usefulness. Any application of geotextiles consisting of synthetic fibers should consider the fact that they cause environmental pollution in their manufacture and use, and may ultimately end up as garbage on the slope and beach.

Hydroseeding can be used independent of or in combination with geotextiles to stabilize surface soils and prevent or control erosion.

Timing Considerations

Grading should be carried out to minimize the length of time soil is exposed and should be staged to allow for planting shortly after. In western Washington, grading is usually carried out during the drier summer and early fall months to avoid runoff and excess sedimentation to nearby streams or coastal waters. Planting can then take place in winter to take advantage of subsequent rainfall that reduces the need for irrigation. South-facing slopes may need irrigation in summer regardless for the first year or two. The following is an excerpt from Cramer (2012), Section 5.4.5 on page T5-22, detailing planting considerations:

> Each plant material type has an optimal planting window, summarized in Table 6 [of Cramer, 2012]. Suitable planting periods for each plant material type must be considered and adequately incorporated into project implementation and construction planning. In the Pacific Northwest, the best time to plant is in the fall after the rains have begun. This allows plants a good chance to get established while soil moisture is plentiful and temperatures are still warm enough for root growth. It also allows plants the most time to get established before they have to endure the summer drought conditions of the Pacific Northwest. Winter is the next best time to install plants, with earlier in the season being better. Conifers are able to photosynthesize throughout most of the winter and do not become dormant like deciduous plants in winter time. Spring plantings often fail to establish adequate roots to enable them to survive their first summer drought. Irrigation can make the difference between survival and failure of a spring planting. Summer installation is not recommended even with irrigation except in extenuating circumstances.

Risk and Uncertainty

An assessment of the risk to infrastructure and public safety should be a part of any site being evaluated for resloping. Both long- and short-term considerations should evaluate at the very least, appropriate slope angles, slope height, disposal of excavated materials, site use, and expected vegetation growth and position (particularly for large trees).

As with any project, there are uncertainties in the long-term success of the project that may result from unclear objectives, poor design, unintended site use, inadequate or poor-quality project materials (plants, mulch, etc.), changing site conditions, off-site conditions transferred to the site (surface and groundwater), or external forces such as large storms, waves, and tides. Continued erosion of the slope toe, with or without the resloping, has the potential to reactivate landsliding and bluff retrogression, and runoff from upland areas can reactivate or introduce rilling, erosion, and landsliding.

Cost

Resloping and vegetating is generally a very cost-effective means of bluff stabilization once it is determined to be appropriate for a site. Ideally, planted vegetation will mimic adjacent slopes and possibly have the added benefit of natural seeding and spreading. Regrading a slope generally requires the use of large machinery, but only for the initial work and for a relatively short period of time. Eliminating the need for an engineered structure such as a retaining wall also provides cost and time savings.

Costs associated with resloping and vegetating can vary greatly. The primary controlling factor is the length of slope being treated, with the largest portion of the project cost likely being the earthmoving. It is therefore important to get estimates of cost per linear foot or per unit area to develop the earthmoving portion of the budget. This part of the budget should also consider the volume of earth to be moved, and whether it will be reused on the site or whether and how far it will need to be removed from the site. Mobilizing earthmoving equipment to and from the site can constitute a large portion of the cost and should be limited to one round trip; therefore staging the project carefully is very important.

Other costs to the project include mulch, plants, and planting. These are difficult to summarize as they depend on site conditions, site access, nursery availability, and who does the planting. Projects might be able to enlist assistance and even grant funding from local nonprofit groups or university extension offices. Because of the great variability in cost for the various equipment and materials, a well-developed design is critical in informing necessary quantities for the various project components.

If topsoil is not available on-site (e.g., stockpiled), it may also need to be purchased, particularly for poor soils with little to no organic material.

Drainage management structures can increase project cost significantly, and appropriate surface- and groundwater management is critical to the success of any project. Addressing drainage issues early in the assessment and design process will save money in the long run. Drainage management may include anything from constructing appropriate slope angles and planting appropriate vegetation to complex collection, storage, and conveyance systems.

The cost of ongoing maintenance, such as ensuring vegetation health described below, also needs to be factored into project costs.

Monitoring

Monitoring should be an integral part of every reslope–revegetation project and be used to evaluate site conditions and processes before and after a treatment is installed, as well as provide a measure of the success of the treatment. Effective monitoring is not possible without clearly documented project objectives and final construction documentation, known as as-built drawings. The frequency of monitoring and methods used must be tailored to the monitoring objectives for both the resloping actions and any vegetation planting. Identifying and reoccupying photo points can be a simple, effective, and inexpensive technique for both project aspects. More detailed data can be collected through surveying using low-cost manual equipment, or high-precision GPS-linked equipment.

Whether or not a reslope–revegetation project is deemed successful can be a matter of perspective, necessarily considering the objectives for the site and project. For instance, mitigation of landward erosion would be measurable as one objective. However, if sediment input to the beach environment is a desired outcome of a restoration project involving resloping, then the conclusions drawn from results of these measurements would have a different interpretation and if the resloping was ‘too’ effective in reducing erosion it might be considered unsuccessful. As always, clear project design objectives should be discussed, documented, and monitored with the appropriate questions in mind.

For resloping and revegetation projects, monitoring components should include at a minimum, the following:

- Stability of surface soils
- Stability of underlying sediment
- performance of surface- and groundwater management features
- Condition of slope toe (existence or/and extent of erosion)
- Survival, health, and propagation of plantings
- Required maintenance of slope substrate and/or plantings
- Continued meeting of project objectives

Additional recommendations include:

- Visiting a newly-installed site regularly the first growing season to check plants, control weeds and assess need for irrigation.
- Write success criteria so that volunteer desirable native plants also count towards meeting the criteria.
- Use reference sites to compare to the restored sites to better understand how project site is progressing.
- If experimental techniques are used, set aside a sufficient portion of the budget for monitoring - quantitative monitoring may be justified to document the advantages/disadvantages of the technique.
- On sites where herbicides are applied, the monitoring area should include adjacent areas within “drift range” of herbicide application.
- Use monitoring activities to identify threats to project success.

Additional information regarding project monitoring elements and protocols is described in Chapter 8 *Monitoring*.

Maintenance

Management of vegetation often requires ongoing control of invasive plants and possible replanting of some native species found to be unsuitable for a particular site (soil moisture, aspect, etc.). A temporary irrigation system, or hand watering, may need to be a component of the first year or two of a project to get plants established. The need for irrigation (and watering in general) depends on aspect, soil moisture, availability of site-adjacent plants for natural recolonization, and practicability of regular maintenance. Irrigated sites must be inspected often to ensure the system is functioning. Watering heavily and infrequently encourages deep root growth for drought tolerance; keeping in mind that small root balls hold a small amount of water, so watering of newly- installed plants may need to be more frequent.

As a potential contributor to the beach of LWD and detritus, vegetation can be successful and beneficial if allowed to topple and slide to the beach through natural processes. Large trees in particular, with branches and roots intact, serve to trap sediment and attenuate wave energy, thereby reducing erosion of the bluff or bank toe.

Trees can be managed as they grow to allow for views (Menashe 1993). A professional arborist should be consulted to achieve the view objectives while preserving the health of the tree(s), and to assure compliance with any regulatory constraints under local shoreline management plans. Project objectives should guide vegetation planting plans to provide the site-appropriate combination of improving slope stability, establishing healthy native plants, and maintaining views. This speaks to the importance of encouraging the various specialists involved in the design, permitting, and construction process to work collaboratively. Deviation from the plan through changes in long-term management strategies might compromise any or all of the original project objectives.

Because vegetation alone cannot be expected to mitigate all slope instability, it is critical to plan for appropriate setback of any structures as well as to thoughtfully consider drainage and surface- and groundwater management for the sites. These will need to be factored into the long-term maintenance costs of sites evaluated for any reslope–revegetation projects.

Any sign of rill or gully erosion should be immediately investigated and repaired as needed (Fig. 7.3-5).

Browsing by deer can also damage and kill new vegetation. Excluding deer from an area requires fencing at least 6 ft high. Other methods that have had mixed success include applying liquid deterrents (such as coyote urine).

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Chapter 7. TECHNIQUE 4
BULKHEAD REMOVAL

Description

Landowners install bulkheads and other forms of shore armor to stop wave attack and erosion, or to reclaim tidelands for upland uses. Armor has been installed in many locations throughout the region where coastal erosion is not a real threat. For example armor exists along many shores with insubstantial erosion in which the bulkhead serves as more of a landscaping feature. Other examples of unnecessary armor include bulkheads used to curb erosion in locations where the natural process is not a pending threat to buildings, roads, or other major structural improvements. There are many examples of armored waterfront parcels with no roads or structures present. Increased awareness of the impacts of shore armor on nearshore ecosystems and sediment transport processes has led to an increase in the popularity of bulkhead removal projects.

There are several examples of armor removal projects in the region, with a large number of projects recently completed or underway. Complete bulkhead removal can restore nearshore processes and habitats by returning the beach and backshore areas to natural or predevelopment conditions. Existing unnecessary armor is also increasingly being relocated (landward) or reduced in scale (length), to lessen the impact and enhance or restore coastal processes. Either complete or partial removal can ameliorate degraded nearshore conditions associated with armor such as allowing sediment input from feeder bluffs, littoral (longshore) drift, exchange of nutrients and other organic material, and the restoration of intertidal and backshore habitat areas. Armor removal can also enhance recreational values by improving beach access, increasing beach area and aesthetics, and lowering the slope of the beach.

The most common types of bulkheads removed include rock revetments, rockery walls, and vertical bulkheads constructed with concrete, large rocks, treated wood, or wood piles. Examples of these are shown in cross section, some of which have fill placed landward of the bulkhead which may need to be removed as well (Figure 7.4-1). In many cases, bulkhead removal is applied in combination with other techniques such as backshore and marine riparian vegetation plantings (*Reslope/revegetation*), beach nourishment, or large wood placement.

Application

Bulkhead removal or modification is appropriate to consider at most beach and bluff shores where a bulkhead is present, though it may not be feasible at every location. Bulkhead removal can be deemed feasible if an existing house or road is unlikely to be threatened by bluff/bank recession now or in the future, or if a (potentially) threatened house or road is deemed unsafe or is being relocated landward out of harm’s way. If the site has low to moderate erosion rates and a reasonable setback distance, removal may be feasible. If no structure or road is present landward of the armor, feasibility is likely. Additional data from the site assessment (discussed in Chapter 3) should be evaluated to further explore feasibility.

Bulkhead removal and modification are conducted to meet a variety of objectives, although in most cases the project’s objective is to restore or enhance beach and backshore areas to approximate natural or predevelopment conditions for recreational and other uses. An analysis of coastal processes and coastal hazard assessment should be conducted before considering bulkhead removal; if removal would not result in considerable risk to infrastructure on the property, then it is reasonable to move on to the design stage. Additional analysis should be carried out to determine if archeological or cultural resources are present in the bulkhead area, as outlined in Chapter 3 *Site Assessment*.

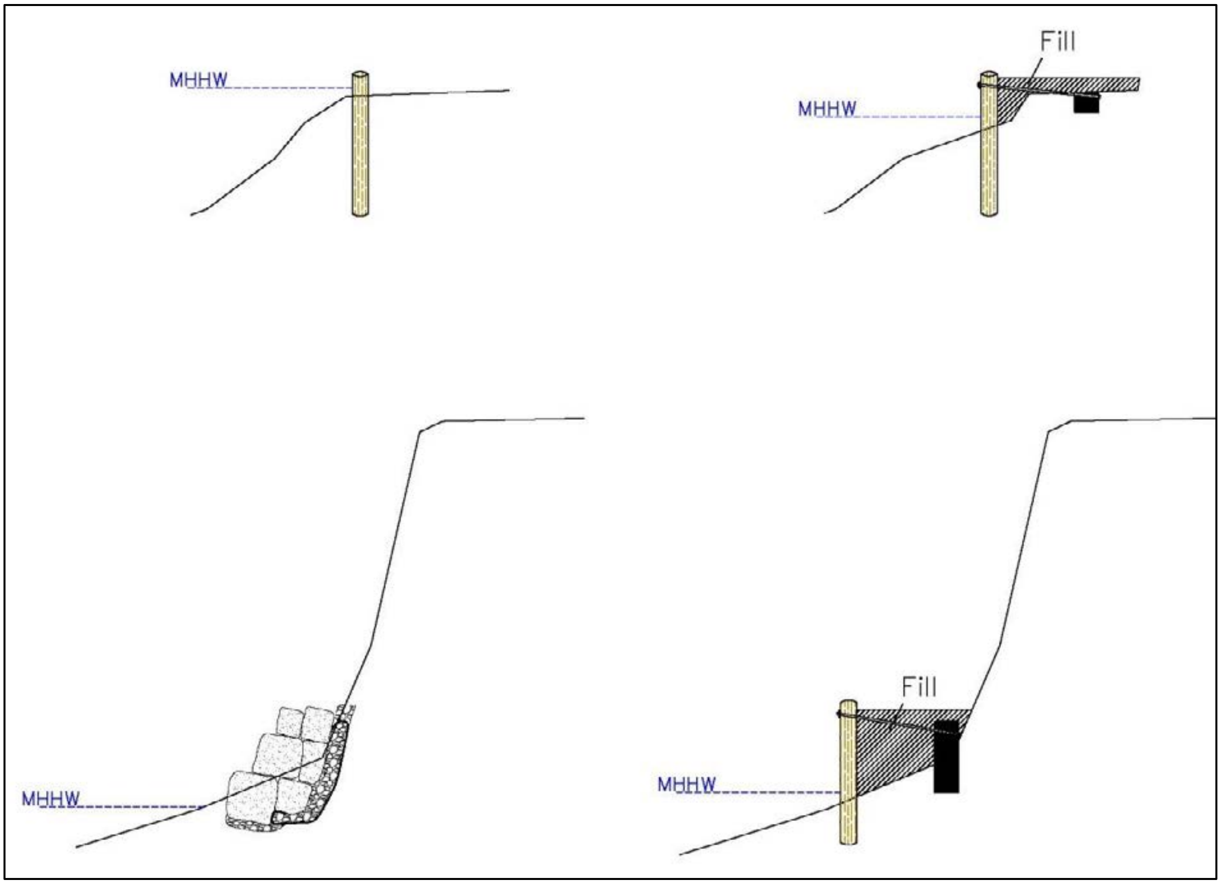

Figure 7.4-1. Typical barrier beach and bluff bulkhead cross sections with and without fill.Top left: Typical barrier beach site with no or minimal fill landward of vegetated (soldier) pile bulkhead. Top Right: Typical barrier beach site with fill placed landward of vertical bulkhead, along with tie-backs and deadman anchors. Bulkhead at MHHW. Bottom Left: Typical bluff site with no or minimal fill landward of (rockery wall) bulkhead, which is above MHHW. Bottom Right: Typical bluff site with fill placed landward of vertical bulkhead, which extends below MHHW.

As discussed below, complete bulkhead removal is not feasible at all sites. Bulkhead removal in Puget Sound has become more common on public lands, including projects located on land owned by cities, counties, Washington State Parks, and the Washington State Department of Natural Resources, as well as Tribal lands.

Bulkhead removal projects can involve a single property or a group of adjacent properties. Even when a bulkhead removal site is focused on a single property, it is important to inform adjacent property owners and ensure that additional erosion will not place neighboring structures at risk. Removing armor from two or more adjacent bulkheads has occurred in recent years, where landowner willingness was acquired from all of participants across a reach of shoreline. Such was the case at the north Orcas Island bulkhead removal and beach nourishment site in Appendix A.

Bulkhead modification may include changing the location or dimensions of a structure, with the goal of reducing its size and impacts (Clancy et al. 2009). This often consists of shortening a bulkhead or reconstructing a reduced length structure in a more landward position. Modifying existing armor structures may be appropriate where circumstances preclude complete removal, such as where the risks to upland development from natural erosion are unacceptable. However, complete bulkhead removal is typically much less expensive than bulkhead modification.

Engineered erosion control structures placed on marine shores are subjected to wave attack, log battering, end-scour, undermining, and material deterioration. The structures are the strongest on the day that construction is completed and weaken from that day forward, with typical functional lifespans of 20 to 50 years (depending on the material and quality of construction and design). Examples of highly degraded bulkheads are shown in Figure 7.4-2. Considerable lengths of shoreline armor were installed prior to the Shoreline Management Act and are reaching the end of their functional lifespan. Between January of 2005 and December of 2007, 389 existing bulkheads were replaced on Puget Sound shorelines, primarily due to structure deterioration (Carman et al. 2010).

Figure 7.4-2. Degraded bulkheads deteriorating in place.

Property owners may be more willing to consider relocation or removal alternatives when they are contemplating replacement of an existing structure. For many unstable bluffs, it may be more cost effective over the long run to relocate houses (or other improvements) landward than to permit, build, mitigate, and maintain a bulkhead in a chronically eroding location. This is due to the repeated expenses of repairing structures and surrounding areas following damage, including the many design, impact avoidance, and permit requirements, in addition to mobilization and construction. Simply allowing a bulkhead that is constructed of untreated wood to deteriorate in place can be a viable option to achieve bulkhead removal over time at virtually no cost.

Effects

The primary intent of bulkhead removal is to restore natural coastal processes and habitats. Bulkheads have varying degrees of impact generally related to disruption and alteration of shoreline processes (Shipman et al. 2010) which removal aims to reverse. The area that benefits from removal ranges from the footprint of the armor at the site to extensive reaches of shore off-site. The greatest spatial extent of benefit resulting from a bulkhead removal project would be the extent of down-drift shore within the drift cell (which would include the down-drift shore from both adjacent cells if the project occurred within a divergence zone), or in the case of a pocket beach the full extent of the shoreform. Direct restoration is achieved by recovering buried nearshore habitat directly beneath bulkheads and other types of armoring. Physical processes restored by bulkhead removal include sediment input (feeder bluff function), littoral drift, sediment deposition at down-drift shoreforms such as spits, and large wood input, which can enhance the stability of down-drift shoreforms (Figure 7.4-3). Restoration of upland and alongshore connectivity of sediment, hydraulics, and vegetative successional processes can facilitate wildlife movement by helping to connect habitats, which include the marine riparian zone (Clancy et al. 2009). Removal or modification of bulkheads that infringe on the intertidal zone can also improve the connectivity of juvenile salmonid migratory habitats and forage fish spawning habitats.

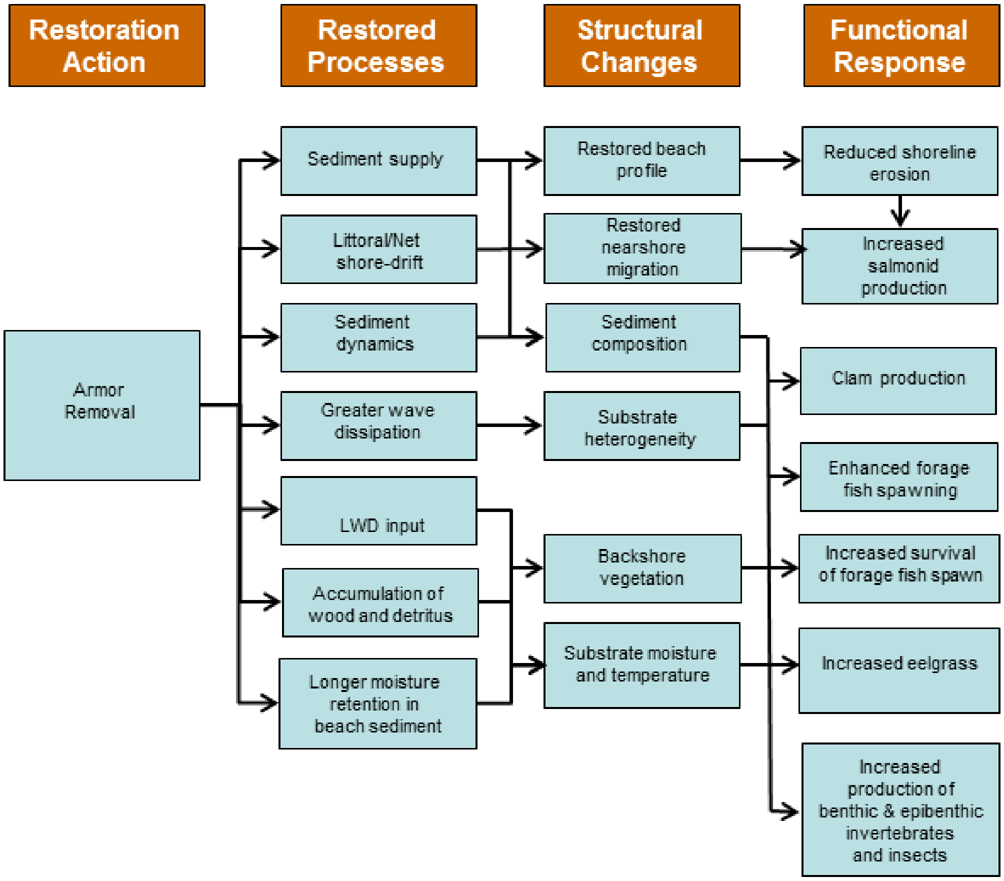

Figure 7.4-3. Conceptual model for armor (bulkhead) removal from the *Management Measures Technical Report* (Clancy et al. 2009).

Bulkheads alter or disrupt wave energy, which can affect coastal processes and habitat in several different ways. The physical presence of the structure along feeder bluffs can eliminate recruitment of bluff and upland sediment that would have otherwise “feed” the beach through landslides and erosion. Disrupted sediment supply affects beach profiles and substrate characteristics on site as well as down-drift (as also discussed in Chapter 1). Bulkheads on all Puget Sound shores—particularly vertical-face bulkheads—can result in increased reflected wave energy, which can lead to coarsening of beach sediment (Kraus 1988, Macdonald et al. 1994) and increased entrainment (causing turbidity) and transport of littoral sediment (Miles et al. 2001). Impacts are greatest when bulkheads are sited where interactions with wave and tidal forces are greatest. Bulkheads can also cause lowering or vertical erosion of the beach profile waterward of a structure (creating a scour trough), cause end scour along shores adjacent to a structure, and cause reduced beach width. Erosion at the base of a bulkhead can undermine the bulkhead footing and cause part or all of the structure to topple. Each of these impacts will likely be exacerbated by changing conditions resulting from climate change and sea level rise. Bulkhead removal is intended to remove the suite of impacts caused by bulkheads.

The common benefit seen among all bulkhead-removal case study sites (see Appendix A) was some degree of augmented sediment input. Beach nourishment was not a component of any of the four bulkhead-removal projects; therefore the sediment composition at the project beaches was dependent solely on local sources. The beach sediment at all of these sites matched adjacent reference sites, which indicates that beach (substrate) conditions were successfully restored. The recent Seahurst Park south bulkhead and fill removal project (not included in Appendix A case studies) had a primary restoration goal of feeder bluff connectivity to the beach (Hummel et al. 2005), a goal shared by PSNERP for a number of potential projects.

In many Puget Sound locations, diverse landforms with a variety of microhabitats historically occurred close together. The diversity of these landforms and the microhabitats found within them are in decline due to extensive modifications which tend to simplify and straighten the shoreline (Fresh et al. 2011). Many nearshore fish and wildlife species rely on functioning high intertidal habitats to provide food sources, migration corridors, cover, and spawning habitat (Brennan 2007). Removal of shore armor can reverse the burial of habitats (placement loss) such as forage fish spawning areas and backshore areas, where drift logs and vegetation create important microhabitats. Restoration of cross-shore connectivity through bulkhead removal can restore overhanging riparian vegetation, LWD recruitment and storage, and groundwater connectivity (Brennan 2007). Bulkhead removal case study sites were considered successful at restoring LWD processes if large wood was available for recruitment as a result of bulkhead removal or was expected to do so in the future. The mature forest and active deep-seated landslide movement at Kopachuck State Park resulted in considerable large wood input associated with bulkhead removal at the site.

Along bluff-backed beaches, bulkhead removal and the restoration of nearshore sediment sources increases the resilience of down-drift shores, which require continued sediment input to naturally adapt to the landward migration of the shoreline (Johannessen and MacLennan 2007; an example is Kopachuck State Park in Appendix A). Bulkhead removal will also preserve intertidal areas that would otherwise be threatened by sea level rise due to a phenomenon referred to as the ‘coastal squeeze’, in which intertidal area is squeezed between a static shoreline (such as along an armored shoreline) and the landward migrating shore. Similarly, removing bulkheads increases the available beach area, which enhances their aesthetic and recreational value, particularly during higher tides.

Four bulkhead removal case study sites were assessed in the first phase of this project (Figure 7.4-4 shows before and after images; more detail is in Appendix A). These bulkhead removal projects are located in four very different Puget Sound environments with contrasting wave regimes ranging from low (Weyer Point in south Puget Sound) to medium (Kopachuck State Park in central Puget Sound) to very high (Birch Point in northern Whatcom County). In evaluating the benefits gained versus impacts realized in bulkhead removal, slightly different perspectives were applied to each project based on the objectives of the removal effort. These included reestablishment of sediment connectivity, removal of creosoted wood from the marine environment, and enhancement of the restoration of a DNR Natural Resource Conservation Area. In some cases the objectives overlapped. Photos from before and after bulkhead removal from case study sites and other projects not surveyed for this effort are found in Figure 7.4-5. These images demonstrate the wide variety of conditions where this technique has been employed in recent years.

Deer Harbor Pool – Before (CGS, 2006)

Deer Harbor Pool – After (CGS, 2008)

Weyer Point – Before (WDNR, 2005)

Weyer Point – After (2012)

Birch Point – Before (CGS, 1999)

Birch Point – After (2012)

Kopachuck State Park – Before (CGS, 2006)

Kopachuck State Park – After (2012)

Figure 7.4-4. Before and after images of bulkhead removal projects surveyed for this study (Appendix A).

Powel Site, Bainbridge Island – Before (CGS, 2010)

Powel Site, Bainbridge Island – After (CGS, 2012)

Piner Point – Before (King Co.)

Piner Point – After (King Co.)

Olympic Sculpture Park – Before (City of Seattle)

Olympic Sculpture Park – After (2012)

Blakely Island – Before (CGS, 1999)

Blakely Island – After (CGS, 2002)

Figure 7.4-5. Before and after images of bulkhead removal projects not included in this study.

Design

The primary purpose of bulkhead removal is typically to restore or enhance nearshore ecosystem processes and functions to increase beach resiliency, habitats, and recreation value. All potential outcomes, including those affecting land uses, should be assessed in the preliminary phase of the bulkhead removal project. The scope and level of detail for assessing feasibility will depend on the project size and location, degree of certainty required (cumulative risk), and documentation requirements of permitting agencies. A small site without upland development near the shore warrants a low level of detailed feasibility assessment while a larger site with valuable upland development will require more in-depth analysis to determine feasibility.

Bulkhead removal case study sites covered a wide variety of settings and levels of development. A thorough review of the original objectives of the installation, bulkhead design, as well as geologic and engineering documentation of the design parameters should be evaluated at the onset of project planning.

There are many factors to consider in the design of bulkhead removal projects including:

- Fill and anticipated erosion
- Effect on adjacent shores
- Slope stability
- New design elements (large wood, sediment/nourishment, slope or backshore vegetation, or structures)
- Potential engineering requirements
- Bulkhead material disposal
- Cost

Analysis for bulkhead/armor removal was divided into feasibility, design, and evaluation phases in the *Management Measures for Protecting and Restoring the Puget Sound Nearshore* (Clancy et al. 2009). That document addresses the general stages of analysis for bulkhead removal, including those carried out in several disciplines, which provides a very useful framework. More specific guidance is provided below in this document. Analysis for bulkhead removal typically involves qualitative work and does not rely on numerical models for assessment and design. Only large, complicated sites with significant risk require intensive analysis, such as wave or slope stability modeling.

Project designs should explain the uncertainties that exist regarding geomorphic and engineering parameters. Ideally the range of possibilities for anticipated outcome and associated risks relative to that range should be discussed. The factor of safety for a residence or large building should be considered more thoroughly than for landscaping or lawn/forest. The scope and design factor of safety should be consistent with the anticipated outcome of the project (bulkhead removal versus modification), specific location, and type of change anticipated.

Fill and Anticipated Erosion

A site feasibility assessment will help determine if bulkhead removal is a viable option for a given site. Of highest importance is an analysis of the amount of fill that may have been placed at the site at the time of bulkhead installation, and an estimate of the likely erosion that may occur after the bulkhead is removed. Estimating the volume of fill at a given location can be achieved by examining the original bulkhead designs (if available), aerial photographs (if of suitable quality to measure shoreline geometry), or analysis of the soils directly landward of the bulkhead. Generally speaking, the greater the volume of fill, the more rapidly that material will erode as the beach naturally adjusts to a more natural (landward) shoreline position. Ideally, if the fill material is non-native it should be removed so that the beach can naturalize.

Determining how the fill material (and shoreline) will respond to bulkhead removal can be conducted by comparing and analyzing historical (and current) conditions at the subject site. Historical analyses would typically include comparing the current and historical position of the shoreline using regional GIS data (Collins and Shiekh 2005) with maps or aerial photographs. Historical (vertical) aerial photography can be georeferenced and analyzed to measure historical erosion rates at the site. Ideally historical site trends can be explored (both the erosion/accretion) prior to bulkhead removal. However, this is not always possible due to limited data and the ability to assess historical conditions at some shaded sites using air photos.

If historical data sources are lacking and examination of soils is inconclusive, another method of estimating erosion or accretion trends following removal can be the use of an appropriate nearby reference site. Reference site selection is critical. A site with very similar wave energy, orientation, shoretype, sediment type, and littoral drift is best for analysis. The reference site needs to be an unarmored site with very similar coastal geomorphic and geologic conditions. Ideally, a reference site from the same drift cell is used in order to reduce variables, or if that is not possible, a reference site from a nearby area which closely matches site conditions should be used. A reference site with different conditions can be very misleading and should not be used.

Assessment of site suitability and design development for bulkhead removal must include characterization of wave climate (Chapter 4, *Coastal Processes*). For most Puget Sound sites this consists of characterizing the major and minor wave fetches to determine the general level of wave energy reaching a site. Sites which are exposed to southerly quadrant fetch experience a relatively greater degree of wave forcing and usually have greater potential erosion rates than sites without southerly fetch.

Effect on Adjacent Shores

If the bulkhead removal site has a bulkhead extending to a shared property line, consideration must be given to potential erosion which may be caused by end effects on the site following removal. Examples where a bulkhead is contained within a property with no adjacent bulkheads, and a property where bulkheads are immediately adjacent are shown in Figure 7.4-6. End effects from the adjacent armored shore are likely to exacerbate erosion along the newly exposed bank or beach. This is due to wave refraction occurring around the end of the adjacent armor focusing scour on the project shore. This would be an issue which must be considered in design of bulkhead removal for the example on the right. If the site is erosional or subject to moderately high energy waves, implementation of additional design techniques to abate end effects may be needed to avoid erosion adjacent to the remaining armor in this case. This is especially true in the case on the far right of the image where the neighbor does not have a return wall. These techniques may include beach nourishment, and/or large wood installations (see Figure 7.2-3f for an example). Also see the *Potential Additional Design Elements* section below.

The length of the subject site shore should be considered, as end-effects can extend up to 15 to 30 ft or more from the end of the armor. The length of shoreline subject to end-effects is a function of the bank/beach geology, wave energy at the site, the angle of wave approach, angle of the return wall, up-drift sediment supply, and the construction material of the structure.

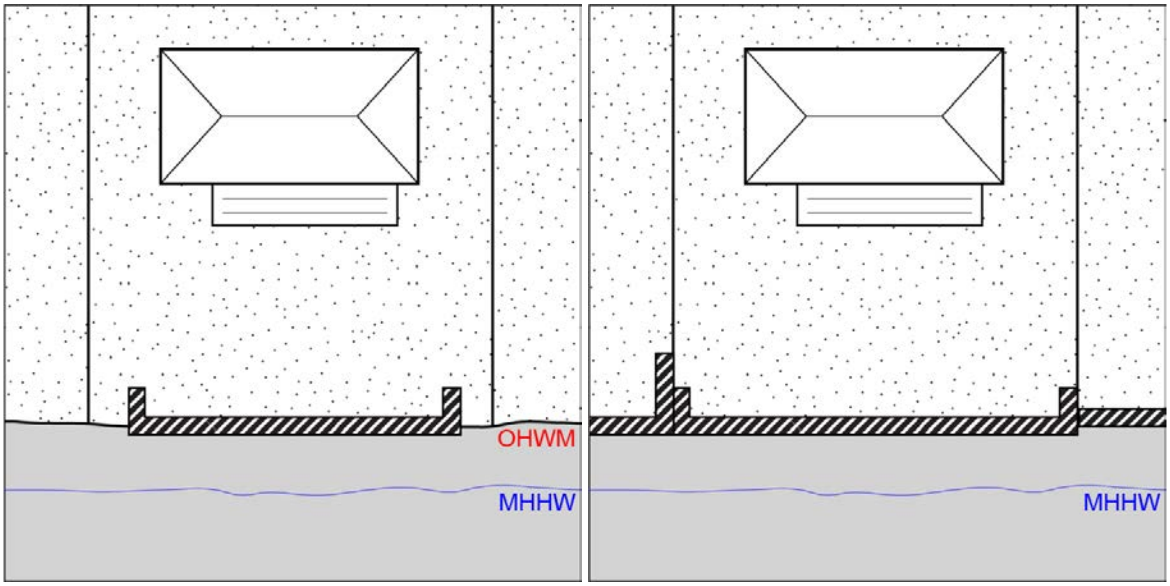

Figure 7.4-6. Sketch of 2 different bulkhead removal scenarios with and without bulkheads on the property line. Where adjacent bulkheads meet the removal area (right), the design will have to consider potential end erosion from the remaining adjacent bulkheads.

Slope Stability

In order to predict with any certainty how the site will evolve over time after bulkhead removal, a geologic slope stability evaluation is required. This is particularly important when the bluff is high or where there is risk to structures or safety concerns. Data from the site assessment and coastal processes assessment is essential for the determination of slope stability related to bulkhead removal. More information regarding what should be included in these assessments is described in Chapters 2 and 3.

Geologic and geotechnical studies consider:

- The strength and cohesion of on-site soils
- Hillslope stability
- The interactions of surface and groundwater

Analysis should include the natural features as well as areas altered by development and address surface water flow and any potential drainage control issues during the design development.

A feasibility assessment for bulkhead removal should evaluate the risk and uncertainty for different project scenarios. The severity of risk can range from intermittent minor erosion, to damage to site improvements, to loss of adjacent improvements or infrastructure.

Potential Additional Design Elements

Bulkhead removal commonly includes some additional enhancement actions such as *Beach Nourishment* and *Reslope/revegetation*. The necessary steps required to identify critical elements to design and the need for inclusion of additional design techniques are outlined below.

The design elements considered at a given bulkhead removal site range from: complete bulkhead removal, to removal and replacement with soft shore protection such as beach nourishment, large wood, and/or vegetation installation, to a new or relocated bulkhead structure with fewer negative impacts. Bulkhead removal and modification projects should attempt to maximize the restoration of natural processes while balancing the need for human safety. It is important to consider the anticipated trajectories of the site with and without different elements installed with regard to the project goals. Overall, a removal design that includes large wood placement, revegetation, and beach nourishment can provide enhanced habitat conditions and productivity; however, some sites do not require these elements.

An analysis using existing site and adjacent site data should be conducted to determine the need for these additional actions to achieve enhanced habitat and/or other goals of the project. For example, some sites simply require removal of the bulkhead to expose native beach and backshore sediment, while others require a large volume of excavation and removal of non-native and non-compatible sediment from the bulkhead area. For this reason, some amount of exploratory investigation into soil/material composition must be made prior to developing the detailed approach and design. For small sites this typically consists of hand-dug test pits or a limited number of shallow cores with a hand auger. For larger sites it may require a series of auger holes or test holes excavated with a backhoe or similar equipment. A site with non-native and non-compatible soils would generally require beach nourishment. (Refer to Chapter 7.1 for details on beach nourishment approaches.) Other sites that have experienced long-term profile lowering due to some combination of bulkhead-induced erosion and cumulative impacts to the drift cell, and that are of suitably low energy to retain placed sediment for some time, should also be considered for nourishment.

Bulkhead removal sites also need to be evaluated to determine if large wood or vegetation would measurably improve habitat conditions and provide a more favorable site trajectory. Some sites have ample input from natural processes transporting LWD alongshore, and the material simply needs space in the backshore to deposit. Some areas have little LWD in the system and would benefit from the placement of imported large wood, which may help the site evolve favorable habitat conditions much faster than if wood was not added.

Another approach to removing a bulkhead is to simply allow a failing bulkhead to disintegrate to the point where it is gradually eroded away and the beach restores itself. This is only advised where the bulkhead is constructed of untreated wood or logs which will then become part of the natural LWD in the drift cell. Often these types of bulkheads contain former beach or bank sediment that was used as fill, however this should be verified before allowing structure to simply disintegrate. If non-native soil such as construction debris or other exotic material was used as fill, these portions of the fill should be removed from the marine environment. Wood that has been treated in any way should always be removed from the marine environment as it contains chemicals known to be toxic to marine life. Rock from failing rock revetments or rockery walls should also be removed.

Climate change and sea-level rise will accelerate coastal erosion and bulkhead removal sites will be vulnerable to this increased erosion. This underscores the importance to plan conservatively and realistically so that property owners are not surprised and support continues for this type of restoration.

Potential Engineering Requirements

Several situations may necessitate the need for engineering analysis and design at bulkhead removal sites. These situations include the following:

- A replacement bulkhead in a more landward position or of a shortened length.
- Reconstructing a beach access stairway on an unstable slope.
- Relocating utilities away from a removed bulkhead.
- Redesign of a dock landing, boat ramp or other built feature.

Altering or partially replacing a bulkhead, referred to as armor modification in the Management Measures report (Clancy et al. 2009), requires engineering analysis and design. It is always the preference for habitat restoration to completely remove a bulkhead, however sometimes this is not feasible due to potential risk to a portion of the property. Ideally a modified bulkhead is reconstructed in a significantly more landward and shortened configuration as compared to the bulkhead being removed. Design guidance, including for minimizing negative impacts from bulkhead construction, can be found in Chapter 7.5 *Hard Armor*.

Construction of beach access stairways at bluff properties often rely on a bulkhead for the stairway landing. Bulkheads typically provide protection from wave attack for these landings. If a bulkhead is to be removed with an existing beach access stairway, structural engineering may be required. Best design practices for minimizing impacts to the beach require the most minimal footprint possible for the stairway landing. Additionally, a short (approximately 4 to 6 ft long) hinged stair section may be used for the lowermost portion of the stairway. This allows the hinged portion to be folded up during winter or other stormy periods to avoid damage.

In some small barrier beach or other no bank parcels, site utilities may be located in close proximity to the bulkhead being removed. These utilities would need to be relocated further landward as part of the project, requiring engineering and coordination with utility providers. It is important to consider the long term implications of sea level rise and climate change for this type of relocation.

Some coastal parcels have docks, piers, boat ramps, or other water-dependent structures in close proximity to or landing on top of a bulkhead to be removed. A generally greater level of engineering analysis and design would be required for modifying these structures, as compared to other topics addressed in this section. It is beyond the scope of this document to provide engineering guidance for modifying these structures, however the same general principals of minimizing footprint of structures over the beach and back shore, avoiding the use of treated wood or other toxic materials, and siting structural elements as far landward as possible apply.

Modification of any of the above listed structures would also require demolition of the pre-existing structures. Disposal of materials must be completed in approved upland facilities.

Bulkhead Material Disposal

Bulkhead materials require proper disposal. Some materials can be salvaged for reuse, which is recommended as it minimizes both disposal costs and the use of new materials for other projects. It is very important to ensure that all components of the bulkhead to be removed are inventoried prior to project implementation. Some bulkheads have structures below ground and most bulkheads are embedded below the surface of the beach for stability. If original design drawings are not available, digging test holes by hand immediately waterward of the bulkhead can help quantify the amount of material below grade. Most vertical bulkheads have varied tiebacks and deadman anchors, which are not always apparent from the face of the wall. One feature to look for is the ends of bolts on the waterward face of a bulkhead. Again, if design drawings are not available, digging test holes landward of the bulkhead can locate tiebacks—although this can be laborious. Soldier pile walls almost always have tiebacks and anchors. All of this material should be removed, particularly in light of the fact that creosoted wood was sometimes used for these anchor systems.

Rock is typically easily salvaged and reused, but efficient reuse requires sorting into several different rock sizes prior to exporting the material from the site. However, sorting can be accomplished in a construction yard or other facility with little difficulty.

Concrete removed through bulkhead removal or related activities should be sent for recycling. Recycling facilities are becoming more common and are not difficult to find or reach. Metal removed from bulkheads or related structures can also be recycled. Parts with a large amount of rust or corrosion may not be recyclable.

Bulkheads constructed of drift logs or untreated log boom logs present another variation on the theme of reuse. Wood pieces that are free of contaminants and treatment can be left on the beach after deconstruction. This material will contribute large wood to the beach system, which has been reduced in recent decades do to development and more careful log handling practices. Leaving un-treated wood on the beach is generally justifiable due to the many benefits of wood, and the fact that this would be without cost, in contrast to costs incurred when logs are purchased and delivered to restoration sites.

Creosote treated or other treated wood products must be disposed of in an approved facility. Creosoted wood is highly toxic to marine fish and wildlife. All creosote treated wood including small pieces and fragments should be retrieved and removed from the project site.

Site Access

Planning for equipment access to the site needs to occur during the design phase. Demolition of the bulkhead, export of these materials, and import of any other material requires equipment that must be brought to the site and then taken away. Different access methods have different associated costs. Some sites are easy to access from the land side; others will require a barge. Planning around the maximum size of equipment that can reliably access the site is required.

Access from the land side requires direct road access adequate for heavy equipment. All standard county and city roads should be suitable, but any narrow or winding driveways in the final approach to the site may be the limiting factor. An access route with minimum curvature should be determined for projects planning to access the site from land. Occasionally, load limits are present for bluff access routes, and these should be investigated. Note that these limits are not always stated or made known in the case of private access routes.

If the site is a barge-only site due to limitations for land side access, constraints to access also need to be investigated. Data needed for planning barge access includes offshore depths, location of eelgrass or other submerged aquatic vegetation, and permit requirements.

Other cost considerations include the location of all utilities, equipment availability, and bulkhead and fill disposal options. Access and demolition staging areas should be planned to avoid excessive impacts to upland vegetation, water features, adjacent habitats, septic drainfields, and wells.

Cost

The cost of removing a bulkhead can vary greatly depending on access and transportation (land vs. barge), the type and quantities of materials removed, and the amount of additional measures designed and installed. In general, bulkhead removal projects cost considerably less than bulkhead construction.

One important method to control costs is to have as much of the fill and other materials removed from the bulkhead area used on-site, as this will minimize haul out and disposal charges. This can be accomplished by using fill or structural elements such as rocks for modifying upland landscaping, landward of the beach and backshore. The North Orcas Island site in Appendix A is an example of this, where rocks from the removed revetment were buried landward of the beach and also used for garden features further landward. Hazardous material disposal can be an unanticipated expense that can add significant cost, such as happened at Kopachuck State Park.

Monitoring

The area of beach and backshore uncovered by bulkhead removal is the most direct measure of habitat improvement. Measuring restored functions (such as increases in backshore vegetation area or density in the vicinity of the project, use of the restored beach by forage fish for spawning, etc.) in and surrounding the footprint of the old bulkhead is valuable and relatively straightforward. However, change in down-drift habitat areas or production is far more difficult to quantify. The rate of sediment input from bluffs where bulkheads are removed can be quantified through repeated bluff toe and bluff face surveying to provide an indication of potential off-site benefits from the project. A total station with reflectorless capabilities or a terrestrial LiDAR system can be used to survey bluff faces, negating the need for a person to climb the bluff.

Project proponents should create a monitoring plan to assess post-construction project performance and maintenance needs whenever possible. Including an adjacent reference site in a relatively natural condition is recommended. As always, acquiring pre-project baseline data is critical to an effective monitoring program. This would ideally include pre-bulkhead construction and pre-bulkhead removal, which would then be compared to as-built conditions, and follow up monitoring. Additional information regarding methods is described in Chapter 8 *Monitoring*. The effectiveness of armor removal or modification can be measured by collecting data or observations on the following (Clancy et al. 2009):

- Topographic stability, sediment erosion, and accretion
- Sediment characteristics and available habitats
- Accumulation of wood
- Soil moisture and temperature
- Backshore vegetation

Additional information regarding project monitoring elements and protocols is described in Chapter 8 *Monitoring*.

Maintenance

The anticipated maintenance of a bulkhead removal site needs to be considered in advance and also compared to the maintenance of a bulkhead in the same location. Designing for possible beach renourishment or vegetation maintenance at a site with improvements close to the shore may be required for bulkhead removal projects. When completing the design process, it is recommended that an attempt be made to design the project such that no maintenance will be required for a minimum of 15 to 20 years. This will keep the project affordable over time, limit site disturbance, reduce the need to obtain additional permits, and prevent the need to gain subsequent access to the site.

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Chapter 7. TECHNIQUE 5
HARD ARMOR

Description

Revetments and vertical bulkheads are two common forms of coastal erosion control structures which have been used in Puget Sound. Together these approaches to mitigating coastal erosion are commonly referred to as hard armor. The design guidance provided in this section is tailored specifically for Puget Sound shores and does not represent an exhaustive review of the topic. When designing hard armor the engineer should also consult the most relevant references available on the topic, most notably the following:

- Coastal Engineering Manual (CEM), US Army Corps of Engineers (Basco 2006, Burcharth and Hughes 2002)
- Shore Protection Manual (SPM), US Army Corps of Engineers (CERC 1984)
- Introduction to Coastal Engineering and Management (Kamphuis 2010)
- Random Seas and Design of Maritime Structures (Goda 2010)
- Basic Coastal Engineering (Sorensen 2006)
- Coastal Processes with Engineering Applications (Dean and Dalrymple 2002)

It should be noted that locally in the Puget Sound region that the terms ‘bulkhead’, ‘revetment’ , ‘rockery’, and ‘seawall’ are commonly used for hard armor structures. The most common term used for coastal armor is ‘bulkhead’. To differentiate between the different techniques and the varying associated design constraints, ‘revetment’ will be used for structures made of sloping, stacked armor stones while ‘vertical bulkhead’ will be used in this report for vertical structures. Figure 7.5-1 below shows examples of a typical bulkhead and revetment used in the context of this report.

Figure 7.5-1. Photos showing a revetment (left) and vertical bulkhead (right).

Revetment

A revetment is a hard shore armor technique that uses stones to form a sloped, permeable structure. The rock revetment has a long engineering history as a protection measure on both marine and riverine banks. Revetments have several advantages when compared to vertical bulkheads. For example, the rough surface of revetment armor stones reduces wave runup more than smoother types of armor and therefore a shorter design height is possible. Stones are cost effective and readily available. Proper placement of the stone and the underlying filter materials contribute to the success of the protection from a revetment.

The basic features of a typical revetment are shown in Figure 7.5-2. The outer stones that face the waves are called armor stones and are sized to remain in position when subjected to the wave energy predicted for the site (design wave energy). The largest armor stone is placed at the toe which is the most waterward and lowest in elevation. Revetments usually have at least one more layer of smaller rock material beneath the armor stones that creates a bedding layer. In Puget Sound, the quarry spalls which generally comprise this bedding layer also allow for drainage behind the structure. Geotextile fabric is also typically used in Puget Sound as a filter fabric between native sediment and the quarry spall bedding layer. Revetments extend below grade to the embedment depth and upwards with a consistent slope to the design crest elevation. Guidance on how to determine the design criteria is described later in *Design*.

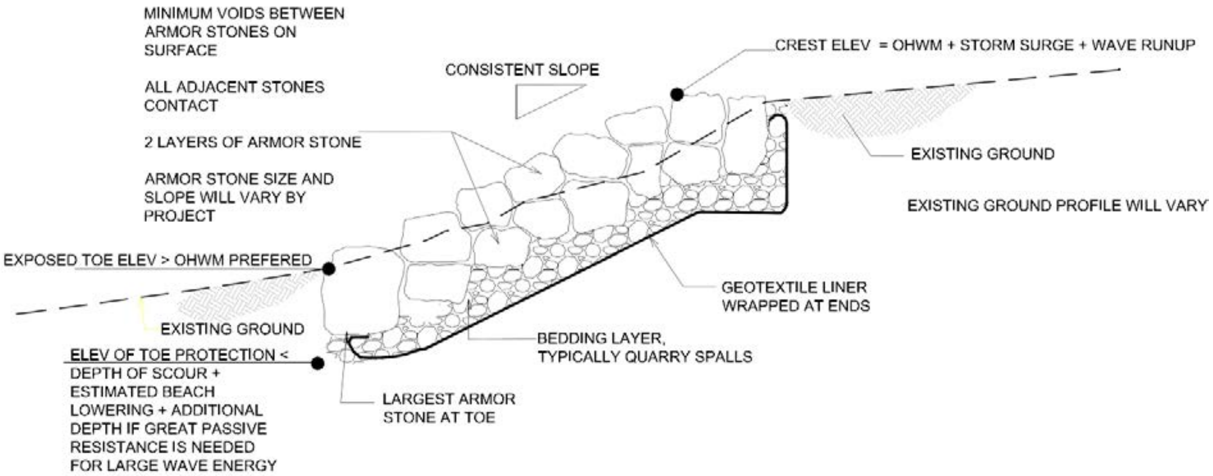

Figure 7.5-2. Cross section of a typical revetment.

Revetments are defined fairly broadly here. A common variation on a revetment in Puget Sound is the near-vertical rock wall, which blends characteristics of a revetment and a vertical bulkhead. These structures are locally called “rockeries,” and are common at single-family residences in Puget Sound. A rockery consists of armor stones placed on top of each other and closely fitted together, forming a steep front face that acts more like a landward sediment retaining wall than a revetment. Armor stones in rockeries are typically larger than those used in sloping rock revetments because the more gradual slope of the revetment supports the weight of the rock on the bedding and allows the use of smaller stones nested together in a tight network. One advantage rockeries have over more traditional revetments is that they cover less beach area. Designers should consult the *Rockery Design and Construction Guidelines* (Mack et al. 2006) for additional guidance for rockery design as these guidelines describe revetment design.

Vertical Bulkhead

Vertical bulkheads are rigid, vertical structures used as shore protection that stop erosion by reflecting waves and retaining landward sediments. These bulkheads are typically constructed out of cantilevered concrete, anchored sheet piles, or wood soldier piles. Vertical bulkheads use the associated fill around and on top of the structure for strength and stability against wave attack. Vertical bulkheads attain structural integrity mostly from ground penetration, therefore the depth of embedment and subgrade landward are paramount design elements. Insufficient subgrade design could result in overturning. Common types of vertical bulkheads used are concrete cast-in-place, wooden piles, and vinyl. Cross sections of common Puget Sound vertical bulkhead types are shown in Figure 7.5-3.

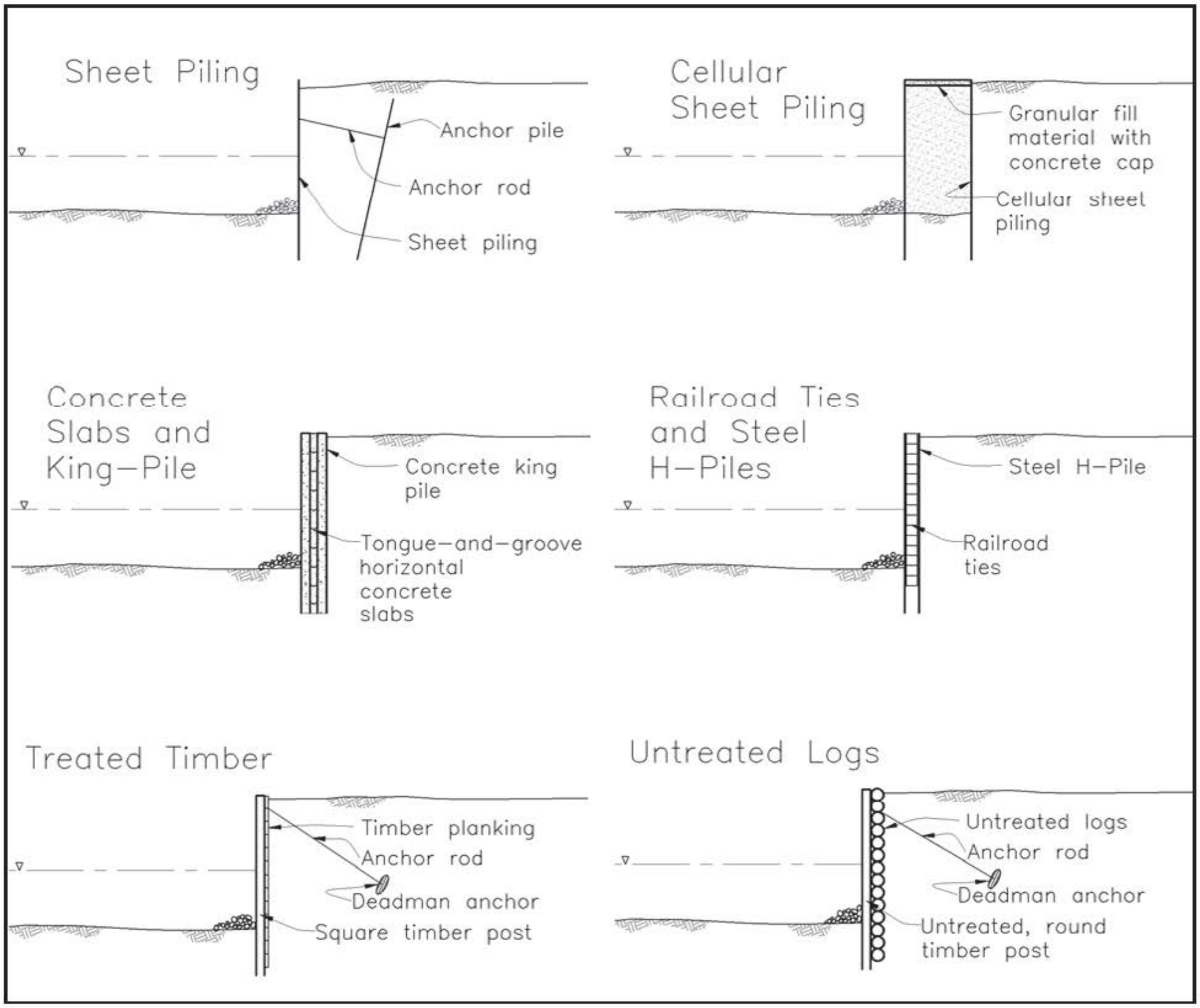

Figure 7.5-3. Typical vertical bulkhead cross sections from CEM Volume 5 (Basco 2006).

Cantilevered seawall installations generally use concrete. Many concrete vertical bulkheads are cast in place and have two typical designs: gravity and zero-clearance. Concrete vertical bulkheads, which have an assumed life span of 50 years, are expensive to install because skilled work is required to excavate the site, install forms, and pour concrete in areas subjected to tidal inundation or wave attack. These projects also often require the use of concrete pumper trucks in addition to concrete trucks, which is a site accessibility constraint. Engineers specializing in structural or geotechnical are also needed for design which increases the design phase costs.

There are two general types of cast-in-place reinforced concrete bulkheads. Typical cross sections for conventional gravity and zero-clearance concrete bulkheads are in Figures 7.5-4 and 7.5-5. Gravity wall construction exposes the bank for footing installation and must have good backfill material to allow for drainage. Most of the time, the backfill material must be imported. Good backfill material, typically quarry spall in Puget Sound, should be angular to allow for interlocking and drainage. The landward excavation requirement for a gravity bulkhead must be considered during the design process since one of the main reasons a vertical bulkhead is viable is due to the small available backshore width. Therefore, there might not be enough backshore width to make a gravity wall viable.

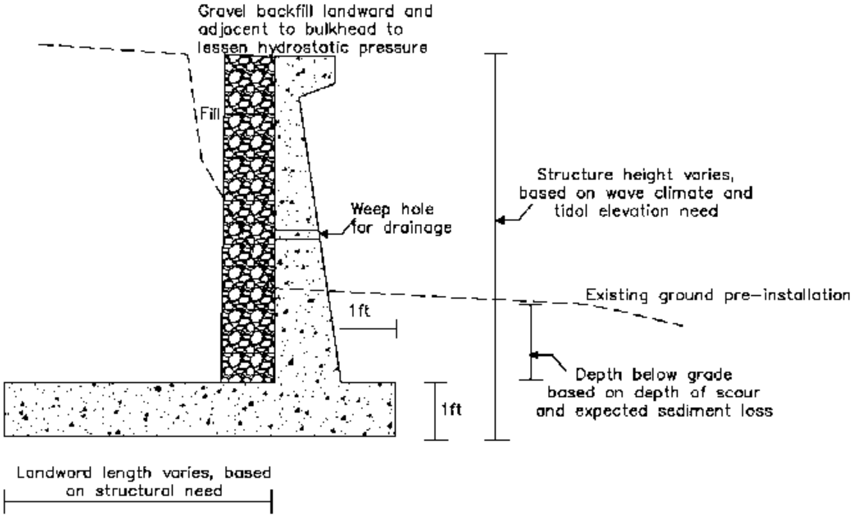

Figure 7.5-4. Typical reinforced, cast-in-place, gravity bulkhead profile (adapted from Cox et al. 1994).

Zero-clearance bulkheads (Figure 7.5-5) allow for minimal landward excavation and can be placed waterward of a failing bulkhead if the available width above MHHW is adequate and still allows for proper landward drainage. The natural sediment where the bulkhead is being installed should also be considered when deciding on concrete bulkhead construction.

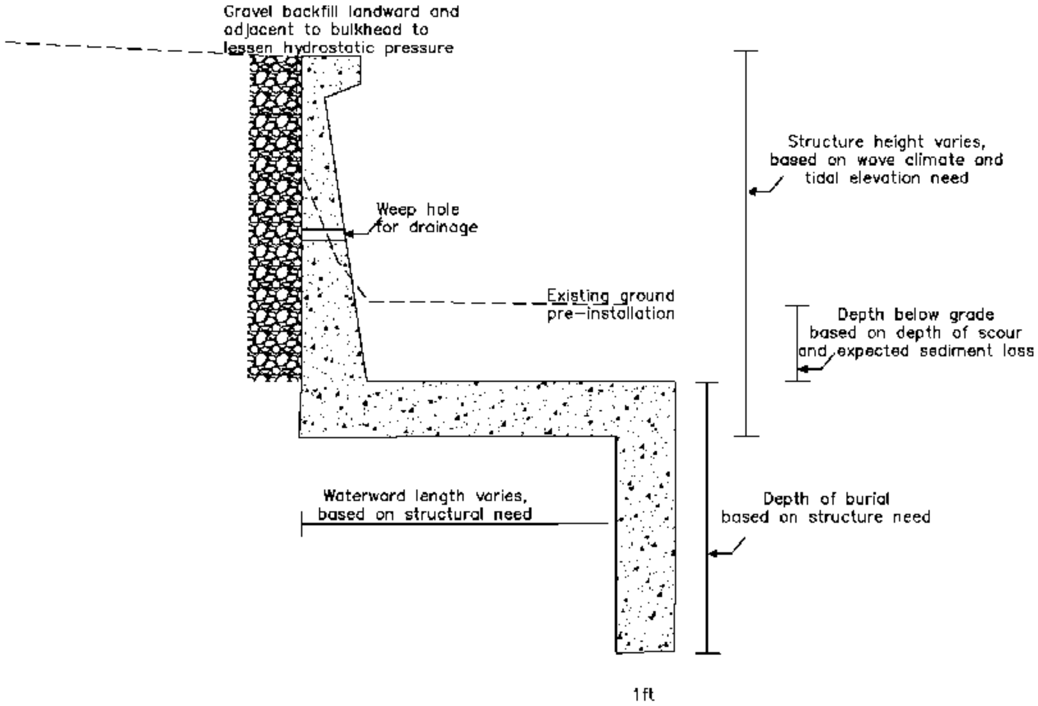

Figure 7.5-5. Typical reinforced, cast-in-place, zero-clearance bulkhead profile (adapted from Cox et al. 1994).

Due to the high costs of concrete bulkhead installations, other types of vertical walls are also used for shore armor installation. Sheet-style walls are anchored bulkheads that can be made from varying material types, but each specific project usually installs rows of consistent material (Figure 7.5-3 above). Sheet walls are made of individual, interlocking sheets driven into depth of refusal or a depth determined by a geotechnical professional. Some regions of Puget Sound have a preponderance of a certain type of vertical bulkhead material, which appears to be primarily a function of what local contractors are comfortable with. Anchored or tie-back bulkheads use support from embedded systems on the landward side or from piles on the waterward side. These tie-back systems are designed to mitigate waterward structural failure of bulkheads. Vinyl and steel can be used for sheet pile walls as well as noncreosoted treated wooden piles. An additional consideration in vertical bulkheads is the need for special driving equipment for installation at a high cost.

Vinyl is one of the most expensive hard armor installation technique; vinyl sheet walls are expensive because they are manufactured in the southeast United States and trucked across the country. Homeowners like vinyl because of the perception that it does not decay and lasts longer than wood piles. However, use of vinyl walls in the Puget Sound region is too new to know if the assumed design life of 50 years is reasonable in this environment, even though the manufacturer has a 50-year warranty on the material. Vinyl sheet piles were not originally designed to withstand attack from large drift log battering. It is recommended to backfill vinyl sheet piles with concrete to allow for less flex and more strength. Concrete-filled vinyl also allows for less sediment to leak out and enhances material containment.

The most economical vertical bulkheads are soldier pile walls in Puget Sound. Creosoted wood should never be used and is not permitted due to the residual ecological effects of harmful toxins to living organisms in the nearshore. High mortality rates of nearshore species from exposure to creosoted wood have been documented (Vines et al. 2000). Wood soldier pile walls have a life span of approximately 25 years due to decay and insect intrusion and are therefore the shortest lived vertical bulkhead.

Costs for each type of vertical bulkhead are discussed in a separate section below.

Application

The designer should have arrived at selection of a hard armor technique as a last resort only after considering site characteristics such as the threat to major improvements, wave energy, and other factors as outlined in the *Alternatives Analysis* chapter. If erosion control is determined necessary and determining soft shore protection is not feasible, hard armor structures should be considered. Revetments and vertical bulkheads have the highest impacts relative to other design techniques and should be chosen for their unique characteristics. Additionally, hard armor installations should be accompanied by compensatory mitigation.

In the past, hard armor was the most common technique used for coastal erosion control in the Puget Sound region, but due to changing permit requirements and increased scrutiny by regulators, they are now rarely installed on new projects and almost all hard armor structures currently installed are replacement structures. These changes are due to observed and documented negative ecologic and geomorphic impacts directly resulting from hard armor techniques (Shipman et al. 2010). Because of Washington State code, most jurisdictions have enacted regulations that prohibit hard armor construction unless direct threat to major infrastructure from erosion within three years can be demonstrated by a geotechnical analysis (WAC 173-26-201). There is disparity in how different jurisdictions handle hard armor installation requests; differences depend upon how a jurisdiction interprets its Shoreline Master Program (SMP) policies and regulations including the acceptance of reports, how recently their SMP was updated, and the interplay between SMP policies and Critical Areas Ordinances.

Site Selection

As covered in the *Alternatives Analysis* chapter, revetments and vertical bulkheads are appropriate for sites only where all of the following are true:

- Soft shore protection is infeasible
- Risk to infrastructure is moderate or high
- Magnitude of erosion is moderate to high
- Erosion is chronic
- There is existing infrastructure that cannot be relocated

As mentioned previously in this document, passive techniques such as moving at-risk infrastructure landward should also be determined to be infeasible before hard armor is selected as the technique to be installed at the project site.

The cumulative infrastructure risk model (outlined in Chapter 5) should be applied to the project to determine if the erosion potential and infrastructure threat result in a moderate to high risk. Scores of 15 and higher in the cumulative risk model are designated as moderate to high infrastructure risk. Generally, project sites with homes or industrial development with at least moderate erosion and minimal to moderate setback distances classify potential sites for hard armor.

Typically, a revetment is preferred to a vertical bulkhead because an impermeable, vertical face has more negative impacts than a sloped, permeable structure. However, a vertical structure has a smaller footprint and can result in less burial of beach at a constrained site. Therefore, site specific evaluation is crucial. If there is adequate backshore width for revetment installation and the project site is not between or adjacent to other vertical armor, a revetment is typically viable. Also, additional designer credentials are often needed for vertical bulkhead design and designs can be more costly.

Revetment

Revetments are only appropriate for sites which need hard armor where all of the following are true:

- Low to medium bank or bluff present
- Adequate backshore width

A bank or bluff must be present at the project site in order to install a successful revetment because at a minimum, revetments need some elevation for design. As discussed in the *Design* section later in this chapter, a typical revetment in Puget Sound has a structure slope of 1:1 and is generally about 5 ft tall above grade, however slopes and elevations vary. Therefore, an adequate backshore and lower bluff width (horizontal distance from the OHWM to the landward extent of the proposed revetment crest) is approximately 7–11 ft (average of 9 ft) wide to allow for structure run out directly proportionate to height (4–6 ft), crest width (2–4 ft), and a 1-ft bedding layer. The adequate structure width will be specific to each project due to actual needed stone sizing and crest height, but this 9 ft rule-of-thumb is a good starting point for revetment feasibility as shown in the simplistic above-grade geometry of Puget Sound typical revetment design (Figure 7.5-6). The revetment would cover a backshore width of approximately 5 ft in the example shown. Revetments should consider less steep slopes when feasible and therefore the adequate structure width could be larger than 9 ft If the available structure width is substantially less than 9 ft, a vertical bulkhead could be considered, especially if the site is in a high-wave-energy environment.

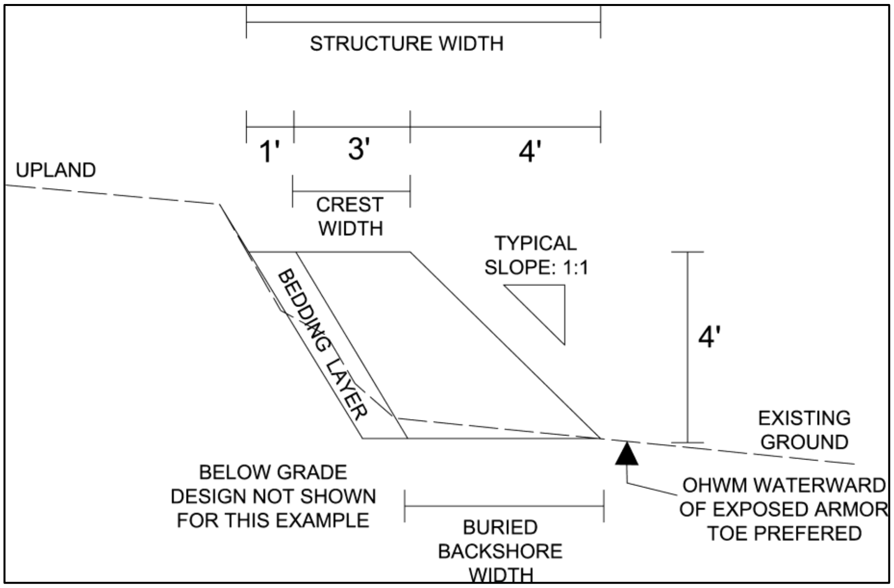

Figure 7.5-6. Typical above-grade revetment geometry used to depict average 9 ft backshore width needed.

Vertical Bulkhead

Vertical bulkheads are only appropriate for sites which need hard armor where all or some of the following are true:

- Narrow or no backshore width available
- Between or adjacent to other vertical shore armor
- Designer and contractor knowledge of vertical armor installation

Vertical bulkheads are viable when a hard armor structure is needed and there is minimal backshore width available and where wave energy does not necessitate a larger structure. A vertical bulkhead might also be feasible if the project location is immediately adjacent to or between other vertical hard armor.

Effects

Hard armor can provide effective erosion control; however, it negatively impacts the nearshore ecosystem in many ways (Macdonald et al. 1994, Rice 2006, Brennan 2007, Johannessen and MacLennan 2007, Clancy et al. 2009, Shipman et al. 2010, Schlenger et al. 2011). In general, these impacts include the following for hard armor techniques:

- Reduction in natural sediment input
- Loss of beach function and habitat by direct burial
- Alteration of hydraulic processes
- End-erosion or end effects
- Potentially increased beachface erosion (“active erosion”)
- Loss and/or removal of nearshore vegetation
- Loss of connectivity between riparian and nearshore habitats

Hard armor structures are designed to prevent erosion; therefore, a successful project precludes natural nearshore processes of sediment supply from the bluff. When armor is placed at the toe of a feeder bluff the armor prevents wave-induced erosion from destabilizing the bluff, which directly results in a decline in the volume of sediment delivered into the associated drift cell from that bluff. If wave-induced erosion is the main driver of the bluff erosion then this method of curbing erosion is typically effective. However, where upland processes (such as stratigraphy, vegetation clearing, or poor management of surface water) are driving bluff erosion, armor may not be as effective. Additionally, armor is not always effective at abating erosion in areas that would naturally be flooded (over-washed), such as barrier beaches. Case study results (Appendix A) revealed that two of the four assessed revetment sites stopped landward erosion. The others did not, as one allowed for substantial erosion at the ends (Lummi View Drive) and the other had scarping landward of the structure due to considerable overtopping (Blakely Island). These applications are not necessarily an indication that the technique is inappropriate but can also be poor design or construction installation. Climate change and sea level rise will most likely increase overtopping at Obstruction Pass and cause scarping landward of the inflexible revetment, because there is no bank for elevation.

Armor not only effectively impounds sediment input but also prevents recruitment of large woody debris, other organic matter, and insects. The cumulative impact from extensive lengths of armored shore amounts to a more widespread decline in nearshore sediment supply and LWD input, the indirect results of which include beach sediment coarsening and long-term changes such as decrease in beach width to down-drift shores. Case study results highlighted the impact of armor on LWD/detritus recruitment and storage when compared to natural adjacent reference sites. Most revetment sites did not have log accumulate in front of the structure, whereas the reference sites did. If there was a log band, it was substantially smaller than that at the corresponding reference site. Other studies have found similar impacts to LWD recruitment when there is shoreline armor in Puget Sound (Higgins et al. 2005).

Wave refraction at the ends of armor structures often creates end erosion immediately adjacent to the structure. Wave reflection waterward of the armor can mobilize fine sediment into suspension, and it is then transported alongshore. This can lead to the development of a scour trough waterward of the structure. It can also result in beach lowering, which can degrade the integrity of the structure over decades. Case study assessment data showed that three (of four) revetments had a beach (profile) slope that was an average of 15% steeper than the natural, adjacent reference beaches. Blakely Island’s waterward slope was the same as the reference beach and Butler Cove had the steepest slope when compared to the nearest reference beach.

The presence of armor may eliminate nearshore habitat functions, through an effect called “direct burial” or “placement loss”. The most dramatic implications of direct burial include the loss of forage fish (surf smelt [*Hypomesus pretiosus*] and Pacific sand lance [*Ammodytes hexapterus*]) spawning areas, as discussed in Chapter 5. Surf smelt spawning is often concentrated near MHHW, including some distance above MHHW (Penttila pers. com. 2013). For reference, the Lummi View Drive revetment project resulted in burial of up to 20 ft of backshore and upper intertidal beach. The spatial extent of the habitat loss and, more generally, the ecological effects of a given armor structure are largely dependent upon its toe elevation (Rice 2010). The lower the toe elevation of the structure, the greater the placement loss and impacts to shoreline biota (Rice 2010, Toft et al. 2010). The lower the armor extends into the beach, the more it truncates or destroys the natural the natural gradient of the intertidal zone and the more species it is likely to adversely effect, as more intertidal habitat zones are encountered.

As discussed in several other chapters in these guidelines, hard armor techniques impact nearshore ecosystem processes and habitats, and except for successfully curbing erosion they provide few benefits only to the landowner and none the nearshore environment. Case study results highlighted the magnitude of impacts and minimal benefits seen at hard armor locations throughout the Puget Sound region (as reviewed in Chapter 5).

Design

Some design elements of a hard armor installation are needed for both revetments and vertical bulkheads. These include the project site wave climate, design water height, depth of scour, and plan-view geometry.

Significant Wave

The most important elements to determine for hard armor design are the design wave criteria at the project site. Wave hindcasting methods use historical wind data (magnitude, frequency, and direction), fetch, and water depths (along with other elements, depending on the research) to approximate wave conditions. Due to its geography, the Puget Sound region is a fetch-limited wave environment. Therefore, only wind waves and not swell waves will be discussed in this guidance.

Wind speed (measured at 10 m above the water surface) and fetch length are required to estimate the significant wave. The 50-year wave criteria in Puget Sound can be calculated using the wave forecasting equation below (CERC 1984, Finlayson 2006):

$$U_a = 0.71 * U^{1.23} \qquad \text{Equation 7-1}$$

$$H_m = 1.616 * 10^{-2} U_a \sqrt{F} \qquad \text{Equation 7-2}$$

$$T_m = 6.238 * 10^{-1} \, (U_a F)^{1/3} \qquad \text{Equation 7-3}$$

Where:

H_m = fetch-limited significant wave height for 50-year storm

T_m = significant wave period for 50-year storm

U_a = wind stress factor

U = wind speed (must be in m/sec)

F = Fetch length (must be in km)

If historical wind data is not known for the project site, several wind data records in the vicinity can be used to develop design criteria. Many scientists, engineers, and scholars have developed methods to estimate wave climate. While this document gives a brief description of the elements used in wave hindcasting, it does not describe detailed methods as there is a reputable model developed that estimates significant wave height and significant wave period for Puget Sound and Juan de Fuca Strait. The model results regarding significant wave height and wave period are shown in Figure 7.5-7. Areas outside the model study area in San Juan, Whatcom, and the majority of Clallam counties should use this guidance to help estimate wave climate at the project site. If the project area is outside the model extents, historical wind record is not available then 10 m/sec should be used for U for fetch-limited shorelines in the Puget Sound region (Finlayson 2006).

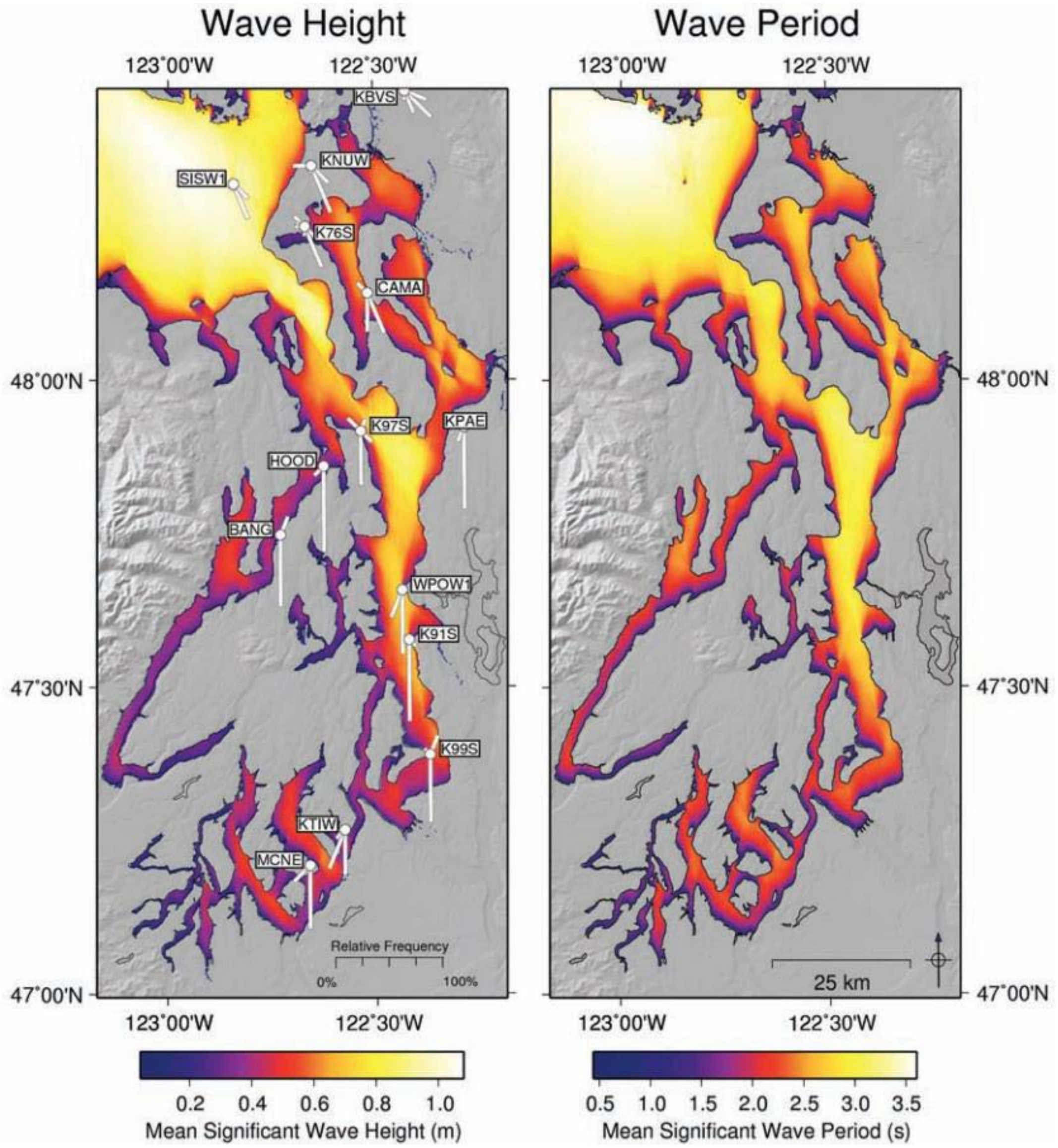

Figure 7.5-7. Model results for estimated mean significant wave height (left) and period (right) (Finlayson 2006).

After the significant wave height is determined, the design wave height should be calculated. The significant wave height, by definition, is the average of the top third largest waves (33%) and the design wave height should at least be equal to the significant wave height; a larger design wave height should be considered if the budget allows. H_{10} is the recommended height to be used as the design wave height (CERC 1984, Sorensen 2010); H_{10} is the wave height where only 10% of the waves are greater and should be substituted for H_m if a more conservative approach is needed and budget allows.

$$H_{10} = 1.27 * H_m \qquad \text{Equation 7-4}$$

Wave Runup

Runup is the maximum vertical extent of wave uprush on a structure above the still-water level (SWL) and is an element to estimate when determining crest height. A definition graphic of wave runup can be seen in Figure 7.5-8. Wave runup increases as the structure slope becomes steeper, particularly in the typical Puget Sound wave climate and with the construction materials generally used, as discussed below. Therefore, the design crest elevation must increase with steeper slopes. This has other implications for structure size and cost when project trade-offs are being considered (CERC 1984, Sorensen 2006).

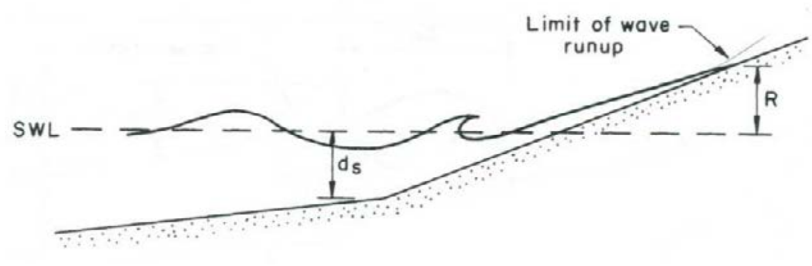

Figure 7.5-8. Definition sketch of wave runup. Runup is the vertical extent of wave uprush above the still-water level (Sorensen 2006).

There have been many studies to predict wave runup when comparing wave criteria, bathymetry, slope, and construction material. The graph below (Figure 7.5-9) is a good starting point for determining wave runup (CERC 1984). It should also be noted that SLR should be considered when determining wave runup as discussed below in the *Crest Elevation* subsection. If a more precise prediction is desired, consult the list of the references given in the *Description* section above; many studies have documented varying design elements that affect wave runup.

For example, in determining wave runup, the largest waves predicted in the Finalyson model shown in Figure 7.5-7 have approximately a 1.0-m significant wave height and a 3.5-sec period, which according to the graph in Figure 7.5-9 results in an $(\frac{H}{gT^2})$ of 0.008. If a revetment slope (also called a rubble mound) is assumed to be 1:2 (V:H), then the associated y-axis $(\frac{R}{H})$ would be approximately 0.76 resulting in runup of 0.76 * 1.0 m = 0.76 m (2.5 ft). Wave runup and allowable overtopping criteria will be used when determining crest height, which is discussed later in this chapter.

Storm Surge

Other factors that affect design height are the still-water depth (SWD) and storm surge. The SWD is the depth of water if there were no waves and should be considered OHWM at a Puget Sound project site for hard armor design conditions. Storm surge is a rise of water associated with low-pressure weather systems. Typically, a design storm surge in the Puget Sound region is +60 cm (2.0 ft) (Finlayson 2006). Another way to determine a design water height in Puget Sound is by using the highest observed water level (HOWL). A designer should use the largest value between OHWM + 2 ft or HOWL for the design water height. If HOWL is not known, it can be estimated for design purposes with the associated NOAA benchmark data sheet that is closest to the project site. Listings can be found here:
http://tidesandcurrents.noaa.gov/station_retrieve.shtml?type=Bench+Mark+Data+Sheets

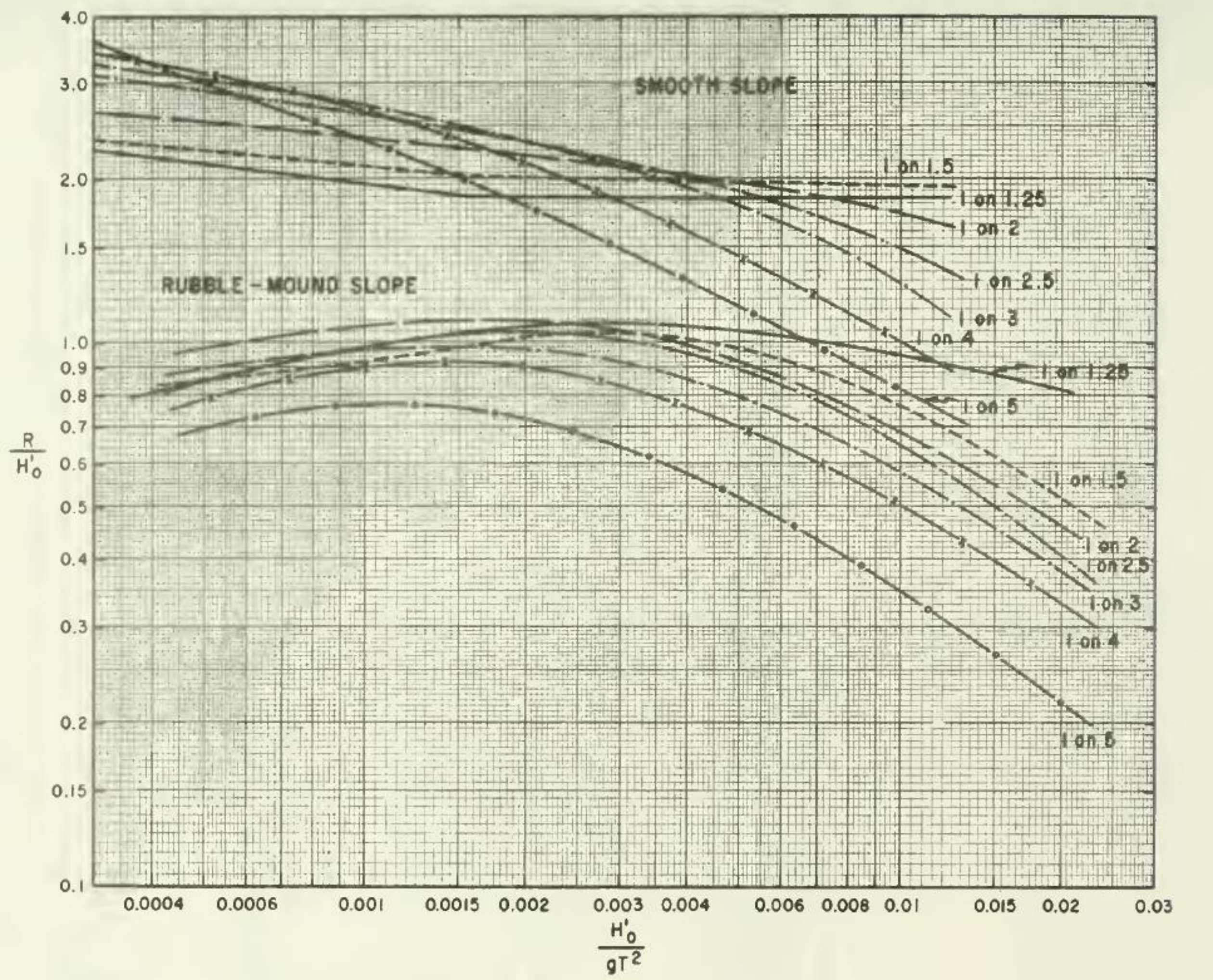

Figure 7.5-9. Comparison of wave runup on smooth slopes and permeable rubble slopes. Note that runup increases as the slope of the revetment becomes steeper (CERC 1984).

Crest Elevation

The design crest elevation should consider SWD, storm surge, wave runup, allowable overtopping, landowner budget, and sea level rise. Consideration should also be given to protecting the bank above the hard armor from splash and spray. There are trade-offs when considering crest height as runup decreases with more gradual structure slopes. Therefore, design crest heights and slopes can be maximized for available budget, backshore width, and construction materials. A more gradual slope results in smaller armor stones and lower crest elevation. It follows that vertical bulkheads should be designed for a higher crest elevation than sloped revetments with the same design wave constraints, because their vertical slope and impermeable construction materials result in increased wave runup. If budget and project objectives allow, an additional 1.5 ft (0.47 m) should be added to hard armor crest height for 50-year sea level rise (SLR) considerations (NAS 2012).

Embedment Depth

The depth of burial (also known as embedment depth or depth of footing) must address:

- Scour
- Beach lowering

- Structural strength associated with depth for hydrodynamic forces
- Bedding layer thickness

As seen in example profile in Figure 7.5-10 below, all the listed factors increase how deep the extent of below grade design should be.

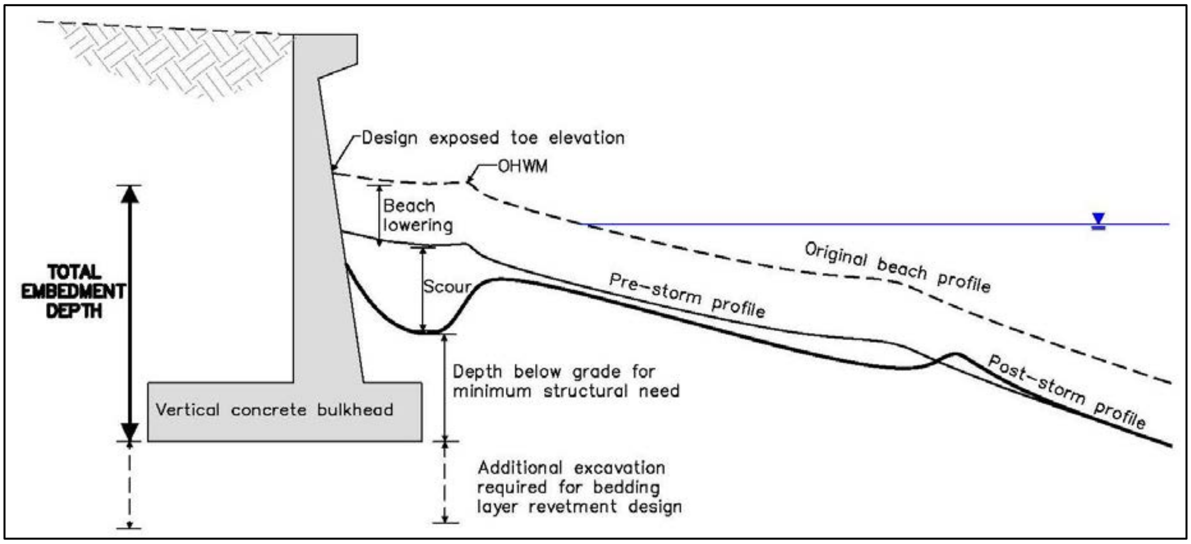

Figure 7.5-10. Total embedment depth factors (estimated beach lowering, predicted scour, structural need, and bedding layer thickness) shown in profile view.

Scour is the removal of sediment in the immediate vicinity of a coastal structure (Kraus 1988). Scour results in loss of hydrodynamic forces of the structure. Maximum scour occurs with vertical walls and plunging waves. Scour depth (the extent downward of scour) increases if there are substantial currents at the project site. Reducing wall reflection (less steep structure slope) reduces scour. Maximum scour depth is approximately equal to the significant wave height of the wave climate at the project site (Burcharth and Hughes 2002). Conditions that promote maximum scour rarely occur in Puget Sound but using the significant wave height (H_m) discussed above in the *Significant Wave* subsection as the scour depth is a recommended start for design.

The design should also consider if there will be any estimated beach lowering due to the structure installation or from up-drift conditions. A beach could be expected to lower if there are sediment-starved up-drift conditions. Additionally, reflective and impermeable structures installed lower on the beach profile increase the probability of beach lowering. Modifications to the up-drift shore such as armor or other sediment budget altering conditions could result in beach lowering at the project site. Historical erosion rates should be estimated to determine probable beach lowering depth.

The burial depth of the structure should also consider the strength needed to combat wave attack. If a revetment is being installed, a substantial amount of the toe armor stones should be buried. The size of the armor stones are discussed in subsection *Rock Sizing and Placement* detail below. Minimally, the largest armor stone placed at the toe should be two thirds buried. A structural or geotechnical engineer should determine the depth of embedment for a vertical bulkhead. The subsurface sediment and wave criteria should be known and given to the engineer for embedment depth determination.

The exposed toe elevation should be determined before the elevation and associated cross shore location of excavation. The exposed toe elevation is determined by above grade design and constraints. Exposed toe elevation should be greater than MHHW minimally and preferably above OHWM as shown above in Figure 7.5-10 and below in Figure 7.5-11. Most Puget Sound counties have Shoreline Master Program requirements which require structures that do not alter the beach at the OHWM. Permitting structures that have an exposed toe lower than OHWM is substantially more difficult. It is important to note that if an exposed structure toe design goes below MHHW, federal permitting will be required in addition to local and state permits. Once exposed toe elevation and alignment is determined, the components listed above that control embedment depth should be combined and subtracted from the exposed toe elevation to define depth of burial.

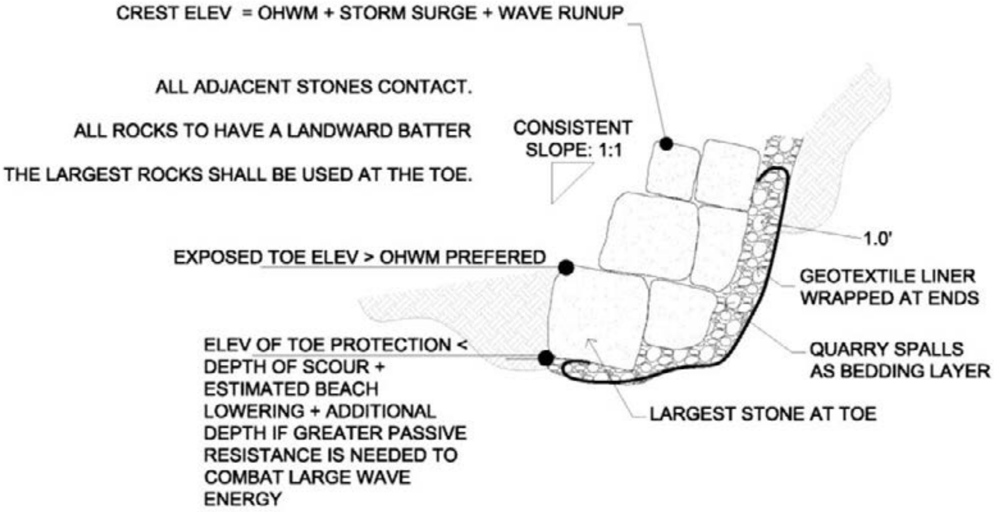

Figure 7.5-11. Typical Puget Sound revetment cross section used on projects with small backshore width availability and large wave climate.

Alignment

The alignment or plan-view geometry of a hard armor structure is based on the site characteristics, property boundaries, and other project and site-specific constraints. For high wave energy sites, the alignment in plan-view should be as uniform and consistent as possible to limit the structure's ability to cause increased erosion from focused wave energy from diffraction and refraction along the structure face. Preferred plan-view geometry to lessen erosion waterward of the structure is shown below in the central configuration in Figure 7.5-12, where the wall is more linear, with short reaches of the bank toe excavated to minimize minor points and lesser or equal concave areas are filled. Some rare projects will require lesser projections onto the upper beach in concave reaches to avoid important habitat areas.

The ends of a hard armor structure should be designed to avoid or minimize to the greatest extent possible wave energy focused beyond the ends of the structure due to wave refraction, reflection, and diffraction. This is generally accomplished by avoiding or minimizing sharp corners. The red alignment at the left in Figure 7.5-12 demonstrate nonuniform alignment and sharp, rigid return wall corners that exacerbate erosion. The ends of armor structures should be gently transitioned into the bank to minimize end effects/end erosion immediately up-drift and down-drift. This in effect makes return walls simply curving sections of the main wall. Standard of practice for return walls suggests a using a 45-degree angle relative to the revetment alignment at the maximum. It should also be noted that all alignments in the figure below have an exposed toe above OHWM which is preferred by permitting agencies.

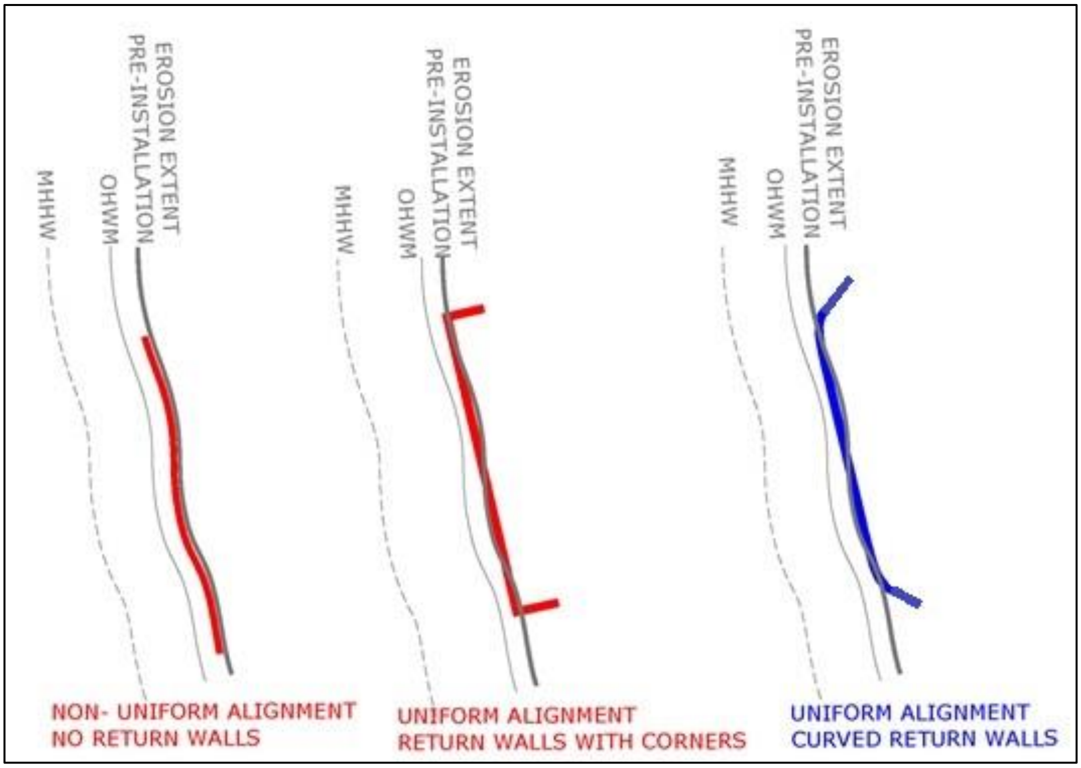

Figure7.5-12. Plan-view alignment options. Blue option (right) is preferred for high wave energy sites to lessen erosion impacts waterward and up- and down-drift.

Slope – Revetment Specific

As seen in typical revetment design cross sections (Figures 7.5-2 and 7.5-11), the slope should remain consistent throughout the structure both horizontally and vertically for minimum wave focusing and therefore minimum impact to the surrounding environment. The slope maximizes material and backshore width availability while considering budget. The design could consider a more gradual slope, which allows for smaller rock size and lower crest elevation but also buries more area (CERC 1984, Burcharth and Hughes 2002, Kamphuis 2010). Typical revetment slopes in Puget Sound are 1:1 or 1:1.5 (V:H). Figure 7.5-11 illustrates a different, more common, variation of Figure 7.5-2 installed in Puget Sound: a revetment installation for an extremely high-wave-energy environment, using a steep 1:1 slope with large armor stones. If a structure slope is needed that is steeper than 1:1, then the structure will actually be a rockery or gravity retaining wall and will have different design constraints than a revetment.

Rock Sizing and Placement – Revetment Specific

The proper stone or armor unit size to use on a reveted slope will be a function of the wave height, slope of the revetment, type of armor placement, and the specific gravity of the armor. Armor stones should be angular, sound, hard, and durable rock. Typical density of stone used in the Puget Sound area is 1.5 tons/cubic yard. Even though most coastal engineering reference documents do not suggest having a steeper structure slope in armor stone revetments than 1:1.5 (V:H) , it is typical practice in Puget Sound to have a slope of 1:1 (CERC 1984, Burcharth and Hughes 2002, Goda 2010), which requires larger armor stones. If the available backshore width above OHWM allows for a structure slope of 1:1.5 or more gradual, it should be used.

The Hudson formula is the most simple and researched formula to determine armor stone size. There are many other more recent and often appropriate methods for determining armor size than the Hudson Equation. This equation is generally accepted as overly conservative in terms of rock sizes needed for stability. The Hudson Equation is a good place to start for armor sizing but other references such as the CEM (Basco 2006). It should be noted that using H_{10} instead of H_s will result in armor stones twice as large. The Hudson formula assumes two armor stones in each layer and is:

$$W_{50} = \frac{w_r H^3}{K_D (S_r - 1)^3 \cot\theta} \qquad \text{Equation 7-5}$$

Where:

W_{50} = design average weight of a single revetment stone

w_r = unit weight of armor stone (2 $\frac{tons}{yd^3}$ or 2,375 $\frac{kg}{m^3}$)

H = design wave height

K_D = stability coefficient (assumed to be 2.2 for typical Puget Sound armor stones in breaking wave)

S_r = specific gravity of armor stone ($\frac{w_r}{w_w}$)

W_w = unit weigh of salt water (1,027 $\frac{kg}{m^3}$)

θ = slope of the structure

To determine the approximate average diameter size of each armor stone (D_{50}), use the following equation:

$$D_{50} = \sqrt[3]{\frac{W_{50}}{w_r}} \qquad \text{Equation 7-6}$$

It is also recommended, though not paramount, to know the approximate “man-rock” size using Washington Department of Transportation 9-13.7(1) Rock for Rock Walls (Table 7.5-1) to help determine size in discussions with construction contractors (WSDOT 2012). Man-rock is approximately how many men are needed to move one single stone and the classifications are widely used by contractors and rock suppliers. Most suppliers have sorted larger stones into man-rock categories.

Table 7.5-1. Rock size classes for revetment sizes (WSDOT 2012).

Rock Size	Rock Weight (lbs)	Average Dimension (in.)
One Man	50 to 200	12 to 18
Two Man	200 to 700	18 to 28
Three Man	700 to 2,000	28 to 36
Four Man	2,000 to 4,000	36 to 48
Five Man	4,000 to 6,000	48 to 54
Six Man	6,000 to 8,000	54 to 60

As mentioned above, a more gradual slope will result in smaller armor stones as determined by the cotangent of the angle in the denominator of the Hudson formula (Equation 7-5). A larger number in any denominator with all other variables the same gives a smaller result.

The thickness of the armor layer is approximately two to three times the size of the largest stone but never less than 1 ft and can be more precisely calculated using the following equation:

$$r = 2.0\left(\frac{W_{50}}{w_r}\right)^{1/3} \qquad \text{Equation 7-7}$$

Where:

r=layer thickness

The placement of the armor stones is also important in successful revetment installations. Armor stones should have a landward batter (backward slope) during installation with all adjacent armor stones in tight contact; these results in a minimum of three points of contact with the stone below and both adjacent stones. The armor stones in the typical revetment cross section above (Figure 7.5-11) show a landward batter.

Equally as important in the success of the armor is the placement of the stone and the underlying filter materials. The bedding layer (typically quarry spalls in Puget Sound applications) should be compacted under the armor stones if the subsurface sediment is not glacial till or other geologic sediment with high strength. The quarry spalls should be compacted until they cannot be compacted further when placement on less structural sediment and have a top elevation equal to the embedment depth. Bedding layer thickness requirements increase based on geotechnical constraints. Each layer should be, on average, about ⅛ the size of the upper layer. If extremely large armor stones are calculated due a large wave climate, a second inner armor layer on top of the bedding layer with smaller dimensions will be needed. Typical Puget Sound applications do not require this. If a revetment is being installed in an extremely high wave energy environment, an engineer should be consulted.

Hard armor design presumes that an adequate filter layer is present as part of the design. Geotextile should be located between spalls and native sediment throughout the installation. Geotextile fabric should be wrapped under armor stone or quarry spall at the extents to prevent the fabric from unraveling and tearing (Figures 7.5-2 and 7.5-11). It is sometimes permissible to not place geotextile fabric below the quarry spalls under the armor stones at the toe.

Armor Stone Toe Protection – Vertical Specific

Armor stones are sometimes placed waterward of the exposed toe of vertical bulkheads to combat scour and enhance structural integrity. A professional should determine if a vertical bulkhead will need armor stone toe protection. Cross shore placement on the beach of the structure and up-drift geologic conditions are some constraints that could require armor stone toe protection. If a beach is expected to lower because of structure installation or heavily sediment-starved up-drift conditions, armor stone protection could be needed. Armor stone toe protection may also be required at high to very-high wave energy sites where the bulkhead cannot be placed far enough landward to avoid the need. Sites with chronic erosion will most likely need toe protection. Armor stones used for toe protection for vertical walls should be angular, sound, hard, and durable rock. Placement needs to be to a sufficient embedment depth to prevent undermining as discussed above in *Embedment Depth* subsection. Armor stones use for toe protection must be appropriately sized for the wave climate using the Hudson Formula (Equation 7-5). All adjacent stones should be in contact when placed. In most cases, armor stone protection is a maintenance measure placed years after the original installation. Armor stone toe protection is seen in Figure 7.5- 13 below.

Figure7.5-13. Armor stone toe protection at a Puget Sound vertical bulkhead.

Maintaining Fill – Vertical Specific

Vertical bulkheads rely on the weight of the associated fill for strength against wave attack. Therefore, one critical element of a good bulkhead design that prevents or limits loss of backfill is allowing drainage of water through or away from the structure. Drainage releases pressure of excessive water from upland seepage, rainwater, and wave overtopping. Weep holes need to be designed to allow water to drain through the structure. Geotextiles allow water, but not sediment, to filter through the structure. Geotextiles are difficult to install over the full depth of the structure because of mechanical pile-driving. Gravel between the bulkhead and native fill also allows for drainage and mitigates sediment loss (Basco 2006).

Another critical bulkhead design element that helps to maintain fill is return wall design. Return walls should be designed to limit waterward reflection of waves but also to retain backfill for structural integrity (Basco 2006). Landward extents of return walls should be designed to maintain sediments while minimizing ecological impacts by not encroaching too far into marine riparian habitat. Typical return wall geometry is shown in Figure 7.5-12.

Design Example

The hard armor techniques are somewhat complicated. To help the designer understand these methods, the Blakely Island revetment (Appendix A) will be used as a design example. It must be noted that soft shore protection is feasible for Blakely Island under these guidelines but the project site is being used for example purposes.

The following project site data are needed for design:

Fetch: 4.8 mi (7.7 km; from Appendix A)

HOWL: +11.2 ft MLLW (3.4 m from station 9449880 Friday Harbor, WA Benchmark sheet)

MHHW: +8.0 ft MLLW

The significant wave height and period are determined using Equations 7-1, 7-2, and 7-3:

Wind stress factor (using equation 7-1): $U_a = 0.71 * 10^{1.23}$ = 12.06

Significant wave height (using equation 7-2): $H_m = 1.616 * 10^{-2} * 12.06 * \sqrt{7.7}$ = 0.54 m, which is also equal to the maximum scour depth

Significant wave period (using equation 7-3): $T_m = 6.238 * 10^{-1}\,(12.06 * 7.7)^{1/3}$ = 2.8 sec

It is assumed that budget allows for a conservative approach and the design wave height should be:

$H_{10} = 1.27H_s = 1.27(0.54\text{m}) = 0.68$ m (Equation 7-4)

Because there is plenty of backshore area on the project site (the setback distance is 31 ft; Appendix A), this example will use two different feasible slopes to numerically depict tradeoffs with slope, crest height, and armor size; however, a slope of 1:2 will be used for the typical design. A slope 1:3 will be used to show the differences in armor stone size needed, backshore burial width, and crest elevation needs. The available backshore area also makes a revetment more viable than a vertical bulkhead.

In order to determine crest height, wave runup (R) and design water height must first be determined. Figure 7.5-9 and the series of resulting calculations will be used for wave runup for this example but there are numerous ways to determine wave runup in the references listed.

Wave runup for crest elevation determination:

$\frac{H}{gT^2}$= x-axis in the graph in Figure 7.5-9 using H_{10}= $\frac{0.68}{9.81*2.8^2}$= .009

$\frac{H}{gT^2}$= x-axis in the graph in Figure 7.5-9 using H_m= $\frac{0.54}{9.81*2.8^2}$= .007

y-axis in Figure 7.5-9 for 1:2 slope and H_{10} = 0.73 = $\frac{R}{H}$ Therefore R=0.73 * 0.68m = 0.50 m

y-axis in Figure 7.5-9 for 1:3 slope and H_{10} = 0.69 = $\frac{R}{H}$ Therefore R = 0.69 * 0.68m =0.47 m

y-axis in Figure 7.5-9 for 1:2 slope and H_m = 0.73 = $\frac{R}{H}$ Therefore R=0.73 * 0.54m = 0.39 m

y-axis in Figure 7.5-9 for 1:3 slope and H_m = 0.69 = $\frac{R}{H}$ Therefore R = 0.69 * 0.54m =0.37 m

Design water height for crest elevation determination:

Design water height = HOWL + SLR = +3.87m

Crest elevation = Design water height + runup

Crest elevation for 1:2 slope: Design water height + Runup = +3.87m + 0.50m = 4.37m MLLW = +14.33 ft MLLW

Crest elevation for 1:3 slope: Design water height + Runup = +3.87 + 0.47m = 4.34m MLLW = +14.23 ft MLLW

The following cross section (Figure 7.5-14) of the current revetment at the project site (Appendix A) shows that the exposed toe of the current structure is at a recommended location because it is above MHHW and most likely is very near or at the OHWM. (The latter was not determined in the field the day of the assessment.) For this exercise, +10ft MLLW will be the proposed exposed structure toe elevation which is equal to the approximate current exposed toe. Therefore, the height of the wall is either 4.33 ft if using 1:2 slope or 4.23 using 1:3 slope.

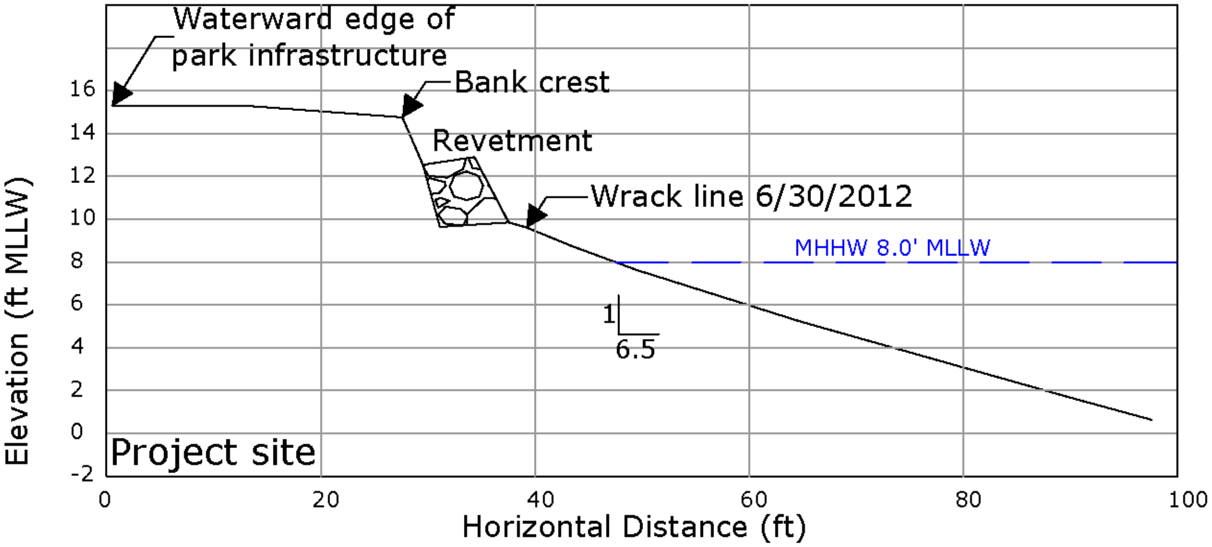

Figure 7.5-14. Blakely Island revetment existing project site cross section (Appendix A).

Armor stone size mass determination using the Hudson formula (Equation 7-5) for a 1:2 slope:

$$W = \frac{2{,}375\frac{kg}{m^3}(0.68m)^3}{2.2\left(\frac{2{,}375\frac{kg}{m^3}}{1{,}027\frac{kg}{m^3}}-1\right)^3 * 2} = 75 \text{ kg} = 165 \text{ mass pounds}$$

Armor stone size mass determination using the Hudson formula (Equation 7-5) for a 1:3 slope:

$$W = \frac{2{,}375\frac{kg}{m^3}(0.68m)^3}{2.2\left(\frac{2{,}375\frac{kg}{m^3}}{1{,}027\frac{kg}{m^3}}-1\right)^3 * 3} = 50 \text{ kg} = 110 \text{ mass pounds}$$

Armor stone size average diameter determination using the Hudson formula (Equation 7-6) for a 1:2 slope:

$$D = \sqrt[3]{\frac{75kg}{2{,}375\frac{kg}{m^3}}} = 0.32\text{m} = 1.1 \text{ ft or a one-man-rock (or very large two-man-rock) using WSDOT (2012)}$$

Armor stone size average diameter determination using the Hudson formula (Equation 7-6) for a 1:3 slope:

$$D = \sqrt[3]{\frac{50kg}{2{,}375\frac{kg}{m^3}}} = 0.28\text{m} = 0.9 \text{ ft or a one-man-rock using WSDOT (2012)}$$

Therefore, the burial depth for armor stones should minimally be $H_m + \frac{2}{3}D = 0.54\text{ m} + \frac{2}{3}(0.32\text{ m}) = 0.75\text{ m} = 2.5\text{ ft}$ unless otherwise determined by a geotechnical engineer. Additionally, excavation depth will include 1ft for the bedding layer. A cross section of this design is shown in Figure 7.5-15.

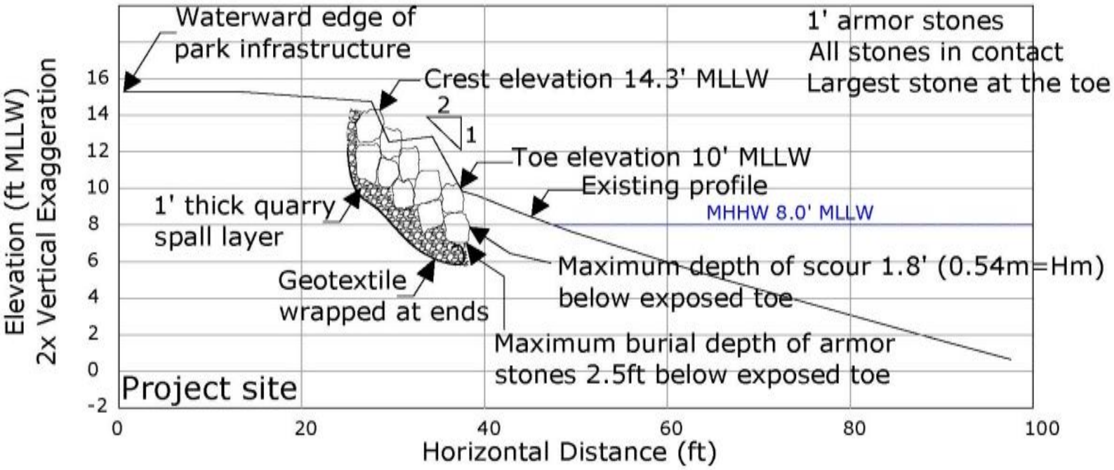

Figure 7.5-15. Cross section of Blakely revetment example developed for this document (2x vertical exaggeration).

Comparison of the existing profile to the design reveals that the original Blakely Island design did not have adequate design height. Field observations showed scarping and LWD landward of the rock structure, as well as inconsistent rock sizing and structure slope as seen in the field photo below. (Figure 7.5-16).

Figure 7.5-16. Field photo from Blakely Island assessment.

Cost

Construction costs are defined for this technique for planning purposes and do not include project site assessment, survey, design, permitting, remote site access, archeological assessment/investigation, or any other project-specific provisions. Smaller projects with fewer linear feet of shore and/or project sites with difficult access generally increase the price per linear foot substantially. Table 7.5-2 lists typical cost ranges for revetments while Table 7.5-3 lists typical construction costs for vertical bulkheads; however, this information is not based on data from the VB or RV project sites as costs of the eight assessed sites were not available. The estimated amounts in these tables are based on professional experience with designing and cost-estimating shoreline structures, in addition to discussions with construction contractors that specialize in Puget Sound shoreline armor installation. Note that site location is one of the most significant variables when estimating costs. Distance from material suppliers is another reason why project location impacts the costs. Remote access could result in barging equipment and material to the project site resulting in an installation cost increase. Also, it is typically more expensive to design a vertical bulkhead, especially a concrete vertical bulkhead, than a revetment.

Table 7.5-2. Material and construction costs per linear foot for residential-scale revetment projects using 2012 dollars.

Wave Energy	Tons of Material/LF	Construction Costs/LF
Low*	2-3	\$125 to \$175
Medium	3-5	\$175 to \$300
High	5-10	\$300 to \$550

Revetment installations at low-wave-energy sites are not optimal or recommended and have extremely strenuous permitting requirements. As stated in the *Site Assessment* chapter, soft shore protection measures must be deemed infeasible by a qualified and experienced professional engineer or licensed geologist before hard shoreline structures are considered under Sound-wide permitting requirements. This low-energy hard-armor option should only be used for cost comparisons in the rarest cases.

Table 7.5-3. Material and construction costs per linear foot for vertical bulkhead projects using 2012 dollars.

Material Type	Wave Energy	Construction Costs/LF
Concrete	Medium	\$300 to \$400
Concrete	High	\$350 to \$450
Vinyl	Medium	\$400 to \$500
Vinyl	High	\$450 to \$550
Wood pile	Medium	\$225 to \$300
Wood pile	High	\$275 to \$350

Monitoring

Hard armor installations should be monitored to determine performance and if maintenance is needed. Monitoring activities specific to hard armor installations are:

- Biannual measurements (prefer in winter and summer) of the structure crest and relative structure toe elevation
- Biannual beach profiles (prefer in winter and summer)
- Biannual photos of the structure (prefer in winter and summer) from fixed locations with scalable reference

- Biannual photos of the substrate waterward of the structure (prefer in winter and summer)
- Storm photos
- Post-storm ground photos
- Water level and wave climate of storm events

Due to the static nature of hard armor the installations can be assumed to be immobile. Therefore, hard armor installations can be their own baselines. Physical and photographic monitoring techniques can be used to monitor a hard armor project (Figures 7.5-17 and 7.5-18). Physical monitoring consists of simple twice-annual measurements of topography of the structure crest, structure toe elevation, and beach profiles to provide baseline data and characterize seasonal beach cycles to determine interannual variability. Beach sediment composition in front of hard armor is also important to record during sampling events. Hard armor should be physically monitored for structure-caused erosion (both end erosion and waterward beach coarsening) and rock toppling. Spray paint or pin flags can be used to mark landward extents of tidal waters and wave climate.

Figure 7.5-17. Simple physical monitoring of a bulkhead showing the scalable photographic technique of using a person or measuring tape in the picture. Photographic monitoring should be biannually at a minimum and in the same location with the same reference. In this case, the same adult should be photographed next to the bulkhead every monitoring cycle. Note pink spray paint line showing king tide elevation extent in the picture on the right as another method of monitoring that can be used.

Sampling periods are at the end of the summer and at the end of winter on days when daytime tides are near or below 0 ft MLLW.

Quantitative wind and wave climate over the monitoring period and high water levels should also be included in monitoring activities. This information can be documented from NOAA (http://tidesandcurrents.noaa.gov/products.html) and is important to understand site behavior that may be a result of a storm event as well as severity of storm events. This quantitative data can be combined with qualitative data of storm photos and post-storm ground photos showing damage. Additional information regarding project monitoring elements and protocols is described in Chapter 8 *Monitoring*.

Maintenance

Revetment maintenance usually involves restacking toppled rock, cleanup of revetment-originated beach debris, and placement of beach nourishment sediment waterward of the structure, usually in the up-drift section. Bedding layer rock that filters through the armor layer onto the beach face should also be removed, especially if in documented forage fish habitat. Landowners can perform simple maintenance but when large construction equipment is needed for maintenance, permits are needed. Additionally, the associated impacts of construction equipment in the nearshore also occur for maintenance. Therefore, rock sizing and design geometry of the structure should be determined such that no structure maintenance will be required for a at least 25 years to keep the project affordable over time, limit site disturbance, and limit the difficulty of acquiring permits. Design for possible beach nourishment at a site with hard armor could be a permit requirement or needed after monitoring has shown substantial beach and end-area erosion.

By design, bulkheads are used when maintenance is not practical and the risk of structure damage is high. Therefore, when maintenance is required, it is costly and is usually because the structure itself produced increased erosion waterward and/or adjacent. Bulkheads should be designed for a long project life but sometimes maintenance is required due to the challenge of being an inflexible structure installed in a dynamic environment. Maintenance could be needed if the structure is no longer vertical or if the footing is exposed. Armor stones have been placed waterward of bulkheads for structure toe protection. The Samish Island site (Appendix A), with one wall reach leaning waterward, was the only vertical bulkhead project that was not consistently vertical, a result of several landslides that occurred after wall installation that threatened the integrity of the wall. The owner mentioned wanting to remedy the issue with structure maintenance but had not obtained the permit and had not determined what type of structural maintenance was to be done.

Maintenance should take into account the causes of damage to the structure. In-depth analysis of subgrade conditions may be necessary to determine these causes, which could include slippage of soil horizons or increased ground-water loading resulting from development of the site. Without this understanding, possible repair of the structure may not result in enhanced design life.

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Chapter 8. MONITORING

Ideally, development of a monitoring approach begins with the initial site assessment. Although a formal monitoring plan may only be required during the permit application process, aspects of a monitoring plan should be considered during both the feasibility and design phases. The primary features of the site and how they fit into a broader coastal context help determine project “success” not by only identifying the specific needs of the site, but also through the level of impact or benefit provided to the nearshore environment. Monitoring of specific types of restoration and enhancement measures is outlined in *Management Measures for Protecting and Restoring the Puget Sound Nearshore* (Clancy et al. 2009). Bluff monitoring methods are discussed in Thorsen and Shipman (1998).

Monitoring should be built into the initial concepts of a project so that project performance—the measure of meeting regulatory, ecological, and homeowner objectives—can be determined, and so that lessons learned can be applied to subsequent projects. On the site scale, monitoring results can guide necessary maintenance and adaptive management. If performance measures are not being met, then contingency steps (pre-established or adaptive) should be put into place. On a broader scale, monitoring contributes to the success of overall restoration goals and improving cost-effectiveness of similar projects in the future.

Statement of Objectives

A clearly stated list of project goals and objectives must be understood by all entities involved prior to implementation. The goals help in the development of a list of measurable parameters for gauging project performance through monitoring.

Project Goals

Of primary concern for judging project performance is how well the project goals are met. An initial goal may be put forward by the project proponent and typically includes stopping or slowing coastal erosion or restoring habitat. Another set of goals comes from the legal or permit requirements of the project, and often includes a “no adverse impact” approach to important habitats such as eelgrass beds and forage fish spawning beaches. All of these project goals should be itemized to determine what and how much monitoring should be performed.

Monitoring Objectives

The Project Goals feed directly into a set of monitoring objectives: a set of elements by which project success can be measured. These are then used to develop a list of specific data that can be collected and documented in an objective and repeatable way in order to measure success relative to project goals.

Success Criteria

Once specific elements are identified for monitoring, then specific thresholds should be identified against which the observations or data can be compared. Success criteria for project performance in terms of reducing erosion (e.g., damage to a structure) and off-site impacts (e.g., end-effect erosion) are both important when developing a monitoring plan. Of course, not all impacts can be anticipated, and personnel performing the monitoring should be trained to watch for and document potential problems or unanticipated project benefits.

Mitigation Steps

Should the monitoring data not meet the success criteria, then mitigation for failure or impact should be allowed for. Specific actions could be listed in the monitoring plan, such as a trigger for the addition of beach nourishment sediment, replanting, or repair of damaged structures. However, often an impact will require examination by a licensed professional for determination of mitigation steps.

Monitoring Protocol

Geographic Extent

The areal extent of monitoring should be identified early in the process. At a minimum this will allow enough data to be collected on-site to determine whether the project goals have been met, but potentially impacted sites (e.g., down-drift beaches) should also be included. Ideally, nearby reference sites will be included for comparison to the project site to aid in determining whether potential success or failure stems directly from the project action or from background influences.

Temporal Extent

The length and timing of monitoring efforts should be determined during development of the monitoring plan. Project complexity and objectives should be considered when deciding how long to monitor, with simple projects requiring less time to determine effects and overall performance than larger complex projects. Monitoring typically takes place for at least 3 to 5 years even for small to medium projects in order to include more than just the initial adjustment phase after construction. For large projects monitoring should occur for a minimum of 10 years. For a select few, monitoring in perpetuity may be appropriate.

Timing of each monitoring event should be consistently repeated in terms of season and tide cycle. Spring (March to early May) and late summer (August and September) are often good choices to capture the winter or summer beach profiles respectively. As discussed in Chapter 3, the physical and biological aspects of the nearshore tend to vary seasonally in Puget Sound, so consistent application of timing will reduce the seasonal “noise” in monitoring observations. For example, dense eelgrass beds seen in middle to late summer may be much reduced in winter or spring; should eelgrass beds in these two seasons be mistakenly compared, erroneous conclusions of heavy habitat impacts could be reached. Monitoring may be performed twice annually, at least initially, to help determine seasonal variability.

Baseline Conditions

Gathering of baseline data is particularly important for monitoring because, without baseline data, conclusions regarding performance and post-project changes cannot be made. Additionally, monitoring elements for the as-built conditions of the project should be measured very soon after project completion.

Common Monitoring Elements

Many monitoring plans are similar in the methods they specify for monitoring the physical and biological characteristics of a coastal site (Table 8-1). Some monitoring activities—e.g., simple beach profiling or periodic photographs—may be undertaken by the landowner, while others will require the help of a professional.

Table 8-1. Common physical and biological monitoring elements and their data collection methods.

Beach Characteristic	Examples of Monitoring Method
Beach profile	Level and stadia rod, two-stick method, total station, topographic survey
Sediment	Grain size analysis, photographs with scale
Driftwood	Map locations, transect counts, photographs
Saltmarsh vegetation	Assemblage mapping, density measurements
Submerged aquatic vegetation	Waterward extent, patch density, turion count
Invertebrates	Benthic coring, drop trays
Forage fish	Sediment sampling with egg counts
Wind/wave climate, high water levels	Photographs, NOAA data

Physical

The geomorphic, hydrographic, and other nonliving features of a project make up the physical characteristics of the site. As with all beach monitoring, it is important to perform monitoring with consistent interannual timing to avoid seasonal variability. Beach profiling can be performed using methods ranging from a very simple two-stick method (Emery 1961) to standard surveying methods using a total station for profile measurement to full beach topography. Permanent benchmarks are typically required for all methods to mark the locations of profiles and to provide a consistent reference elevation. The most common benchmark is a length of rebar (sufficiently long to be immobile) driven into the backshore away from storm waves.

Topographic surveying may be employed for larger sites, or where detailed quantitative analysis of results is necessary. The topographic data produced can be used not only to develop beach profiles, but also to determine the volume change of a beach over time. While the results are often considered a reliable way to analyze physical changes, the cost may be prohibitive for some sites such as small residential projects.

Changes in beach sediment over time can be an important indicator of impacts to the nearshore. Coarsening of the beach could indicate increasing wave energy at the site due to focusing or reflection of wave energy (Shipman et al. 2010). The most reliable method of sediment characterization is to collect a sample for grain size analysis. This involves sorting the sample into size fractions using a series of sieves of decreasing size to determine the proportion of each weight class within the whole.

Scaled photographs may also be taken of specific beach locations and elevations for a more qualitative analysis of change over time. Photographs taken at specific sampling times from fixed locations with a scalable and consistent reference are best (Figure 8-1). Beach sediment composition can be quickly documented using a quadrat with scale markings during and potentially between the main sampling events. Photographs of the substrate waterward of soft shore or hard armor installations should be documented while monitoring.

Figure 8-1. Photographic monitoring looking onshore with scalable reference at vertical bulkhead. Photographic monitoring should be done yearly at a minimum in the same location with the same reference. In this case, the same stadia rod or other known length scale should be used. Beach sediment quadrat also in photo for spatial location reference.

Biological

Saltmarsh vegetation plays an important role in the nearshore environment, and should be monitored for changes in coverage and assemblage. The simplest of methods is to identify the elevation, cross-shore width, and primary species of salt-tolerant plants. More advanced methods include the use of random quadrat placement for plant density and abundance measurement. It should be noted that interannual and seasonal variability are to be expected, so a longer-term record may be necessary to determine significant trends.

As with saltmarsh vegetation, submerged aquatic vegetation assemblages provide important habitats for monitoring, with eelgrass species the most noteworthy (*Zostera marina* and *Z. japonica*; Mumford 2007). Submerged aquatic vegetation is primarily monitored to determine the impact a project has on the special extent of the habitat. Monitoring may consist of simple mapping of the landward (and potentially the waterward) extent of the eelgrass bed, but could also include density measurements (e.g., turions per m^2) obtained through dive surveys. The growth period of eelgrass in the project area should be noted to time monitoring for the middle of the summer growth period and avoid other seasons when eelgrass may be removed by wave action.

Invertebrate assemblages are usually impacted in some way, often negatively, by shoreline modifications, either temporarily through direct disturbance of beach substrate during construction, or through long-term alteration of the character of the nearshore environment (Shipman et al. 2010). Invertebrate monitoring can be used to track how shoreline alterations impact these assemblages in abundance and diversity. Typically sediment cores are collected for laboratory analysis of species diversity and other relationships.

Forage fish are important marine species that are considered a primary food source for adult salmon and a wide variety of marine animals (Penttila 2007). Included are three species that make exclusive use of the nearshore for spawning purposes: surf smelt (*Hypomesus pretiosus*), Pacific sand lance (*Ammodytes hexapterus*), and Pacific herring (*Clupea pallasii*). Pacific herring spawn within eelgrass beds and macroalgae, while surf smelt and sand lance spawn on the upper beachface. Communities of these fish spawn in a variety of locations and seasons throughout Puget Sound. Spawn presence and timing should be investigated to determine need prior to developing a method of monitoring for spawning activity. For the best available science concerning sampling and analysis for surf smelt and sand lance eggs, see Moulton and Penttila (2001).

Qualitative

Smaller projects may not require the level of data gathering (and potential cost) of a large monitoring effort. For small projects qualitative assessment methods may be developed to help streamline the monitoring process while still measuring project performance in a reproducible way. The simplest method is development of a set of "photo points": from each point a photo is taken in the same direction at regular intervals with some fixed object for comparison year-to-year (Figure 8-2). A landowner may be able to take these photographs at monthly intervals for long periods as well as capture major events such as severe wind storms. Data collected in this way should still be examined by a trained professional prior to determination of project success. Photographic methods can reliably estimate changes in beach elevation and sediment composition over time.

Figure 8-2. An example of the beginning of photo monitoring from a fixed point over the first year post-project looking alongshore, with a rebar monument and conifer in the background as consistent reference points.

Reporting Monitoring Results

Monitoring data and analysis should be compiled at least annually in a consistent format that allows subsequent analysis against the established success criteria. Project data is best displayed as graphs and maps.

Monitoring Plan Checklist

While each monitoring plan will be tailored to the specific requirements of each project, some elements are common to all such plans. This checklist serves as a starting point for developing a plan that includes all relevant information.

1. Statement of objectives
    a. Project goals
    b. Monitoring objectives
    c. Success criteria
    d. Mitigation requirements
2. Monitoring protocol
    a. Geographic extent of monitoring, outlined using appropriate maps and figures showing data collection locations and permanent reference points such as benchmarks
    b. Temporal extent of monitoring, with duration and frequency of monitoring elements outlined to include both seasonal and tidal considerations

    c. Data collection methods and techniques for each monitoring parameter described, including specific equipment and training required
3. Mitigation requirements
    a. Mitigation threshold, explaining method for measuring the need for compensatory mitigation of project impacts
    b. Mitigation steps to be taken should a mitigation threshold be crossed. For example, specific steps such as addition of beach nourishment or a more general need for determination by a trained professional
4. Reporting protocol
    a. Number and distribution of copies of monitoring report
    b. Formats for reports and data
    c. Frequency of monitoring report submission

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Chapter 9. RESEARCH AND DEVELOPMENT

The *Marine Shoreline Design Guidelines* were developed by integrating new and existing design performance data with applied knowledge from Puget Sound professionals with expertise in the fields of coastal geology, engineering, geomorphology, ecology, and management. The case study assessment data (Appendix A) were conducted to inform the development of these guidelines. Although the case study assessment data have limitations, they provide a valuable foundation for future research. The management recommendations described in this document are also dependent on the current incomplete state of understanding of regional coastal and nearshore ecosystem processes in the region. Therefore additional research opportunities were identified that could refine engineering approaches and designs, improve management, and enhance local understanding of local coastal ecosystem processes.

Additional Performance Evaluation

The case study assessment entailed new quantitative field data collection at sites containing each of the 5 marine shoreline design techniques (beach nourishment, large wood, reslope/revegetation, bulkhead removal, and hard armor-which included both revetment and vertical bulkhead designs) as well as from adjacent reference sites. Significant effort was made to collect high-quality data and to make sure that the measurements could be replicated. Revisiting these same sites to document changes in site conditions could be informative, as the episodic, event-driven nature of Puget Sound geomorphic conditions results in changes that are often difficult to discern across shorter time periods. Continued monitoring and analysis could provide additional information on the long-term success or failure of designs and specific design elements, which would contribute to advancing project success in the future.

Additional case study sites that meet the project criteria should be surveyed to bolster the data set. Considerable time was spent identifying case study sites that met the site selection criteria, and acquiring permission to access these sites. Several potential sites were identified but not included because they did not meet the 3-year minimum project installation criteria when this project was initiated in 2011, but in time these sites will meet those criteria. Also, several design techniques had additional sites that fit the criteria but would exceed the identified number of case study sites to include. Projects installed several decades ago would be most beneficial for additional data collection in order augment longer-term performance data.

With enough additional sites, a more robust statistical analysis could be performed to aid in the identification of thresholds and further inform the degree to which particular variables drive project success. Effort could also be put into having the full range of shore conditions represented in the expanded data set.

Project Database

A regional database of shoreline design projects regularly maintained and updated by one entity (e.g. WDFW or Ecology) could be valuable in many ways, such as by aiding enforcement and academic research and providing data to design professionals. The database would ideally house permit, design, and monitoring data for all Puget Sound projects, and could be organized geographically and by project type. The database should also include ownership data, original design drawings, baseline and as-built surveys, before and after photos, contractor information, monitoring requirements, monitoring results, and other supporting reports and assessments. Long-term monitoring data could help researchers discern background noise or natural variability from subtle changes in the variables that are driving geomorphic trends or the success of a given shoreline design technique. This type of database could enhance the efficacy of project tracking, monitoring success, and eventually be used for a larger analysis that could further inform recommendations offered in this guidelines document.

Specific Data and Research Needs

Substantial research and mapping efforts have been applied across the 2,500 miles of the greater Puget Sound shore in recent years. Millions of dollars are invested annually in restoration projects in the Puget Sound region, yet there are still data gaps that need to be addressed for better management. Addressing the following broad scale data gaps could considerably decrease the uncertainty associated with project success for many nearshore restoration engineers and designers. Some of the regional data set needs (listed below) would allow for a large number of data users to take advantage of a common information base, allowing for the advancement of working with an understanding of both physical and ecological processes, as well as engineering practices. Broad scale data and research needs include:

- **Nearshore Bathymetry**. This is highly variable and generally lacking in resolution throughout the region, but is integral to the coastal modeling that is fundamental to design. Running blue-green LIDAR within a quarter-mile of the shoreline could provide valuable information for management applications.
- **Wave Energy**. Systematically defining wave energy with reasonable accuracy.
- **Erosion Rates**. Quantifying the range of erosion rates and sediment input across different drift cells and geomorphic shoretypes within the region to advance the baseline understanding of geomorphic processes in Puget Sound.
- **LiDAR.** Improving standardized application of airborne and ground-based LiDAR.
- **Sediment Budgets.** Characterizing and quantifying littoral sediment budgets in a limited number of representative drift cells to augment existing knowledge on basic processes and further inform analysis and design.
- **Biological Effects of Hard Armor.** Investigating the effects on biota from the range of alternatives to hard armor (with comparison to the impacts from hard armor) could be very informative. Similar to a recent study conducted by Megan Dethier and her colleagues at the University of Washington this potential research could inventory biota from soft shore protection sites along with paired reference sites.
- **Relocation Analysis.** Examining the long-term (25-50 years) effects and costs associated with installation and maintenance of erosion control as compared to relocation of buildings/roads.
- **Soft Shore Protection Definition**. Developing a robust and easily quantified definition of soft shore protection for regulatory and other use in the Puget Sound area (begun at Ecology).

A number of more focused research and data needs specifically relate to developing and advancing the details of different design techniques. The following list outlines areas of work which would be very beneficial for advancing the science of these design techniques:

- Studies into the mobilization and transport of different gravel clast sizes at beach nourishment and reference beach sites.
- Sediment volume loss rates at beach nourishment sites and identification and quantification of events causing moderate sediment loss.
- Wave and log interactions.
- Effects of anchored large wood on sediment and LWD stability and transport. Detailed monitoring at large wood sites is much more limited than at beach nourishment sites.
- Development of low-cost, semi-quantitative, and consistent ways to evaluate effectiveness of vegetation in stabilizing different soil/sediment types. Detailed work attempting to isolate the effects of different slopes and vegetation relative to different soil types would be very useful.

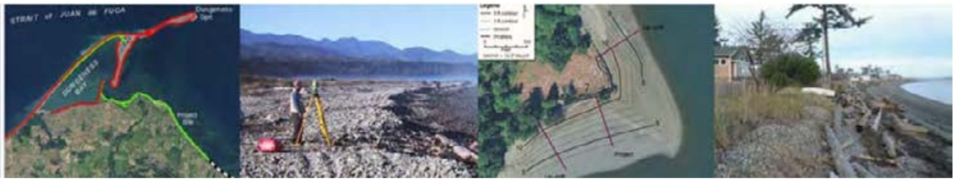
- Sediment mobility/stability in relation to utilization by biota at bulkhead removal sites.
- Hard armor and beach interactions at mixed gravel and sand beaches in the Puget Sound area. . Data is lacking from sheltered marine shores, which has hindered detailed analysis of bulkhead impacts.

Many opportunities exist to expand on the data derived from this effort. Augmenting and formally developing a shoreline design database could provide exceptional value for managers, researchers, and designers alike. Further research that aims to quantify the range of variability in geomorphic conditions across space and time in the Puget Sound region, higher resolution mapping of nearshore bathymetry, and wave data could further inform restoration designs. Together these research and data management developments could lead to greater certainty in the success of restoration designs and result in improved management with reduced negative impacts to habitats. Additionally, these data would yield improved local understanding of how Puget Sound nearshore conditions may change across time, particularly in the context of climate change and sea-level rise.

Outreach Needs

In addition to these research and development needs, ongoing outreach and education is critical in order to engage the growing number of marine shore landowners in informed and responsible stewardship. Approximately two-thirds of the Puget Sound shore is private property, and the management decisions of these landowners can either continue to increase negative impacts or result in improvement. Involving and supporting landowners in increasing their own knowledge of coastal processes, alternatives and their impacts, and providing guidance for enacting habitat improvement projects at private is therefore critical.

Marine Shoreline Design Guidelines



APPENDIX A

Case Study Report

2013 Final

Prepared for:

The Aquatic Habitat Guidelines Program

Prepared by:

Coastal Geologic Services Inc.

With Qwg Applied Geology

Prepared for:

Washington Dept. of Fish and Wildlife

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Introduction

Shoreline modification—the construction of bulkheads, seawalls, and other types of shore protection—has become a significant environmental issue on Puget Sound. These modifications, also called shoreline armor, affect beaches and other coastal habitats, alter coastal ecology, and reduce the resilience of the coast to rising sea level (Shipman et al. 2010, Johannessen and MacLennan 2007). Shoreline modification has proliferated in the Puget Sound region. Bulkheads, nearshore fill, roads, and other structures modify approximately 27% of the Puget Sound shore singly or in combination (Schlenger et al. 2011). Most residential development along Puget Sound shores occurs at the common bluff-backed beaches and barrier beaches. The bluff-backed beaches are cumulatively 33% armored, and the barrier beach shoretypes are cumulatively 27% armored Sound-wide (Simenstad et al. 2011).

Protecting Nearshore Habitat and Functions in Puget Sound (EnviroVision et al. 2007) and the majority of local shoreline master programs state that planners should enforce or encourage the use of alternative design methods in nearshore development projects to avoid and minimize environmental impacts where erosion control is needed. Currently, no comprehensive document provides a technical foundation for the design of alternatives to rock and concrete bulkheads or for the myriad of other projects, including restoration projects, which are proposed for our shores.

The term “soft shore protection” is used to describe alternative shoreline erosion control approaches in this region (Johannessen 2000). A study by the Washington Dept. of Ecology titled *Alternative Bank Protection Methods for Puget Sound Shorelines* (Zelo et al. 2000) outlined the locations and approaches used for a variety of soft shore protection techniques around Puget Sound and included varying amounts of design data. However, the document lacked a performance assessment. In addition, many projects examined were either new or still in progress. A later study titled *Alternative Shoreline Stabilization Evaluation Project* (Gerstel and Brown 2006) outlined a different suite of projects in Puget Sound. That study included a general qualitative assessment of project performance, but lack of funding prohibited actual data collection or quantitative performance analysis.

In this two-phased project, Marine Shoreline Design Guidelines (MSDG) will be developed through collection and utilization of new field measurements, coverage of a greater number of sites than in previous studies, and a rigorous, quantitative assessment of project performance. Coastal Geologic Services (CGS) was contracted by the Washington Department of Fish and Wildlife (WDFW) to conduct the Phase 1 Survey and Assessment of Shoreline Armoring Techniques in support of the MSDG development. In Phase 1, the subject of this document, 25 shoreline protection sites were examined, each of which uses one of six general design techniques commonly used on Puget Sound shorelines. Phase 2 will use the data collected in Phase 1 to develop engineering methods and the design guidelines document.

The overall goal of this project is to develop a scientifically sound tool for improved management of shoreline armoring, a document that can be used by:

- Shoreline owners, project designers, and contractors to improve construction methods;
- State and local governments to improve shoreline decision-making;
- The broader Puget Sound community to increase awareness and stewardship of shorelines and beaches.

An additional goal includes direct use of the guidance document to:

- Present alternatives that could avoid or minimize ecological impacts to Puget Sound nearshore habitat,
- Facilitate better decisions by resource managers and restoration planners about siting and design of alternative erosion-control projects,
- Help local jurisdictions and willing citizens properly steward aquatic and riparian ecosystems in their communities and watersheds.

The specific objectives of this Phase 1 contract were to:

- Create the conceptual framework and quantitative basis for the development of soft shore-protection methods,
- Publish at least 24 case studies that include the six major shoreline-protection techniques (listed below) and contain all the resources and data collected in connection with Phase 1.

This document is organized into several different sections. The *Project Approach* section describes the types of design techniques and provides an overview of the analysis process. The *Methods* section provides a description of field and analysis methods used to prepare the case study narratives. This is followed by the 25 *Case Study Narratives*, and finally a brief *Discussion* section, which includes a summary of the findings from the case studies. A project database, delivered separately, contains all of the data collected in this phase of the project. Additional analysis of the case study data and results will be completed using the project database in Phase 2 to develop engineering methods and write the design guidelines document.

Project Approach

Design Techniques

The Phase 1 Survey and Assessment addresses six general design techniques (Table A-1) commonly implemented on Puget Sound shorelines. We initiated the study with a project performance evaluation approach incorporating factors that contribute to project success. To evaluate methods of assessing appropriate technique selection, we developed draft models for the six design techniques and a detailed approach for measuring project benefits and negative impacts. We also developed several supporting tools, including field data forms, a narrative template, and the foundation for the project database. Each of these products was intended to capture the goals and objectives outlined above, but with greater detail. The outline for this study was initially conceived by WDFW, developed by CGS, and refined in collaboration with the steering committee.

Table A-1. Shoreline protection design techniques assessed in this project.

Design Technique	Description
Beach Nourishment (BN)	Beach nourishment is the addition of sand and gravel to build the beach to mitigate coastal erosion.
Large Wood (LW)	Placement of large wood to retain beach materials and dissipate wave energy (may contain some rock to provide ballast but not in excess of 20% areal density).
Reslope/ Revegetation (RE)	Resloping is lowering the slope of the bank to increase stability. Revegetation is planting a bank with native riparian vegetation to create a root network (and ultimately, shrub or tree canopy) that reduces erosion. It can be applied to the existing bank or one which has been resloped. This technique is exclusively applied to the upland (above MHHW and the OHWM).
Bulkhead Removal (BR)	A beach restoration design technique applied along shores where coastal erosion is not substantial or where armor serves solely as a feature of landscaping. The beach may be restored while infrastructure remains unaffected.
Hard Armor-Rock Revetment (RV)	Placement of stationary sloping rock, e.g., “riprap”.
Hard Armor-Vertical Bulkhead (VB)	Vertical face structure constructed of concrete, sheet pile, rock, or wood.

Study Design Overview and Phases

For the purpose of this project, CGS assumed that a successful shoreline erosion control design would include the following key elements:

- Appropriate design technique for site conditions at the landscape (process-unit) and site-specific (parcel) scale.
- Adherence to general design standards.
- Maximized benefits and minimized negative impacts to nearshore processes and habitats.

We developed project selection, data collection, analysis, and assessment steps and that integrated each of these elements. All of the steps in the larger analysis are described in detail in the *Methods* section, below. An overview of the approach is outlined here to put the steps in context (Figure A-1).

First, a list of appropriate erosion control projects needed to be compiled and assessed to select a representative list of case study sites for completing measurements and assessment. Early on in the project, we created a hypothesized design model for each of the design techniques examined in order to shape data collection methods and allow for testing of specific design criteria in Phase 2 of this project. GIS/CAD assessments applied a larger scale approach and wherever data allowed explored such characteristics as drift-cell condition, up-drift sediment supply and transport, topography, and erosion trends and rates. Following data collection and analysis, assessment data were imported and organized into the database for further analysis.

Performance of each case study project was evaluated by assessing effectiveness of erosion control and the degree and type of both benefits to nearshore processes and negative impacts to these processes and habitat areas. The analysis included how appropriate the design was at both the landscape and site-specific scales. Results from these analyses are a combination of quantitative scoring and qualitative assessment that integrates elements discussed here (Figure A-1).

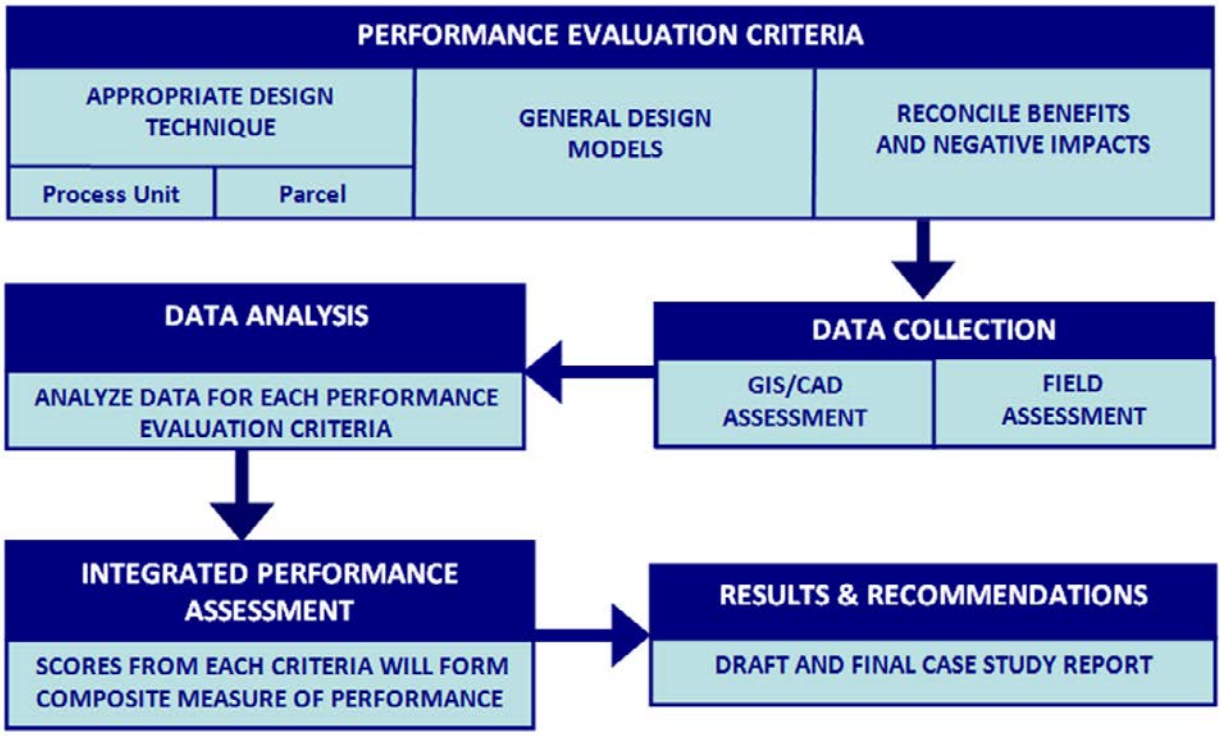

Figure A-1. Outline of approach to case study project design and performance assessment.

Results of the Phase 1 work are presented as case studies for each site. A summary of performance was included on the final page of each case study and an overall summary of how the suite of projects for each design technique performed is discussed following the case studies. The *Discussion* section that follows includes brief additional analyses integrating these case-study results across the different sites. While we did not expect one-size-fits-all designs to be the outcome of this phase of the work, the case studies identified a suite of general design approaches and specific project-design elements appropriate for different conditions.

The engineering analysis and guidelines (Phase 2) will entail examining the range of conditions at each site and within each of the design techniques, identifying design oversights, testing hypothesized design models, and contrasting project benefits and negative impacts. Analysis will be linked with field observations and GIS/CAD outputs to identify critical site conditions, elements that contributed to project success or failure, and approaches to maximize project benefits and minimize negative impacts for each design technique.

Methods

The methods used for field sampling and analysis in Phase 1 were designed by CGS to fulfill the requirements of the Scope of Work and the Quality Assurance Project Plan (QAPP; CGS 2012). These called for a comprehensive technical foundation for the design of alternatives to shoreline armor and for proposed restoration actions for shorelines, such as bulkhead removal. This project design involved three fundamental elements carried out sequentially for each case-study site to assess the performance of each project:

- Site selection
- Data collection and analysis
- Performance evaluation

Task 1 included development of the assessment design in the form of the fully reviewed and approved QAPP. The QAPP provided guidance for the sampling process, including the approach and general methodology, detailed design methods with hypotheses to be tested using data collected in the field, detailed protocols for field data collection, and a draft field form.

Site Selection

Task 2 involved site selection for the case-study sites that represent the six erosion-control techniques defined by WDFW (Table A-1) that this project assessed. . Initial planning called for four case-study sites and one alternate to be selected for each of the design techniques. A list of potential case-study sites compiled in a project spreadsheet showed attributes of each site, including design technique, right of access, site survey type, shoretype, maximum fetch, year of construction, orientation, contact data, upland topography, geology, and drift-cell name. For case-study sites on private property, landowners were contacted by phone or email. Sites were selected based on a range of conditions (primarily fetch and wave exposure and geomorphic shoretype), available data (from sources that included design drawings, preproject and as-built documents, and follow-up monitoring), and permission from owners.

After gathering approximately 110 projects in the working list from a wide variety of sources, we selected 33 projects based on goals identified in the scope of work. The selection process incorporated the following considerations:

- The landowner must grant permission,
- Conditions must be safe for the contractor to do the work,
- There must be adequate baseline information (baseline survey, construction drawings, as-built surveys, previous monitoring, and photographs) to document performance over time,
- The project must be at least three years old and have experienced one or more significant storm events,
- The majority of projects must use only one design technique,
- The project should have been properly constructed using appropriate materials for the conditions. Failure should not be due to poor materials or workmanship,
- For a site to be considered “soft,” the majority of the project (80%) must be constructed of naturally occurring materials used in ways that are consistent with current nearshore processes,
- Site selection should minimize the variation in site-specific conditions that often confounds efforts to generalize performance trends,
- Sites should be stratified by shoreform and exposure (e.g., barrier beach, medium SE fetch),

- Sites selected for each design technique should represent a range in process-unit conditions to show a gradient across which the technique has been applied.
- From the list of eligible candidates for each design technique, four were selected.

The majority of the projects identified came from the following sources:

- Hugh Shipman of the Washington State Department of Ecology (Ecology),
- WDFW habitat biologists,
- Coastal Geologic Services project files,
- San Juan County Planning and Community Development,
- City of Bainbridge Island and City of Anacortes Planning,
- Alternative Bank Protection Methods for Puget Sound Shorelines (Zelo et al. 2000),
- Alternative Shoreline Stabilization Evaluation (Gerstel and Brown 2006),
- Consulting firms.

The intent was to identify projects across the range of physical conditions, project sizes, design approaches, and the spatial extent of Puget Sound. To augment the new data collected for this project and allow for a robust analysis, projects with completed survey and physical monitoring data were included. The team was not able to compile enough data on many sites, and was unable to get the required five projects (four plus one alternate) for the bulkhead removal and reslope and revegetation design techniques. Fewer bank reslope and revegetation projects have been constructed in recent years in the Puget Sound region, fewer than anticipated when the study was envisioned Efforts to complete those lists continued at several levels at government agencies, nonprofit organizations, consulting firms, and others for approximately three months.

Finding projects with adequate baseline information (construction drawings, as-built surveys, previous monitoring, and photographs) to document performance over time proved difficult, even before satisfying other requirements. Some potential project sites contained large gaps in design data or in as-built surveys, or lacked any type of documentation of installation or performance. Some site owners or designers would not allow access to the site or design drawings. Many other potential projects failed to qualify because they were less than three years old. The shortage of projects with even most of the required baseline information made it necessary to include more CGS-designed projects than initially intended; these projects generally had full design details and much more quantitative data available.

In order to clearly understand the performance of a given project type, the study design required that projects consist mainly of one element. This requirement precluded a large number of potential projects that consisted of a combination of elements. Where it was difficult to find enough projects that met all of the requirements, this standard was relaxed slightly to allow for the selection of several projects with multiple elements but in which one element clearly dominated the design. Most of the reslope and revegetation projects identified did not meet site-selection criteria; about half of all projects identified were eliminated because they were constructed landward of roads, driveways, or hard shore protection and were not slowing coastal erosion at the toe of a slope. The number of reslope and revegetation projects was reduced to two, and the number of beach nourishment and large wood projects was increased to five each. This new distribution of projects probably reflects the actual proportion of each type constructed and their relative suitability for most situations.

Data Collection and Analysis

Data Collection

This section briefly describes the field protocol and equipment. A more detailed description of the field manual, field forms, design models for design techniques, GIS data checklist, and quality assurance approach are found in the Quality Assurance Project Plan (QAPP; CGS 2012). The project database is included as a separate deliverable.

Overall, length and distance measurements were made with a tolerance of 0.5 ft and beach slopes within 5%. Vegetation cover and areas of erosion, harder to measure quantitatively, were estimated within 10% of width or area.

Field Protocols - A glossary of terms and field data collection protocols were established for each attribute included on standardized field data forms (see QAPP). Field data were collected from each site using consistent protocols and equipment to assure a high level of quality, consistency, and repeatability across sites.

Survey dates for each site were selected based on the tidal elevation of design features and assurance of access. Preparation for fieldwork included reviewing as-built or baseline survey data, historic photos, and CAD files and establishing local control sites for the survey total station.

Field Forms - Standardized data-collection forms were used to record site attributes. Field data forms listed the attributes to be measured, mapped, and characterized at each site. Slightly different forms were created for different design techniques to capture the most relevant characteristics and specifications of the various design applications.

Quantitative measurements such as length and height were measured directly with appropriate devices (e.g., 100-ft tape measure). Qualitative assessments of field form elements such as sediment characterizations were made by a qualified field technician. Individual field-form entries were defined in detail in the QAPP.

GPS Data - Geospatial data were collected using one of two handheld differential GPS units (Trimble Geo-HX 2008 and Trimble Geo-HX 6000) to both locate and augment field data. All data were collected and processed using CGS's internal Standard Operating Procedure (SOP) for GPS data: point, line, and polygon data were collected with an attached note briefly describing the data being gathered. Every effort was made to produce location data of the highest horizontal accuracy, with the aim of achieving 1- to 2-ft post processed accuracy for most data using data from the nearest WA CORS (Continuously Operating Reference Stations) base station. The QAPP provides additional detail.

Survey Data - For sites with prior field-survey data, a topographic survey was completed using a high-quality total station with direct rod measurements. A Leica TCR-1105 total station, regularly calibrated at a certified Leica shop, was used. Staff members authorized to operate the total station were first trained in CGS's survey SOP. All efforts were made to locate and reoccupy project monuments and established survey monuments/bench marks, if available, to maintain the same project coordinate system. In the absence of survey control, other location data were used, such as building corners, piles, signs, or other fixed objects that match previous project surveys. Survey monuments and location data were augmented by occupying each control point with a differential GPS unit for a minimum of 6 minutes, which was post processed using the nearest WA CORS base station as above.

Each survey point was collected in Leica GSI format with position, angle, and distance data. Measurement files were converted to comma-separated text files using Leica's Gifcon program and then examined in Microsoft Excel, where any corrections based on field notes were applied. The corrected file was imported into AutoCAD

Civil 3D. Any corrections for position and orientation were then applied by aligning points to known locations from survey benchmarks or GPS data. Some features mapped by survey were digitized from the survey points and exported to ESRI shapefile format for inclusion in the project geodatabase. Both raw and corrected survey point files, along with point descriptions used in this study, were archived in the project database. Information on data quality control can be found in Audits & Reports sections in the QAPP (CGS 2012).

Ground Photos – Site features, design project components, and the context within the site were digitally photographed during each field visit. Previous ground photos were reproduced for comparison to project data during performance analysis. Field data collected included the following:

- Physical beach data: beach slope from hand-level profiles or total-station survey equipment; sediment composition; signs of marine-induced erosion; backshore upper-beach character; vegetation waterward of any structures at risk such as houses or roads; and freshwater sources, drainage, or seeps.
- Treatment or structure data associated with the design technique: condition of design feature; dimensions of design feature; toe elevation, height, footprint; presence or absence of backfill; indicators of wave overtopping; waterward or adjacent scour; intact connectivity alongshore and across shore; access; adjacent impacts or effects associated with the design technique; and maintenance required.
- Adjacent site data: same or different shoretype; slope; drainage; whether armored and if so the basic structure information; sediment composition; and signs of erosion.
- Upland conditions immediately landward of the design technique: characterization of vegetation, including marine riparian vegetation assemblages; disturbance or presence of nonnative species; condition of native vegetation as related to slope stability such as jack-strawed trees; setback of house or other structures related to design technique; bank or bluff geology if applicable; and upland topography.

Models and Data Compilation

Data Compilation - Some data which complemented site surveys were compiled in the office using GIS applications or by viewing oblique or vertical aerial photographs. These included drift-cell length, drift-cell condition as compared to historic condition, design technique impact on sediment processes, calculated background erosion rates from analysis of shore change using historic aerial photographs where applicable and possible, upland drainage, potential additional sources of wake such as local marina and ferry traffic, and, where available, cost of treatment per linear foot.

All data collected in the field and compiled in the office were documented in the Microsoft Access database. GPS data, photos and videos, and hand-level and survey data were processed after returning from site surveys. Plan and cross-section views were created for each case-study site in AutoCAD and GIS. Other field survey data were brought into GIS or CAD for comparison with baseline and/or as-built surveys to determine areas of change and in cases with complete data sets, to create topographic surface change and/or determine erosion trends and rates.

Attributes collected for each case-study site, either in the field or via GIS, were recorded and include the following:

- Characteristics of successful or failed project elements if apparent,
- Shore orientation and fetch to assess low, medium, high, or very high wave energy,
- Drivers of erosion, either marine, subaerial (e.g., stratigraphy/groundwater), or human-induced,

- Upland relief,
- Shoretype.

The field data were analyzed to evaluate the success or appropriateness of each design technique for shoreline erosion control. Completed case-study narratives display data in a variety of ways, including maps, field photos, and survey data in plan and cross-section views, and other relevant field data.

Performance Evaluation Criteria

Performance evaluation criteria help determine how well-suited a design technique is for the site conditions and how well it was designed. Each of these factors—suitability and design quality—commonly contribute directly to project success or failure, either independently or in combination.

Site Characteristics

The process of selecting appropriate design techniques is fundamental to a successful design project. Site characteristics at the landscape and site-specific scales are both important. Miscalculating or neglecting to account for either set characteristics can result in project failure.

Landscape-Scale Criteria - The landscape-scale assessment was limited to characteristics of the net shore-drift cell, also called a shoreline process unit in previous work by the Puget Sound Nearshore Ecosystem Restoration Project (PNSERP), and other larger physical parameters such as fetch and bluff morphology. Landscape or shoreline process-unit attributes that influence design success (Table A-2) were assessed both in the field and in the office using GIS and CAD. Measured maximum fetch with aspect and shore orientation provided measures of wave energy potential and the frequency at which a site endures considerable wave attack. Geology and topography data helped characterize landscape-scale processes occurring within the process unit. The location of the site with respect to the drift cell, generally described relative to origin, center, or terminus of the cell, and the orientation of the site relative to the predominant wave approach can be used to infer or estimate the relative rate of sediment transport. These landscape-scale criteria, developed based on work by Keuler (1988), Finlayson (2006), Johannessen and MacLennan (2007), and Clancy et al. (2009), represent site characteristics that contribute to erosion at a given site (Table A-2).

Table A-2. Landscape-scale criteria that contribute to erosion and project design.

Criterion	Purpose	Data source
Maximum measured fetch, aspect	Maximum wave energy	GIS
Angle of predominant wave approach	Wave energy and sediment transport	GIS
Bluff/bank morphology	Indicator of erosion/ mass-wasting processes	LiDAR/GIS
Location in drift cell	Sediment transport	GIS

Site-Scale Criteria - As discussed above, location within the net shore-drift cell sometimes gives an indication of the general amount of littoral drift that can help naturally replenish the beach at a site. Several other characteristics specific to a site or parcel influence design technique selection and development and each of these, collected by field and/or GIS assessments, was assessed as part of the performance evaluation (Table A-3). Identifying the predominant driver of erosion/recession at a site is relevant to the selection of an appropriate design technique. For example, if erosion occurs largely due to poor surface water management on the uplands, installing a rock revetment to preclude wave-induced erosion does not adequately address the issue.

Upland geology was investigated because bluff stratigraphy greatly influences erosion and mass-wasting, and therefore bluff stability. A bluff comprised of outwash sands is less cohesive and has a flatter slope than a bluff comprising more consolidated material such as dense silts or till. The movement of groundwater and surface water also affects slope stability and bluff processes. These conditions, in combination with setback distance (e.g., from a bluff crest) and structure type helped identify the degree of risk associated with a given shore protection technique.

Table A-3. Site scale criteria that contribute to erosion potential and performance assessment.

Criterion	Purpose	Data source
Dominant driver of erosion:	Technique selection evaluation	Field assessment
Groundwater and surface water	Drivers of recession, stability	Field assessment
Upland geology, bank	Drivers of recession, stability	GIS
Bluff/bank morphology	Drivers of recession, stability	Field assessment
Setback distance	Risk	Field assessment/ GIS
Background erosion rate/trend	Design evaluation	GIS
Upper beach/backshore width/condition	Design evaluation	Field assessment
LWD band presence/width	Design evaluation	Field assessment
Beach slope	Design evaluation	Field assessment
Evidence of erosion	Design evaluation	Field assessment
Adjacent shore(s) condition	Characterize natural range of conditions	Field assessment

Criteria in Table A-3 are useful for assessment at the site level. Some are categorical observations recorded as either present or absent. The width and slope of the upper beach and backshore determine the area available for installing a design technique and whether topographic alterations are required. Backshore elevation and indicators of marine-induced erosion, such as wave-erosion scarps, and the presence of large woody debris can indicate the frequency and magnitude of significant wave action at a site. The conditions of “untreated” adjacent shore or reference shores were used to provide a reference to natural conditions to inform design selection, particularly if the baseline data were sparse or the subject site was already modified.

How to Measure Cumulative Risk

A cumulative risk model was developed for these guidelines which integrates natural conditions with risk to infrastructure (Table A-4; also outlined in the section by the same name in Chapter 3). The model was calibrated and refined using data from the 25 case study sites, along with some additional site data from Shipman et al. (unpub.) and unpublished data from other sites. The first step of the risk model entails quantifying the erosion potential of the site by evaluating its shoretype and maximum fetch. Shoretype mapping (sometimes called feeder bluff mapping) was recently compiled and completed for Ecology (MacLennan et al. 2013). The sites with the greatest erosion potential are high bluffs with considerable wave exposure that are characteristically receding and contributing large volumes of sediment to the nearshore (feeder bluff exceptional and feeder bluff, in order). Shoretypes that typically have minimal erosion (accretion shoreforms) receive a lower score under erosion potential, while bedrock and low energy shores (with no appreciable drift – NAD-LE), get the lowest score. Sites with greater fetch have greater erosion potential; hence the shoretypes with greater fetch receive a higher score in this category. The shoretype score is then added to the fetch score to give the resultant erosion potential score (Table A-4).

Table A-4. Cumulative Risk Model. Fetch = whichever is greater: maximum fetch from southern quadrant or half of maximum from other aspects. Setback distance = measured distance from bluff crest (or OHWM for no-bank) to most waterward infrastructure. This is the same table as Table 3-4 in the main document.

CUMULATIVE RISK MODEL			
EROSION POTENTIAL			
Shoretype	**Score**	**Fetch**	**Score**
No Appreciable Drift (NAD)-Bedrock/Low Energy	0	0–1 mile	1
Modified, Accretion Shoreform, NAD-Delta	1		
NAD- Artificial , Transport Zone, Pocket Beach	2	1–5 miles	2
Feeder Bluff	3	5–15 miles	3
Feeder Bluff Exceptional	4	15+ miles	4
Erosion Potential Score =	**Shoretype Score + Fetch Score**		
INFRASTRUCTURE THREAT			
Setback	**Score**	**Infrastructure Type**	**Score**
>60 ft	1	Property without structures	1
36–60 ft	2	Septic drainfield or unattached residential infrastructure, not lived in	2
21–35 ft	3	Home or residential building	3
0–20 ft	4	Major infrastructure	4
Infrastructure Threat Score =	**Setback Score + Infrastructure Type Score**		
CUMULATIVE RISK TOTAL (product):	**Erosion Potential x Infrastructure Threat**		

Because the natural processes of erosion and mass wasting do not pose a risk unless infrastructure is threatened, the type and proximity of infrastructure are critical to qualifying risk at a site. Minimal risk is assumed for shores in which structures are adequately setback from the shore, regardless of value or erosion potential. The magnitude of the risk directly corresponds to the setback distance, type of infrastructure, its value, and whether or not it can be relocated. Landscaping features are not considered for risk scoring as they are assumed to be mobile and therefore not a true risk. The setback distance from either the bluff crest, or from OHWM for sites without a bluff or bank, to the infrastructure provides an indicator of the magnitude of cumulative risk: the lesser the setback, the higher the setback score risk number (Table A-4). The highest score for infrastructure type is given to major infrastructure such as primary commercial or industrial buildings, or public roads, followed by a home or residential building. The two infrastructure threat variables (setback and structure type) are then added together to estimate the infrastructure threat.

The final step in the cumulative risk model is to multiply the erosion potential score by the infrastructure threat score to provide the cumulative risk score, which represents the magnitude of risk. With this model, the highest possible cumulative risk score is 64. The highest cumulative risk score for the 25 MSDG case study sites was 42.

Examination of the cumulative risk model results (Appendix A) allowed for determination of different risk classes (e.g., low, medium, high) as follows:

- Low risk scores between 0 and 15
- Moderate risk scores between 16 and 36
- High risk scores greater than 36

The cumulative risk model score helps to distinguish the perceived and actual need for erosion control at the subject site. The risk model score along with other site characteristics will help define which design techniques are appropriate for the subject site.

Project Benefits and Negative Impacts—All Projects

Building on the initial analysis of the landscape-scale analysis and field assessment work, a key study element was documenting project benefits and negative impacts to the nearshore. Project benefits included the degree to which infrastructure was successfully protected by slowing on-site erosion (excluding bulkhead-removal projects), the degree to which various nearshore processes were directly or indirectly enhanced (e.g., augmented sediment volume), and whether or not the project was of reasonable cost and simple to install. Benefits were contrasted against negative impacts associated with each project/design technique.

Many of the negative impacts potentially associated with erosion-control projects have been inferred and are rarely, or never, quantified in the field or in direct association with a design. It was therefore critical to document the types, magnitude, and spatial extent of benefits and negative impacts associated with individual projects and project types. Knowing the full range of impacts will shape the development of the design guidelines and better inform practitioners as to which design technique and material sizing/placing best matches site conditions and accomplishes project goals while incurring the lowest possible negative impacts to the nearshore. Towards this end, a consistent and quantitative approach was needed to score both benefits and negative impacts.

The list of potential negative impacts was compiled from *Puget Sound Shorelines and the Impacts of Armoring—Proceedings of a State of the Science* (Shipman et al. 2010) and a series of earlier studies and papers. Negative impacts include such effects as the burial of backshore/intertidal areas by engineered structures, or reduction of the littoral sediment supply. The complete list of potential benefits and negative impacts used for all projects with associated qualifications, scores, and scoring criteria are listed in Table A-5. With the exception of the first benefit (stopped landward erosion), which scored double points, scores for *none* or no effect received a 0, *low* scores received 1 point, *medium* scores received 2 points, and *high* scores received 3 points.

Table A-5. Project benefits and negative impacts scoring criteria for all design techniques.

Benefit (all projects)	Scoring criteria			
Positive	None	Low (+1)	Medium (+2)	High (+3)
Effectively stopped or slowed landward erosion/protected infrastructure *(except bulkhead removal)*	Erosion	*Minimal landward progression or scarping*(+2)	*Stopped landward progression with significant overwash, no scarping *(+4)	*Stopped landward erosion, minimal overwash and no scarping *(+6)
Sediment volume augmented (from placement or bluff input)	None	Nourishment	Input from Feeder bluff allowed	Feeder bluff input and Nourishment
Input/exchange of LWD, detritus	Impeded alongshore and cross-shore	Allows either alongshore or cross-shore	Allows both alongshore and cross-shore	Improved input/exchange to alongshore and cross-shore
Backshore vegetation enhanced (composition, area, or both)	none	<3' average width enhanced	3'–10' average width enhanced	>10' averaged width enhanced
Marine riparian vegetation enhanced (composition, area, or both)	none	<6' average width enhanced	6'–20' average width enhanced	>20' averaged width enhanced
Low cost and simple installation	>$350/LF	$225–$350/LF	$100–$225/LF	<$100/LF

Impact (all projects)	Scoring criteria			
Negative	None	Low (-1)	Medium (-2)	High (-3)
Bury backshore /intertidal area	+ or 0	0–3ft width	3–7ft width	>7ft width
Impound littoral sediment supply	+ or 0	Bank 0–5ft elevation	Bank 5–30ft elevation	Bank +30ft elevation
Coarser/ steeper beach profiles created	+ or 0	Slope <5%	5–15%	>15%
LWD/ organic matter recruitment reduced	+ or 0	Log width reduced 25%	Reduced 25–50%	Reduce >50% or no log zone
End erosion adjacent	+ or 0	One end 0.25–2ft	One end >2ft OR both ends 0.25–2ft	Both ends>2ft OR one end>4ft
Required maintenance interval	None or >30 years	15–30 yrs	5–15 yrs	<5 yrs

*Scores for criteria in the first benefit (effectively stopped/slowed landward erosion) are doubled.

Benefits were scored positively and impacts negatively. For example, if a project stopped landward erosion but had significant overwash without any major scarping, the project would score +4 for the first benefit because this is defined as the *medium* criterion. Scores for this first benefit are doubled to reflect the importance of landward erosion on shoreline design. Most shoreline design projects exist because of shoreline erosion and access and coastal erosion typically drives original project installation. If the project included beach nourishment in its design and also allowed the feeder bluff to continue to supply sediment into the system, it would score a *high* in the second potential benefit line, for a score of +3. Each benefit and negative impact was evaluated and scored in this way for all projects, with the single exception of bulkhead removal projects. The breakdown of how each project scored and why is included in the final section of each project case study.

Criteria and scoring are quantitatively outlined in Table A-5 (above) and are further defined below.

Benefits

Effectively stopped or slowed landward erosion/protected infrastructure: Criteria used were the horizontal measurement of landward erosion in the form of erosional scarps or damage landward of the structure, or significant overwash and loss of sediment, or both. Criteria scores for this benefit were doubled to stress the importance of whether landward retreat in the project area was reduced.

The bulkhead removal technique had a different scoring approach for the first project benefit (only) because bulkhead removal often has the opposite goal of restoring as opposed to altering natural coastal processes. Instead of awarding higher points for stopping/slowing landward erosion, the general criteria of restoring natural processes through the removal was the focus of the first scoring parameter. An example of restoring natural processes would be to remove a bulkhead and fill to allow for natural exchange of sediment, LWD, and other material and to restore upper beach, backshore, and marine riparian areas. Another example would be removing a bulkhead to restore feeder bluff sediment input, along with some combination of other natural processes. Therefore, the degree of restoration of these processes was the focus of this first criterion.

Sediment volume augmented (from placement or bluff input): Benefit evaluation criteria were developed to capture if the project enhanced the sediment volume in the drift cell by removing armor to restore bluff sediment exchange processes and/or by importing sediment that was suitable for inclusion into the beach system.

Input/exchange of LWD and detritus: Benefit evaluation criteria were developed to determine if the project design allowed for or enhanced LWD and detritus exchange on the project site. A project that allows alongshore exchange is one that continues to let LWD/detritus move along the drift cell and does so without down-drift blockage. Impeded alongshore exchange could be due to a structure that collects LWD/detritus. Cross-shore exchange is defined as the movement of LWD/detritus from landward locations of the project to waterward areas and vice versa. Enhanced cross-shore exchange would result if the project allowed for a potential increase in LWD/detritus because removal of a barrier allowed for fallen trees/branches to be deposited in the system. Impeded cross-shore exchange could be due to a structure of sufficient height and/or one placed out on the beach so as to inhibit cross-shore movement of LWD/detritus.

Backshore vegetation enhanced (composition, area, or both): Benefit evaluation criteria were developed to determine if the project enhanced the backshore vegetation by either adding to the assemblages found on the site preproject or by planting new backshore area with appropriate vegetation.

Marine riparian vegetation enhanced (composition, area, or both): Benefit evaluation criteria were developed to determine if the project enhanced the marine riparian vegetation (necessarily including native tree species) by either adding to the assemblages found on the site preproject or by planting new marine riparian area.

Low cost and simple installation: Benefit evaluation criteria were developed to determine if the project used techniques that are relatively low cost and straightforward when compared to other shoreline design techniques.

Impacts

Bury backshore /intertidal area: Impact evaluation criteria were developed to determine if the project design caused burial of preproject backshore or intertidal area, and if so the horizontal degree to which it was buried.

Impound littoral sediment supply: Impact evaluation criteria were developed to determine if the project design and installation limited or eliminated preproject littoral sediment supply by creating a cross-shore barrier to wave attack at the feeder bluff and/or by blocking sediment delivery from bluff to beach. These impact criteria are based on the height of the feeder bluff.

<u>Coarser/ steeper beach profiles created:</u> Impact evaluation criteria developed to determine if the project site beach profile was steeper than adjacent profiles or if the site beach substrate was coarser than that at adjacent beaches at the same elevation(s).

<u>LWD/ organic matter recruitment reduced:</u> Impact evaluation criteria were developed to determine if the project inhibited or eliminated recruitment and retention of LWD or organic matter to the site, measured in terms of average cross-shore width of the log band.

<u>End erosion adjacent:</u> Impact evaluation criteria were developed to determine if the project design or installation exacerbated erosion immediately adjacent to the project ends. These criteria do not include adjacent site erosion from beach retreat from other natural processes, only immediately adjacent erosion greater than surrounding area erosion which appeared to be caused by project site design elements.

<u>Required maintenance interval:</u> Impact evaluation criteria were developed to determine if the project has required maintenance since installation. These criteria help determine if the project had the correct design life and appropriate installation, and most importantly, if the project design was a sustainable choice for project-specific elements.

Project Benefits and Negative Impacts—Technique-Specific

Technique-specific scoring criteria were defined for different design techniques to allow for analysis of important parameters that were not well covered in the primary scoring table. These additional criteria and delineation of scoring categories were developed by the CGS team to ensure that projects in each design technique were evaluated completely. The key elements of each technique were analyzed to determine which design elements most directly captured key benefits and negative impacts, without being redundant with project-wide scoring criteria. Minor redundancy was tolerated if criteria were determined to be critical and scoring approach varied somewhat. The criteria are listed with associated threshold values for each benefit/impact and associated scores in the following tables. Scores from design-specific criteria were summed and combined with the project-wide scoring to calculate an overall score for comparison with other projects.

Potential project benefits and negative impacts were coupled with specific considerations for each design technique (Tables A-6 through A-11). Baseline data and/or as-built data were used for comparison to field-measured conditions. In the absence of good-quality older data, or when possible to augment those data, the most similar and unmodified adjacent or nearby reference beaches were used for comparison. Details of technique-specific scoring for each project scored are included in the lower portion of the scoring table at the end of each project case study.

Table A-6. Beach nourishment (BN) design-specific benefits and negative impacts scoring matrix. IT denotes intertidal area.

Beach nourishment (BN)		None (0)	Low (1)	Medium (2)	High (3)
Benefits (positive)	Enhance potential forage fish spawning habitat	No fine sediment enhancement	Minor fine sediment increase in upper IT	Significant potential habitat along portion of project length	Significant potential habitat along project length
	Sediment benefit down-drift beaches in process unit	Very little nourishment, backshore only, or at end of drift cell	Moderate nourishment, backshore only, with down-drift cell	Moderate volume nourishment including intertidal, with down-drift cell	Significant volume nourishment including intertidal, with down-drift cell
Impacts (negative)	Smothered eelgrass beds/other fauna	No nourishment sediment moved to lower IT and no significant change in upper IT	Minor nourishment sediment moved to lower IT or slightly coarsened upper IT	Nourishment sediment has moved to sub-tidal or significantly coarsened upper IT	Nourishment sediment has moved to sub-tidal and significantly coarsened upper IT
	Loss of substrate heterogeneity	Intertidal and backshore sediment resembles surrounding areas	Intertidal or backshore sediment resembles surrounding areas	Moderately coarser intertidal and backshore composition	Uniformly coarser intertidal and backshore composition

Table A-7. Large wood (LW) design-specific benefits and negative impacts scoring matrix.

Large wood (LW)		None (0)	Low (1)	Medium (2)	High (3)
Benefits (positive)	Natural materials used (minimal hardware)	Moderately large amount of exposed hardware	Small to moderate amount of exposed hardware	Little exposed hardware	No exposed hardware
	LWD facilitates fine sediment deposition	No (fine sediment) deposition	Small amount of deposition	Small to moderate deposition	Significant deposition
Impacts (negative)	Placement causes scour, disturbance	No scour	Small amount of scour	Small to moderate amount of scour	Significant scour
	LWD can become detached or cause damage	No detachment	Minor adjustment/ possible detachment immanent	LWD detached, no damage	LWD detached, caused damage

Table A-8. Bank Reslope and Revegetation (RE) design-specific benefits and negative impacts scoring matrix.

Bank reslope and revegetation (RE)		None (0)	Low (1)	Medium (2)	High (3)
Benefits (positive)	Vegetation re-established without slope failure	No successfully established native vegetation	Native vegetation establishing over min. 50% site length but needing supplementing	Native vegetation establishing over >75% site length	Native vegetation established, healthy, and self-propagating over >90% site length
	Surface and groundwater adequately managed	No surface/ groundwater observed at site	Surface/ groundwater collected and directed to base of slope	Surface/ groundwater managed with native plantings and aesthetic, maintenance-free landscaped water feature	Surface/ groundwater managed naturally with native plantings only
Impacts (negative)	Slope failure within the project area	No slope failures observed over project length	<20% of project length experiencing slope failure	20–50% project length experiencing slope failure	>50% of site length experiencing slope failure
	Nonnative/invasive vegetation	All plants on site are native	<15% invasive plant species on treatment site	>15% nonnative invasive species on treatment site, but not dominant	Blackberry, J. knotweed, or other invasive plants out-competing natives

Table A-9. Bulkhead Removal (BR) design-specific benefits and negative impacts scoring matrix.

Bulkhead removal (BR)		None (0)	Low (1)	Medium (2)	High (3)
Benefits (positive)	Restored cross-shore connectivity	No change in sediment / LWD movement	Low bank/ little sediment/ LWD available for transport	Med–high bank/moderate sediment/ LWD available for transport	Major improvement in sediment/LWD input
	Reclaimed or created backshore/upper intertidal substrate	Fill remains, no backshore substrate	Some fill removed, upper intertidal only substrate reclaimed	Most fill removed, upper intertidal and some backshore substrate reclaimed	All fill removed, upper intertidal and backshore substrate created
Impacts (negative)	Infrastructure threatened	No infrastructure present or none threatened	Small or low-volume road threatened in next 30+ years	Home or high-volume road threatened in next 15–30+ years	Home or high-volume road in short-term danger
	Off-site erosion increased substantially	Minimal landward progression or scarping	Desired infrastructure buried by sediment	Desired habitat buried by sediment	Infrastructure damaged and desired habitat/ infrastructure buried

Table A-10. Revetment (RV) design-specific benefits and negative impacts scoring matrix. MHHW = mean higher high water, OHWM = ordinary high water mark.

Revetment (RV)		None (0)	Low (1)	Medium (2)	High (3)
Benefits (positive)	Structural integrity & function maintained	Erosion control compromised, erosion present	May deform, toppled pieces	May deform, crest irregular	May deform, maintains crest
	Cross-shore location of exposed structure toe	Below MHHW	Above MHHW	Above midpoint between MHHW & OHWM	Above OHWM
Impacts (negative)	Scour at structure	None	>0.25 ft vertical	0.25–0.5 ft	>0.5 ft
	Debris (rock, concrete, other) on beach from structure	None	<20SF/100LF	20–75 SF/100LF	>75 SF/100LF

Table A-11. Vertical bulkhead (VB) design-specific benefits and negative impacts scoring matrix.

Vertical bulkhead (VB)		None (0)	Low (1)	Medium (2)	High (3)
Benefits (positive)	Structural integrity & function maintained	Erosion control compromised, erosion present	May deform, toppled pieces	May deform, crest irregular	May deform, maintains crest
	Exposed structure toe cross-shore location	Below MHHW	Above MHHW	Above midpoint between MHHW & OHWM	Above OHWM
Impacts (negative)	Beach scour at structure	None	>0.25 ft vertical	0.25–0.5 ft	>0.5 ft
	Debris (rock, concrete, other) on beach from structure	None	<20SF/100LF	20–75 SF/100LF	>75 SF/100LF

Introduction to Puget Sound Beaches

This study focuses on beaches and associated habitats, all of which are part of a larger coastal system. A beach is defined as an accumulation on the shore of generally loose, unconsolidated sediment that extends landward from the lower reach of the waves upslope to a definite change in material and form, such as to a bluff or dune. Puget Sound area beaches are unusual in that most are very limited in sediment supply and the volume of sediment in the beach itself; most of the beaches are bluff-backed beaches, which have a bluff of some height immediately landward of the beach. These beaches are often only several clasts of gravel thick vertically, and are typically less than one foot thick on average, overlaying dense glacial or interglacial deposits (Downing 1983).

Puget Sound beaches commonly have two distinct foreshore components: the beachface, often called high-tide beach, and a low-tide terrace (Figure A-2). The high-tide beach consists of a relatively steep beachface with coarse sediment and an abrupt break in slope at its waterward extent. High tide beach sediment in the Puget Lowland ranges in size from very fine sand up to pebbles, cobbles, and occasionally boulders, often also containing shelly material. Low wave energy beaches are composed of poorly sorted sediment, with a relatively narrow backshore and intermittent intertidal vegetation. Beaches where wave energy is higher contain areas with well-sorted sediment over a broad intertidal and backshore area, usually devoid of fringing marsh vegetation. Coarse durable materials are more likely to be retained on the upper beachface and provide natural bluff protection within a relatively narrow width. Beaches of the region typically have an active berm up to several feet higher than the elevation of mean higher high water (MHHW) and, except at more protected beaches, a higher elevation "storm berm" that is activated during high-water windstorms (Johannessen and MacLennan 2007).

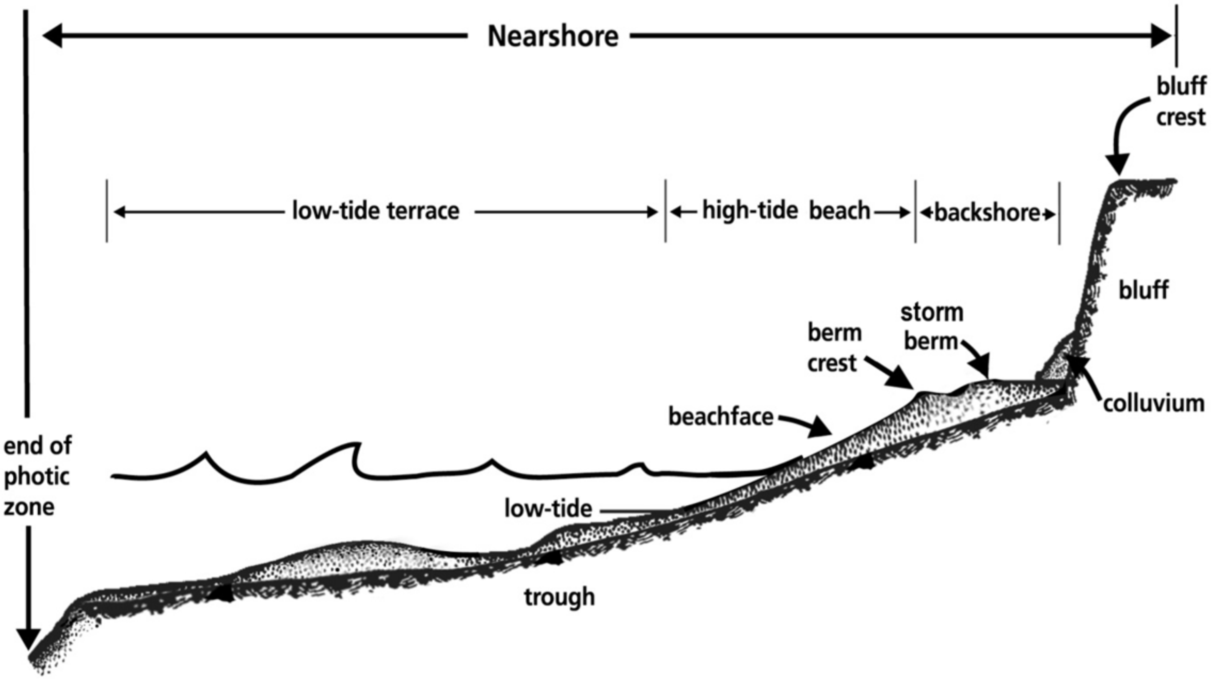

Figure A-2. Typical Puget Sound beach cross section and parts of the beach (Adapted from Komar (1976).

Extending waterward from the toe of the high tide beach, the low-tide terrace typically consists of a gently sloping accumulation of poorly sorted, fine-grained sediment (Komar 1976, Keuler 1979). Considerable amounts of sand in a mixed sand and gravel beach are typically winnowed from the high-tide beach by waves (Chu 1985) and deposited on the low-tide terrace (Figure 3). Lag deposits derived from bluff recession are often found in the low-tide terrace. Lag deposits are the largest clasts (boulders) left behind, as bluffs and beaches erode and finer grain sediment is transported away. At some high-wave-energy shores, extensive lag deposits naturally armor the low-tide terrace. The width and slope of the low-tide terrace affects the degree of wave energy dissipation that occurs along a beach (Jackson and Nordstrom 1992).

Puget Sound beaches are composed primarily of sediment derived from bluff erosion (Keuler 1988). Puget Sound beach morphology and composition are dependent upon exposure to wave energy and windstorms and available sediment sources (Johannessen and MacLennan 2007). Outside of the Strait of Juan de Fuca where ocean swell dominates the wave climate, Puget Sound area beaches are shaped by wind-generated waves (Finlayson 2006). Wave energy is controlled by fetch—the open-water distance over which winds blow without any interference from land.

Most Puget Sound shores are fetch-limited due to isolation from ocean conditions, their highly convoluted shape, and their relatively low degree of exposure (Finlayson and Shipman 2003). Even with winds occasionally reaching more than 60 mph, short fetch distances strongly limit wave height. Winds from the south (southerly winds) are both prevailing (most commonly occurring) and predominant (strongest) (Finlayson 2006). Southerly windstorms and waves are most common in winter months. Summer brings lower velocity northerly winds. Beaches exposed to the south are therefore more subject to change, compared to beaches exposed to the north.

The composition of bluffs and local wave energy influence the composition of beaches. The exposed strata of the eroding bluffs in Puget Sound are largely composed of sand, gravel, and silt. These same materials dominate sediment found on the beaches, with the exception of silt and clay, which are winnowed from the beachface and deposited in deeper water; these fine materials thus do not contribute to the active beach profile (Bray and Hooke 1997). Waves sort coarse and fine sediment, and large waves can transport cobbles that small waves cannot.

Due to the wide range of sediment supplied by area bluffs, Puget Sound and the Northern Straits have mixed sand and gravel beaches (Finlayson 2006), which differ from much more common sand beaches in that a significant proportion of gravel allows the slope of the beachface to be far steeper. Gravel-rich beaches can be as steep as 4:1 (horizontal:vertical), as compared to outer coast sand beaches that have slopes on the order of 100:1. This makes Puget Sound beaches “reflective” as compared to “dissipative,” in that the narrow beachface does not absorb wave energy as much as low slope beaches. Mixed beaches also function differently than purely gravel (shingle) beaches, which are very porous and less prone to erosion.

Initial Case Study Discussion

Selecting an approach for managing coastal erosion is a complex decision that should ideally incorporate clearly defined goals and objectives and a thorough understanding of potential environmental impacts, economic viability, and the measurable degree of risk as well as a site’s conditions and history. A wide variety of techniques are currently used to manage shoreline erosion, ranging from hard or soft shore protection to managed shoreline retreat.

More recently, the beach itself has been recognized as a potentially effective wave attenuator, and efforts increasingly have focused on trying to retain or enhance the beach to protect adjacent lands from loss or damage. These are typically referred to as “soft” methods (Shipman 2002, Cox et al. 1994). No erosion-control technique is perfect, each is limited in performance, and the site-specific nature of the success of erosion control structures cannot be emphasized enough. The principal factors in determining appropriate shore-protection methods for a specific location should include local shoreline geology and geomorphology, wave-energy regime, and the goal of the shore protection. Only the first and second factors should be used in defining an appropriate solution, without regard for the goal (Cox et al. 1994).

This initial discussion is a preliminary overview of important findings from the case study work. Major elements of the different design techniques are outlined briefly in this section. Phase 2 of the study will go into greater detail on the engineering aspects of each design technique and will use the data collected in the Phase 1 work along with design and other data as available in preparation of the guidelines document.

Beach Nourishment (BN)

Beach nourishment projects selected for assessment and analysis were distributed over the full extent of the Puget Sound (American portion of the Salish Sea). Projects were located between the Nisqually Reach, the Strait of Juan de Fuca, and Whatcom County. Sites assessed for the study covered a wide range of conditions and design approaches, and were installed between 1972 and 2005, with the majority installed between 2002 and 2005. As there were more beach nourishment projects than projects using other design techniques, we were able to select most projects with 7 to 10 years in-place to allow for assessment of medium-term performance.

Along with the intensity of large windstorms, the relative wave energy (wave climate) is a critical factor in determining the amount of erosion at a site. Larger waves usually equate to larger littoral drift rates, and can lead to loss of nourishment sediment. Conditions varied considerably at the six nourishment sites assessed, from low to very high wave energy and with dominant wave fetch ranging from 6 to 101 miles. Fetch exposures also varied, with three generally southern-aspect sites, two generally northern-aspects sites, and one site exposed to very long fetch from the northeast (East Dungeness).

The beach nourishment sites also covered a wide range of project beach lengths, from 50 ft at Snakelum Point to 1,500 ft at the East Dungeness site. Four of the projects were residential areas, with two at single-family properties, and two encompassing adjacent properties. The remaining two projects were at park shores. Project length is interdependent with placement type and the lower extent of nourishment elevation. Project sites of short length are generally unable to use placement that extends into the intertidal because any nourishment sediment placed lower on the beach on a short project would be quite unstable. Sites at two of the longer project reaches, Marine Park and East Dungeness, allowed for nourishment to extend across most of the intertidal. The single-family nourishment projects were limited to placement above MHHW.

Gravel beaches have proven to be an efficient practical form of coastal protection (MAFF 1993). Gravel tends to remain high on the intertidal and supratidal beach profile, minimizing loss to the adjacent subtidal area. Nourishment sediment ranged from primarily coarse sand with pebble to coarse gravel (cobble). Nourishment sediment mixing is an important aspect of any design, and will be examined in detail in the next phase. Most Puget Sound beach nourishment projects have relied primarily on rounded gravel greater than 0.5 in or larger. This was true for five of the six projects surveyed for this effort. The East Dungeness project had a mix of coarse sand with medium pebble, atypical for most nourishment projects in the region. One project (Marine Park) used mostly greater than 0.5 in, but had a much wider mix of sediment sizes, mainly to aid in recruiting additional fine gravel and coarse sand for habitat improvement and for recreational benefits.

Background erosion, sometimes called “passive erosion,” refers to historic coastal erosion that occurred at a site prior to project installation. This is noticeably different from “active” or “structural” erosion, which is caused by engineering structures. Beach nourishment is typically initiated at sites where background erosion has persisted (Dean 2002). The magnitude of background erosion must be quantified and considered in the beach nourishment design process. The six project sites had a wide range of erosion processes in play, making them difficult to compare. For example, the Marine Park site is located in a highly modified reach of shore (termed “artificial” in PSNERP mapping) with a moderately high rate of background erosion in the absence of shore protection. Although it was not possible to determine background erosion rates at most of these sites, it is clear that erosion rates were far lower at the more protected sites such as Snakelum Point or Tolmie State Park.

Additional elements of beach nourishment design and performance will be assessed in the next phase of this study. These will include much more in-depth analysis of the above-mentioned elements, as well as site geometry, volume density, slope, toe elevation, and berm crest height.

Large Wood (LW)

A wide variety of large-wood placement projects were surveyed and assessed for this study, including sites with relatively low wave-energy in semi-protected locations up to those with very high wave energy exposed to predominant and prevailing storm conditions. The project locations ranged from South Puget Sound in Thurston County to Northern Whatcom County and west to the Dabob Bay area in Hood Canal.

The large-wood project sites were similar in several ways. They were all at single-family residential properties, so none were larger than residential scale. While other design technique projects assessed were located across the extent of the beachface, all large-wood installations were installed above MHHW. Several projects with large wood placed below MHHW were identified earlier, but either design details were lacking or access to the designs was not granted, and these projects could not be surveyed.

Initial examination of the field survey data led to some general conclusions. Most large-wood placements were at least several vertical feet above MHHW and were intended to protect the backshore and adjacent portions of the properties from storm waves that occur at high tides only. These projects were not using larger portions of the beach profile to attempt to reverse or completely mitigate coastal erosion or severe storm damage.

Fewer than half of the large wood installations were completely dominated by large-wood placement only. Three of the five projects (Birch Point, Oak Bay, and Dabob Bay) contained small amounts of coarse-gravel nourishment sediment placed high on the beach profile. This was generally representative of the larger pool of large-wood projects that we are aware of. The selected sites did not include just exclusively wood placement projects because those lacked design data, access permission, or other essential information. We hope in the next phase to assess large-wood design approaches for several sites that did not have adequate information available for this report. Also, note that the beach nourishment case studies and summary discussion describe several nourishment sites that contained small amounts of anchored large wood.

The remaining two large wood projects had differing amounts of boulder placement, with more at the East Eld Inlet site and very little at the Whidbey site. Boulder placement at the Northwest Whidbey site was intended to add to the stability of the placed logs and also to help retain natural drift logs. The East Eld Inlet site used boulders ranging from 2.5 to 5 ft placed generally on top of the beach grade and were likely used to add to the stability of placed logs. The NW Whidbey site contained a few 3- to 4-ft boulders placed against large logs, with approximately one-third of the boulders set into the beach substrate.

Three of the five projects (Birch Point, Oak Bay, and Dabob Bay) included small backshore planting areas. This typically consisted of dunegrass (*Elymus mollis*) placed landward of the anchored logs in the more landward portion of the preproject backshore. These plantings seemed to enhance the stability of the finer sediment during times of very high water and wave run-up.

All five projects had anchor systems installed for the placed large wood. This was also true of most potential project sites investigated during the early phase of the project. It appears that designers and owners generally want to ensure that the fairly expensive large wood remains on site for a long time to provide as much benefit as possible. Anchoring designs at the survey sites included several different approaches. Four of the five projects used deadman anchors, buried well below grade. These consisted of large "ecology block" concrete anchors measuring either 2 ft by 2 ft by 4 ft or 2 ft by 2 ft by 6 ft, with respective weights of approximately 2,500 and

3,800 pounds. These anchors are very affordable and easy to work with as long as they can be secured by passing the attachment through the deadman anchor and not by relying on the small rebar lifting eye, which tends to rust rapidly in the marine environment. The blocks for these projects were always set at least 2 to 3 ft below grade in order to ensure they remain below grade in the future.

The East Eld Inlet project utilized auger or screw-type anchors made of galvanized steel. These anchors were, however, installed as a maintenance action less than a year after the original rebar pins used to anchor the logs had failed. The auger anchors generally require a special head for a backhoe or excavator that can screw the auger into potentially dense underlying deposits. At the East Eld Inlet site, many augers were not screwed far enough into the substrate to get their heads below beach grade. These remained exposed, with some bent over; such exposure leads to loss of galvanizing and corrosion as well as a hazard for beach users.

The large-wood placement projects studied appeared to mitigate coastal erosion of the backshore area to varying degrees. One of the projects (Birch Point) appeared to have been much less successful than the other projects. It was installed at a very high-energy site where the rates of bluff toe erosion and landslide have decreased only incrementally. The Birch Point site performed poorly because the direct wave attack was fairly extreme and the limited backshore area did not allow for good log placement or creation of an elevated backshore area. The project, installed in 2000, required maintenance in the form of log reattachment and lowering after two years, and a maintenance need is projected in the next decade. Beach lowering, which appeared to be undermining the anchored logs at the Birch Point site, was not a result of any project elements. It appeared instead to have occurred area-wide due to the very high wave-energy scouring the glacial deposits underlying the veneer of beach sediment on the wave-cut platform, along with a fairly high littoral drift rate.

As opposed to the Birch Point project, the other very high-energy project surveyed, the Northwest Whidbey Island project was at an accretion shoreform (also called a barrier beach or no-bank site). This site had ample backshore area in the existing logs for placement of anchored logs in configurations designed to encourage recruitment and retention of natural drift logs. Although the installation was in place for only four years, it appeared to have recruited and aided in the retention of a substantial number of naturally occurring drift logs. No beach nourishment sediment or backshore planting was included in this project, and the backshore showed no evidence of additional erosion following several moderately intense winters. It appeared that the project had been successful in mitigating wave erosion during high-water storm events. For this and all other projects, additional years of observation and data would be very useful for documenting conditions during more extreme events.

During the course of this study, we became aware of issues relating to failure and success of several different log-anchoring techniques within a single project at the Northwest Maritime Center in Port Townsend. The project had required several repairs, as the original anchoring was not completed to design. Subsurface investigation by CGS allowed for evaluation of the various techniques. We recommend additional investigation at the site and through review of project files and photos in the engineering evaluation portion of Phase 2. This could document the success and failure of these different anchoring techniques at this high-energy site.

Bank Reslope and Revegetation (RE)

Two reslope and revegetation projects were evaluated for this study, as other projects did not fit the site selection criteria. Each had a slightly different design focus, which introduced some challenges in evaluating project design and performance. A third project (Weyer Point), evaluated as a bulkhead-removal treatment, did involve a short section of resloping and revegetating where the vertical concrete bulkhead was removed, but was not rated on that aspect of the treatment. Evaluated benefits and impacts for the two RE projects were based on their intended mitigation of slope instability and to a lesser degree, successful establishment of native vegetation, rather than on erosion control. Both projects were located on bluffs of low to medium height and establishing connectivity of sediment source to beach was not an objective of either project.

The West Lummi Peninsula site involved a designed reduction of the bluff slope gradient with subsequent vegetation planting. Lowering the gradient of a slope is a common technique of slope stabilization where oversteepening is both a cause and a consequence of landsliding. This technique is generally applied to the upper portions of a slope, but in the case of shorter slope lengths can be successfully applied to the entire slope, as it was at West Lummi Peninsula. Because the objective of the project design was to mitigate the effects of the earth slump and resultant retrogression of the slope crest, there was a consequent reduction in the potential for sediment input into the beach environment. Continued erosion of the slope toe, with or without resloping, would likely reactivate such slumping and retrogression. The addition of vegetation plantings, coarse gravel, and a large shore-parallel log has greatly reduced that likelihood. Perspective plays a role in evaluating the success of resloping and revegetation as mitigation for landward erosion. If sediment input is considered a positive consequence of treatment, then the resloping at West Lummi Peninsula could be considered unsuccessful although the project design objectives of stabilizing the slope were met.

The East Drayton Harbor site involved primarily a vegetation management design with no slope regrade. To date this has had little effect on landward erosion, and undercutting of the slope continues to provide sediment input to the beach environment. It is important to note that this project has only been in process for 2 to 3 years. Revegetation efforts take 5 to 10 years for root establishment and the realization of a clear benefit to slope stability, so it is premature to judge the overall project success.

As a potential contributor of LWD and detritus, revegetation can be successful and beneficial if it allows toppled vegetation to reach the beach. In both project sites in this category, there appeared to be only limited large wood available, allowed to grow to maturity, or planted as part of the treatment. The formation of a functioning marine riparian zone therefore seems unlikely in the short to medium term. Backshore vegetation was enhanced where treatment provided for maintaining the appropriate beach elevation during prevailing waves.

Because there were no structures, except for the large log placed at West Lummi Peninsula at or above the OHHW, there was no consequent impoundment of littoral sediment or adjacent end-effect erosion caused by the treatment.

Both of the reslope and revegetation sites evaluated for this study, as well potential future vegetation management projects, will likely require ongoing control of invasive plants and possible replanting to replace species found to be unsuitable for a particular site. Because vegetation alone cannot be expected to mitigate all slope-stability concerns, it is critical to plan for appropriate setback of any structures and carefully consider drainage and surface- and groundwater management. These will need to be factored into the long-term maintenance costs of the sites evaluated for this project and any future resloping and revegetation projects.

Bulkhead Removal (BR)

Four of the 25 projects evaluated for this study involved the removal of some form of shore armor or bulkhead. The bulkhead removal projects are located throughout Puget Sound in wave energy environments ranging from relatively low (Weyer Point in south Puget Sound) to medium (Kopachuck State Park in central Puget Sound) to very high (Birch Point in northern Whatcom County). Armor material removed from these sites included logs, concrete, pit-run basalt rock, cobble-filled gabion baskets, and a creosoted wood soldier pile wall. At Weyer

Point, three different material types were removed. In evaluating the benefits gained versus impacts realized in bulkhead removal, slightly different perspectives were applied to each project based on the objectives of the removal effort. In one case the objective may have been to reestablish sediment connectivity or remove creosoted wood from the marine environment; in another, to enhance the restoration of a State DNR Natural Resource Conservation Area. Sometimes objectives overlapped.

The effectiveness of landward erosion mitigation is scored using a different perspective for bulkhead removal than for other treatment types. Bulkheads are generally removed to restore beaches and/or increase sediment connectivity and input to beaches. Therefore, success of a project is generally rated higher when sediment input is increased. The treatment does NOT mitigate landward erosion. Likewise, the removal of the structures precludes evaluating it for sediment impoundment impacts. Measuring the success of a treatment involving bulkhead removal may consider reduction in end-effect erosion caused by the existing structure, as in the case of the gabion basket bulkhead at Birch Point. Of the four bulkhead-removal projects, all but Deer Harbor are actively providing increased sediment input without threatening residential structures or public safety, and were therefore deemed successful. Because Deer Harbor is not negatively impacting sediment input, its rating on this criterion was more neutral.

Where large wood was made available by bulkhead removal or was expected to become available in the future from trees planted as part of the project design, project success was rated higher for input and exchange of LWD and detritus, or enhancement of marine riparian vegetation. Trees of any size were either absent or very small at two of the sites. The mature forest and active deep-seated landslide movement at Kopachuck State Park resulted in a high rating for LWD input as a result of bulkhead removal. None of the bulkhead-removal projects exhibited much, if any backshore, resulting in neutral scoring on its enhancement at these sites.

The common benefit seen in all bulkhead-removal projects was some degree of augmented sediment input, which allowed for observations on the type of sediment delivered. Because beach nourishment (importing sediment from offsite) was not a component of any of the four bulkhead-removal projects, sediment type depended solely on local sources, generally from exposed bluffs at or adjacent to the treatment site. Beach surface sediment appeared to reflect the coarser fraction of material exposed in the bluff, because natural beach protection is typically formed by the coarse grains that end up at the beach surface; the finer fraction is typically winnowed out and transported down-drift. This was particularly apparent at sites with higher wave energy such as Birch Point, but even at Weyer Point sand-size particles dominated the beach in the treatment reach. The finer silt and clay particles observed in the bluff face there were likely transported offshore into the mud flats.

The cost of removing a bulkhead can vary greatly depending on access (land vs. water), materials being removed, and transport and disposal of removed materials. In general, removal costs less than construction. Sometimes removal costs much less than installation, such as when most material can be left on site, as at Birch Point. This was not the case at Kopachuck State Park, where hazardous materials (creosoted wood) required appropriate disposal. No maintenance or treatment was or is necessary at any of the bulkhead-removal projects as long as bluff recession is accepted as a consequence of project success. Should mitigation of these effects be desired in the future, for example for long-term protection of the tram at Birch Point, additional maintenance may be required.

Hard Armor-Rock Revetment (RV)

A revetment is a permanent shoreline modification technique that uses stones to form a sloped, permeable structure. The outer stones that face the waves are called armor stones and are usually similarly sized throughout the structure. Revetments usually have at least one more layer of rocks beneath the armor stones that are smaller and create a bedding layer. Some revetments are placed on top of geotextile fabric for native sediment containment. This research assessed four different projects that installed armor stone structures; all installed a traditional revetment as defined except Butler Cove. Instead of a typical revetment, the Butler Cove project installed a “rockery”. Near-vertical rock seawalls, locally termed “rockeries,” are common at single-family residences in the Puget Sound region. These allow for armor stones to be supported by their own structure in that they have a steep front face with individually placed rocks and minimal voids between rocks. Armor stones are typically larger than those used in sloping rock revetments. One advantage rockeries have over more traditional revetments is that rockeries do not place stones on angled slopes and typically cover less beach area.

All four sites had medium wave energy, with some exposed to the southerly quadrant and predominant and prevailing storm conditions. The projects ranged geographically from the most southern in Butler Cove in Budd Inlet to the most northern on Lummi Peninsula in Hale Passage. Two projects were in the San Juan Islands.

This research aimed to select new projects that consisted primarily of one element constructed at least three years ago. It was hard to find revetment projects constructed in the last 3 to 10 years and with a reasonable level of design detail that were not replacements of older structures or that did not have beach nourishment as an additional design element. It was decided that a replacement structure was more acceptable for the objectives of the research than a revetment that had beach nourishment sediment added. Therefore, none of the four revetment projects had any beach nourishment in the design or maintenance plans, but one of them (Butler Cove) was a wall replacement. The reslope and revegetation design technique was applied landward of the revetment at Butler Cove, but it was accepted in the research because the design, which did not augment the beach, allowed for structure and waterward comparisons. It was also difficult to find revetment projects that met the required criteria of good construction and precise placement of armor stones. Only Butler Cove had precise stone placement with consistent rock sizing during construction. The armor stones of the revetments in the other three projects appeared to be much less carefully placed in the design footprint and used varying rock sizes.

Some general conclusions were drawn from initial examination of project field survey data. The revetment projects were constructed at varying heights in the beach profile, with two (Butler Cove and Lummi View Drive) having exposed toes below MHHW. None of the projects had an exposed toe above the OHWM. Half of the revetment projects were at residential properties, while Lummi View Drive was constructed to protect industrial infrastructure and North Blakely Island was at a small private park.

The revetment projects ranged in length from 100 ft at northwest Blakely Island to 240 ft at Butler Cove. The Obstruction Pass revetment had the smallest average width while at some locations Lummi View Drive had a width of 15 ft. Only at the Obstruction Pass project had all of the placed rock remained within the original design footprint. The other three projects had rocks on the beachface away from the structure. Lummi View Drive had toppled armor stones and quarry spalls throughout the beach, while only small armor stones fell to the beach at northwest Blakely Island. Butler Cove had quarry spalls that had filtered through the armor stones waterward of the structure. Half of the projects (Lummi View Drive and NW Blakely Island) have had maintenance since installation.

Butler Cove had the steepest slope at 1:4 (horizontal:vertical). Lummi View Drive and northwest Blakely Island had slopes of 1:1, and the revetment at Obstruction Pass had a slope of 1:0.8. Butler Cove and Lummi View Drive had high risk due to higher fetch and small setbacks (risk indices of 6 and 7, respectively), while Obstruction Pass and northwest Blakely Island had low structure risk (risk indices of 3).

The revetment projects studied appeared to mitigate coastal erosion of the backshore area very well, but have caused significant impacts to the beach and associated habitats, especially at Lummi View Drive. Lummi View Drive scored the lowest on the Benefits/Impacts index when compared to all projects, study-wide.

Design analysis and comparisons of quantitative relationships will be investigated in detail in the engineering analysis stage at the beginning of Phase 2 of this project. These include but are not limited to crest elevation, toe elevation, slope, wave energy, and swash alignment. Relationships and data will be compared with those from all revetments as well as other design techniques in order to define successful and appropriate techniques.

Hard Armor-Vertical Bulkhead (VB)

A variety of vertical bulkhead projects were surveyed and assessed for this study. Sites ranged from relatively low wave-energy up to very high wave-energy, with exposure to predominant and prevailing storm conditions. Wave fetches ranged from 2.7 to 70 mi at project locations from South Puget Sound in Thurston County (Snyder Point) to Skagit County (Skyline Marina, Samish Island) and the high-energy west-facing shore of Whidbey Island (Swan Lake).

This study sought to include projects at least three years old and consisting primarily of one element. However, it was difficult to find vertical bulkhead projects constructed recently (in the last 5 to 10 years), as regulators no longer permit many vertical structures on the shore due to perceived negative impacts, and rockeries have been used more than vertical structures in recent decades. With an average age of 20 years since installation, the vertical bulkhead projects in this study were not only older than projects using other design techniques; they also had less background data available.

The vertical bulkhead projects were constructed at varying heights in the beach profile. One (Samish Island) had an exposed toe along much of its length below MHHW, but none had an exposed toe above the OHWM at the time of the assessment. Half of the vertical bulkhead projects were at single-family residential properties. Skyline Marina was at a condominium complex, and Snyder Point was protecting an institutional recreational area. The largest single project was Samish Island at about 600 ft long. The Swan Lake and Skyline Marina sties each consisted of one bulkhead in a long, continuous line of vertical bulkheads at different properties.

Initial examination of field survey data revealed that some general conclusions can be drawn from these projects. Half were constructed out of concrete and the other two were soldier pile walls. Only one, Swan Lake, has had documented maintenance since installation. At least a minor amount of toe protection had been placed after original installation at Swan Lake and Skyline Marina, which was not known before the site visits. Snyder Point, one of five project-wide sites that scored only a 1 on the risk index scale, has the lowest risk index of all shores modified by hard structures. None of the vertical bulkheads had documented any other design elements (such as beach nourishment or vegetation) at the time of installation.

The vertical wall projects studied appeared to mitigate coastal erosion of the backshore area very well except at Swan Lake. This project was installed at a barrier beach (no-bank), very high-energy site frequently overtopped with waves, as evidenced by LWD well landward of the structure. The Samish Island site, with one wall reach leaning waterward, was the only vertical bulkhead project that was not consistently vertical. This site had several landslides that occurred after wall installation and threatened the integrity of the wall. The owner mentioned wanting to remedy the issue with structure maintenance. All the vertical bulkheads seemed to have maintained their design crest height.

Design analysis and quantitative relationships will be investigated in detail in the engineering analysis stage at the beginning of Phase 2 of this project. These include but are not limited to comparison between a normalized beach profile and crest elevation, toe elevation, construction material, slope, and swash alignment. Relationships and data will be compared with those from all vertical bulkheads to define successful and appropriate techniques.

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Field Manual and Glossary

General Definitions

Backshore: The upper zone of a beach beyond the reach of normal waves and tides, landward of the beachface. The backshore is subject to periodic flooding by storms and extreme tides, and is often the site of dunes and back-barrier wetlands (Clancy et al. 2009). Width is measured cross-shore from the waterward extent of the backshore to the waterward extent of upland vegetation or anthropogenic modifications.

Bank/Bluff: A steep slope rising from the shoreline, generally formed by erosion of poorly consolidated material such as glacial or fluvial sediments. Height is measured from the break in slope at the base of the bank, or colluvium if present, to the bank crest where the slope transitions to the uplands.

Beach: The gently-sloping zone of unconsolidated sediment along the shoreline that is moved by waves, wind, and tidal currents (Clancy et al. 2009). Width is measured cross-shore from the break in slope between the upper beach and the low-tide terrace to the waterward extent of the backshore.

Drift Aligned: A beach that is orientated differently than the predominant incoming waves at breaking (after refraction in the shallow nearshore).

Marine Riparian: The transitional zone between the uplands and aquatic environments adjacent to marine waters.

Shoretype: The Shipman typology classification for the project area (Shipman 2008). BLB=Bluff backed beach, BAB=Barrier Beach, BE=Barrier estuary, BL=Barrier lagoon, OCI=Open coastal inlet, CLM=Closed lagoon/salt marsh, PB=Pocket Beach, RP=Rocky platform, PL=Plunging rocky shore.

Swash Aligned: A beach that is generally parallel or near parallel to the predominant waves at breaking (after refraction in the shallow nearshore).

Upland Assessment

Bank Composition: Sediment characterization of the marine bank/bluff, and geologic deposit type if discernible.

Bank Face Seepage: Specific information about ground water seeps on the marine bank face.

Drainage Control: Anthropogenic drainage control devices such as pipes, swales, drains, etc.

Ground Water: Indicators for ground water flow through the site such as seeps or water flowing through the beachface.

Septic: Both septic drain fields and tanks.

Setback: Distance of the nearest major infrastructure element (house, road, etc.) from the shoreline, measured from bank/bluff crest where there is one, or from OHWM for no-bank sites.

Slope: The general ground angle of the uplands, measured as the vertical rise over a horizontal distance (H:V).

Slope Failure: An area of mass wasting at the marine bank, measured alongshore for width. Identify indicators and measurements of slope failure on the site, including alongshore width of the failure, height, and approximate age.

Surface Water: Note indicators of surface water such as erosion, ponding, gulleys, or flattened vegetation.

Vegetation Maturity: The approximate level of establishment of a plant community.

Beach Assessment

Backshore Sediment: Qualitative assessment of sediment in the backshore zone.

Backshore Species Composition: Major species making up the backshore vegetation zone.

Backshore Vegetation Width: Cross-shore dimension of the backshore vegetation zone (not on bank face or adjacent landscaped area).

Backshore Width: Alongshore dimension of the backshore vegetation.

Depth of Beach: The vertical thickness of beach sediment veneer on the upper intertidal beach.

High Tide Beach Width: The cross-shore distance from the toe of the beach to the waterward extent of vegetation

Landslides: Observations of mass wasting on the marine bank; include dimensions of failure surface and approximate age if possible.

LWD Band: Describe as either continuous or patchy and record average width of deposit. Characterize range of LWD sizes.

LWD Recruitment: Notation and observations of LWD being actively/recently recruited or eroded from adjacent uplands. LWD with root wads could also be noted.

Toe Erosion: Observations of erosion at the base of the marine bank (if present).

Upper IT Sediments: Qualitative observations of the sediment comprising the upper half of the beachface and the waterward extent of vegetation.

Upper IT Slope: The slope (H:V) of the upper half of the beachface between the base of the upper beach and the berm crest.

Adjacent Shores

The adjacent shores are generally considered the immediate vicinity of the project site itself from the project boundary to approximately 100 to 200 ft alongshore to either side. The length of adjacent shore should extend beyond the area of apparent impacts from the project. Parcel boundaries should be ignored when considering the adjacent shores. Measurements and observations at the adjacent shores shall follow those for the project site, although a slightly lower level of detail may be required.

Revegetation/Reslope Treatments and Bulkhead Removal

Area Regraded: Total area that has been regraded following removal or resloping.

Backshore Vegetation: The species and percent cover of the backshore zone.

Current Slope: The slope (H:V) of the project treatment area; more than one slope for complicated reslope projects.

Extent: A description, to include length and width, of the project area.

Landward Vegetation: The species and percent cover of vegetation landward of the project.

Materials: The composition and placement of materials used in revegetation, bank stabilization, etc.

Native Bank Material: The sediment composition of native soils within the marine bank/bluff.

Overhanging Vegetation: Note the species and percent cover of any vegetation overhanging the resloped area over the beach.

Previous Slope: The slope (H:V) of the project site prior to implementation, to be filled out prior to field assessment if available.

Riparian Vegetation: The species and percent cover of the marine riparian zone.

Treatment Length: The alongshore dimension of the project treatment area.

Treatment Width: The cross-shore dimension of the project treatment area.

Waterward Vegetation: The species and percent cover of vegetation waterward of the project.

Waterward LWD: Describe as either continuous or patchy and width of deposit. Characterize range of LWD sizes.

Beach Nourishment or Large Wood Treatments

Anchored or Embedded: LWD anchoring characteristics (if discernible) and depth of LWD embedment below surface.

Backshore Sediment: Characterize the sediment within the backshore at the site.

Condition: The relative state of the project in terms of need for maintenance and ability to provide intended erosion control benefits.

Extent: A description, to include length and width, of the project area.

Landward Vegetation: The species and percent cover of vegetation landward of the project.

Length: The alongshore dimension of the project.

LWD elevation: The minimum, maximum, and mean tidal elevation at the sediment surface of the LWD used in construction.

Materials: The materials used in construction of the project, including size and quantity of LWD, anchoring equipment (if present), and any associated berm sediment.

Overhanging Vegetation: Note the species and percent cover of any vegetation overhanging the treatment area over the beach/backshore.

Risk: The relative need for the given structure in terms of setback distance, structure type, and estimated erosion rate. Erosion rates estimated from maximum measured fetch.

Sills: Describe the use of LWD, rock, or other drift sill materials used to hold or slow alongshore sediment transport at the site. Include materials used and length, width, and depth measurements.

Upper Extent: The overall height of the project site.

Upper IT Sediment: Characterize the sediment on the upper beach waterward of the wrack/approximate MHHW at the project.

Waterward LWD: Describe as either continuous or patchy and width of deposit. Characterize range of LWD sizes.

Waterward Vegetation: The species and percent cover of vegetation waterward of the project.

Revetment or Vertical Bulkhead Structures

Backfill: The materials found immediately landward of the structure.

Buttress/Return Walls: A brief description of buttresses and/or return walls to include quantity, spacing, and dimensions.

Condition: General condition of the structure in terms of apparent structural stability, strength, and overall condition.

Depth of Footing: The depth of burial of the toe of the structure; indicate depth of investigation if unable to find the base.

Drainage: Note drainage features associated with structures (e.g., weep holes).

Height: The vertical distance between the toe and crest of the structure.

Landward Vegetation: A description of the vegetation community landward of the structure to include species and percent cover.

Length: The alongshore dimension of the structure.

Material: The materials used in construction of the structure.

Risk: The relative need for the given structure in terms of setback distance, structure type, and estimated erosion rate. Erosion rates estimated from maximum measured fetch.

Overhanging Vegetation: Species and percent cover of plants that overhang the structure over the beach.

Signs of Overtopping: Describe any evidence of wave overtopping the structure (e.g., wrack or LWD behind structure).

Substrate Density: The density and composition of the subsurface sediment/geology, which inform appropriate selection of LWD anchoring mechanism. Loose, less consolidated material would be amenable to deadman anchor. In moderately consolidated material LWD could be effectively anchored with an auger anchor. The best LWD anchoring mechanism for sites with higher density or lithified subsurface geology (e.g., bedrock) is ballasted LWD.

Toe Elevation: The tidal elevation of the beach in front of the structure. May be recorded relative to local water level (with time notes in local time), ideally at or near a low or high tide.

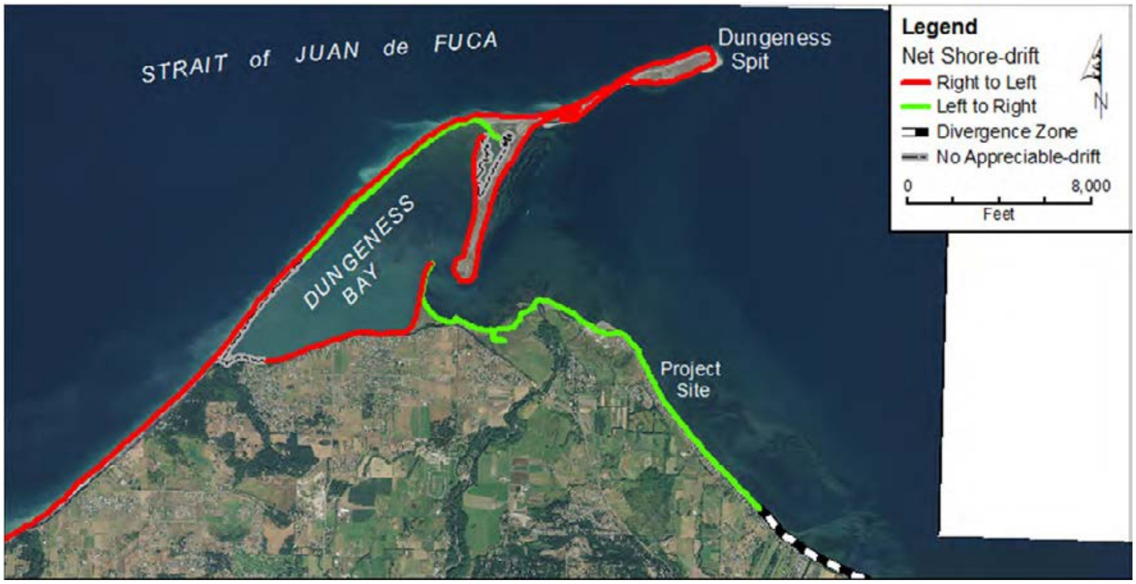
Waterward LWD: The width and density of LWD waterward of the structure.

Waterward Vegetation: A description of the vegetation community waterward of the structure to include species and percent cover.

Width: The cross-shore dimension of the structure; include separate measurements of return walls or other associated structures.

EAST DUNGENESS – Beach Nourishment (2006)

Waterbody: Dungeness Bay	Shoretype: Barrier beach	Net Shore-drift Cell: JF-16-6	Direction: Westward
Project Elements: Sand and gravel dune nourishment, anchored or interlocked logs, backshore planting		Objective: Slow coastal erosion in front of residential properties and reduce backshore flooding associated with wave overtopping	
Fetch: 36.0 mi NE Wave Energy: Very high Aspect: NE	Land Use: Residential MHHW: +7.4 ft MLLW Toe Elev: +6.5 ft MLLW	Structure: Single-family homes Setback: 35 ft Risk Index: 25	Benefit Index: 15 Impact Index: -2 Total BI Index: 13



Project site as red star with dots showing all other beach nourishment projects Sound-wide.

Project Background

This high-wave-energy site lies along a very-low-elevation area in the lee of Dungeness Spit. It is near the middle of a 4.5-mile-long drift cell originating at Kulakala point southeast of the site and ending at Cline Spit inside Dungeness Bay. Net shore-drift was mapped as northwestward based on field indicators and the longer fetch from the east. However, short fetch from the Dungeness Spit complex and frequent northwest winds can cause significant southeastward sediment transport, particularly within the project-site portion of the drift cell.

Prior to development, the area had a low-elevation berm fronting hundreds of acres of low-elevation, marshy backshore. Initial site development involved raising the elevation of the individual house sites, but not any form of shore protection. Infrequent, large, southeast to northeast windstorms at high water caused significant flooding around houses preproject. A large concrete bulkhead, tide gate, and outfall structure have been in place for at least 15 years adjacent to the northwest end of the site. Houses were generally built at the required 50-ft setback from OHWM in the late 1980s to 1990s.

The periodic, localized reversal of net shore-drift tended to create pockets of erosion, as did the structures at the northwest end of the site. Erosion and flooding in the February 4, 2006, storm instigated action. Erosion was most pronounced immediately adjacent to the structures by the northwest end. Owners were very interested in trying to limit erosion of the backshore dune area and reducing coastal flooding. The existing community association served as a good vehicle for a forming coordinated response. The leadership of one individual proved critical to the development of an integrated strategy with several design variations.

Southeastward view of the project site prior to implementation. Note accumulation of drift logs in the backshore and proximity of houses to the beach.

Southeastward view of the project site prior to implementation, showing lack of backshore relief.

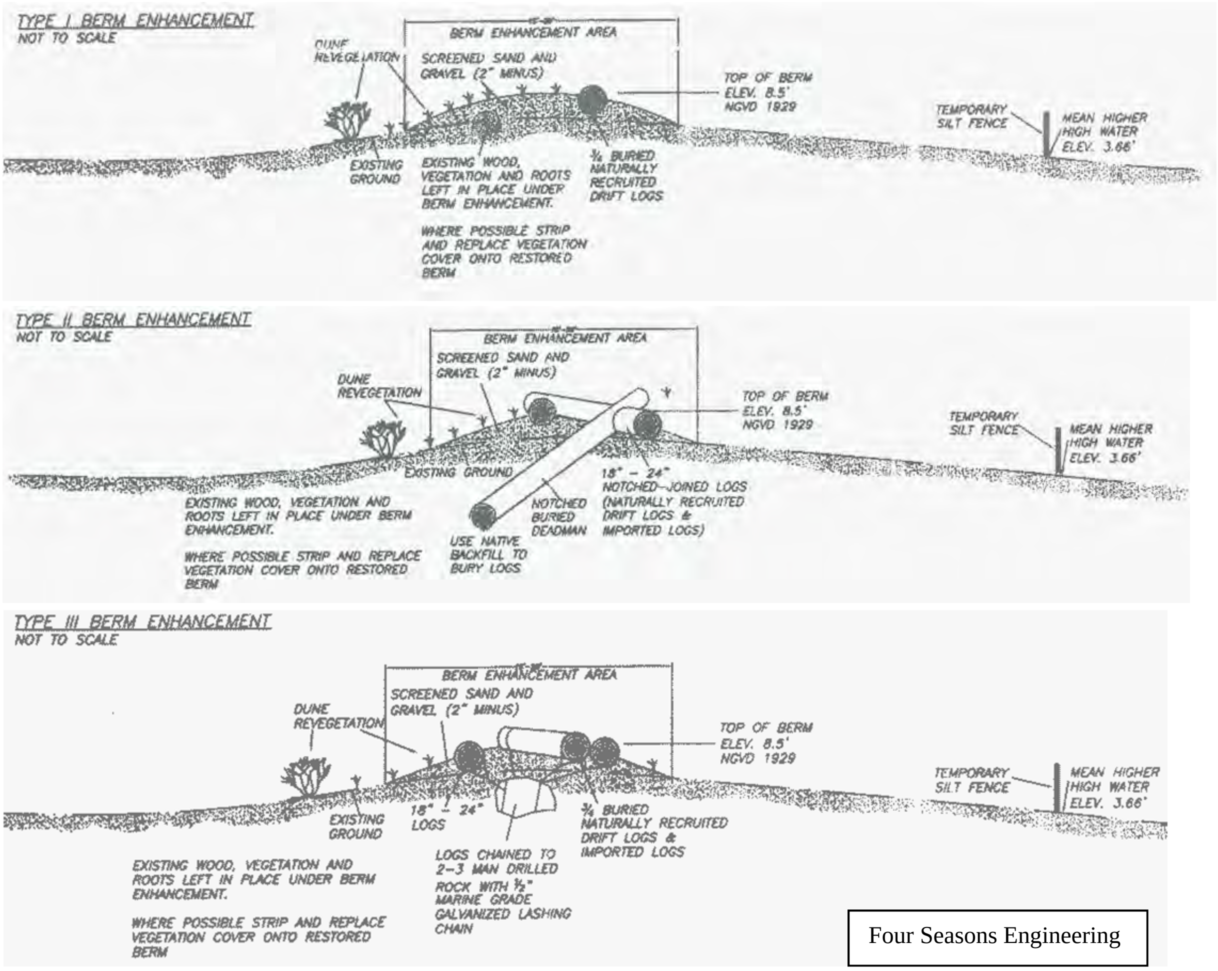
Design

This project is an example of backshore or dune beach nourishment at a low-elevation site with very high wave energy. The designers gave community members copies of *Alternative Bank Protection Methods for Puget Sound Beaches* (Zelo et al. 2000), which increased their awareness and interest in pursuing a "soft" project instead of the riprap revetment they had originally been considering. The project designers stated that an important element of the project design development was a site visit by agency, tribal, and other staff. Agency staff encouraged the community not to raise the intertidal beach profile and push it waterward, but instead to focus the work on the backshore/dune area.

The design involved building an elevated gravelly sand berm in the position of a dune fronting 15 adjacent lots within the small community. Design details for the 2006 project included the following:

- The enhanced dune was constructed landward of the OHWM starting at approximately +9.8 ft MLLW and extending up to +12.5 ft MLLW, with a 10-ft-wide crest across all lots.
- 1,740 CY of nourishment sediment was used along 1,500 ft, resulting in a nourishment density of 1.2 CY/ft.
- The sediment was unscreened "pit run" from a nearby sand and gravel pit located in a relatively coarse-grained deposit. Nourishment sediment was a coarse to very coarse sand with about 20% to 40% pebble (wide range of grain sizes up to 2 inch), although no detailed specification or grain-size analysis was performed.
- The landowners were provided three types of log placement to choose from (see cross sections below). Most of the owners, particularly at the northwest end, opted for the most robust design type: rock anchors installed with chained logs within and atop of the constructed berm (Type III in figures below). Some chose an option (Type II) that included notched, interlocking logs within the dune that were anchored only by a buried "deadman" log. Several selected simple placement of logs partially buried in the berm (Type I). No follow-up monitoring was completed prior to the 2012 field work.

Dune planting included dunegrass (*Elymis mollis*) and Nootka rose (*Rosa nutkana*), installed by a trained crew. The association insisted that each lot include planting of these species, with approximately 200 dunegrass shoots and 20 rose plants installed on each lot. Many owners bunched the rose plants in one or several areas.



Four Seasons Engineering

Project design cross sections.

Current Conditions

Technique condition – Most of the constructed berm appeared in good condition, with only minor scarping of the waterward face. The northwest portion of the dune showed more severe erosion. The periodic shift in the direction of alongshore sediment transport and local wave refraction around the western bulkhead and tide gate likely caused exposure and undercutting of the dune and internal log structure. The Type III berm profile was located at the most heavily impacted site, where end effects from the adjacent bulkhead resulted in severe erosion of the berm. Additional large rock and logs were brought into this site at the northwest end of the treatment area shortly after project completion to prevent further loss of uplands.

Upland threats – The berm appeared to be working as intended to reduce hazards at the houses. Backshore flooding has been largely mitigated. Additional scarping of the berm in the eroded west end could result in large-scale point failures and allow water to flood the backshore again. Of particular concern is the northwesternmost house, where erosion of the berm has been most severe. Additional log and rock placement in this area (second maintenance) was planned for the summer of 2012.

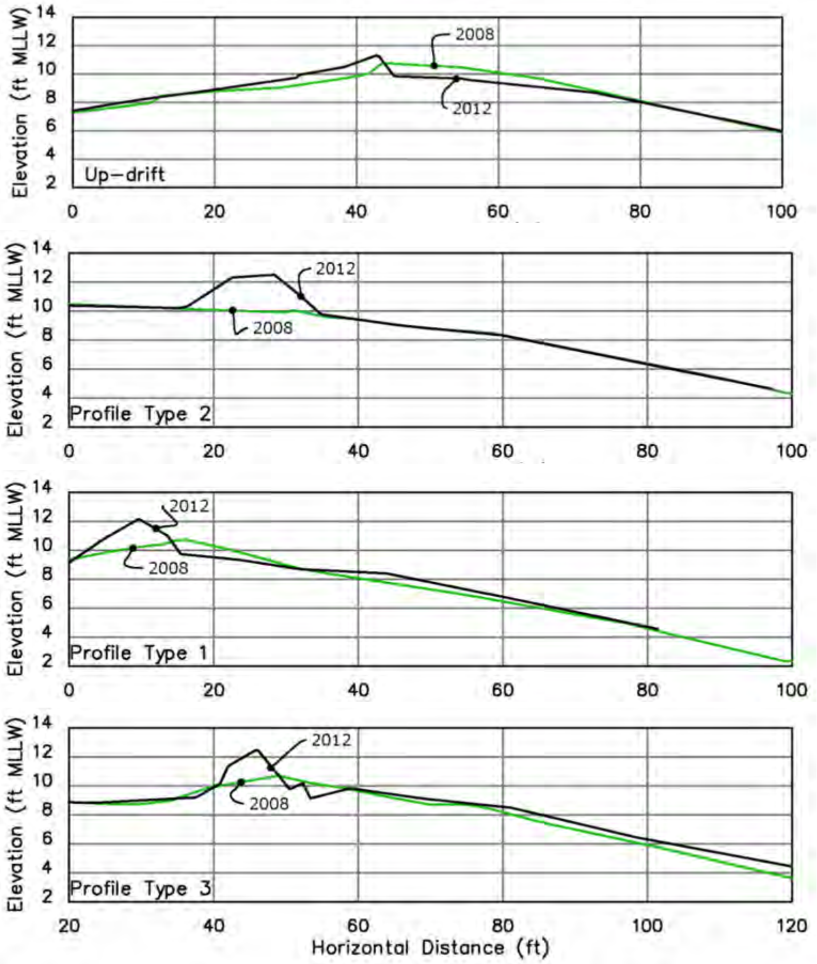
Beach characteristics – The beach was predominantly sand with some pebble and there was little variation throughout the project site. The fairly flat beach slopes included a very broad low-tide terrace.

Adjacent shores – The up-drift, adjacent shore is a no-bank portion of shoreline with an undeveloped, low-lying backshore with a stream running through it farther east. The stream exits the beach low on the beachface through a culvert with a flap gate on the beach side. The culvert acts as a minor groin that has become full and allows sediment transport around and over the structure. The up-drift beach was very similar in both sediment composition and slope to the project site, such that besides the culvert/groin there was little to no transition between them. However, the backshore dune was on the order of 1.0 ft lower than the project dune, with most of the higher elevation area more than 1.5 ft lower than the project area dune. The down-drift shore is demarcated by another stream with a culvert and tide gate that acts as a groin. The uplands have been heavily developed to include continuous bulkheads. The beach there tended to be coarser and narrower than at the project site.

Northwesternmost portion of project looking northwest toward the adjacent bulkhead and outfall. Note rocks added after initial dune enhancement to mitigate erosion at this end of the treatment area.

Project site looking southeast. Note dense dunegrass growing atop the nourished dune, with some installed berm logs exposed in the foreground.

Topographic map of conditions during the 2012 site visit.



Beach profiles from monitoring and the 2012 site visit.

General beach features mapped during the 2012 site visit.

Comparison of beach surface sediment at project and adjacent sites.

Location	Backshore	Difference	Upper Intertidal	Difference
Up-drift	COARSE PEBBLE, sand	finer	SAND, coarse pebble, medium pebble	same
Project site	COARSE PEBBLE, cobble	-	SAND, coarse pebble, medium pebble	-
Down-drift	SAND, coarse pebble	similar	SAND, coarse pebble, medium pebble	same

Performance

Most of the project site appeared in very good condition at the time of the site visit and significant erosion did not appear to be occurring except in the northwestern end. A summary of conditions and performance follows:

- The dune/backshore was in place with dense dunegrass and thickets of Nootka rose growing on top.
- Internal logs have become exposed by wave-induced erosion in a few places, although appeared to have been dislodged.
- The berm was constructed high enough to prevent wave overtopping, and overtopping or breaching did not appear to be an issue.
- Drift logs have accumulated waterward of the berm in some areas, and many logs appeared to have been naturally incorporated into the structure.

Coastal flooding had been mitigated to some extent during initial site development by raising the properties and providing adequate drainage through a series of ditches. The dune enhancement clearly helped, however coastal flooding may still occur in the future. The northwesternmost portion of the berm appeared to be experiencing end-effect erosion from the tide gate, outfall, and large bulkhead immediately west of the site. Much of the dune there had been eroded a short time after installation, leaving behind a shallow, low backshore where the dune had been built. Additional wood and large rock has since been added in this area to prevent complete failure of the structure, and additional log, cobble, and rock placement was planned for summer 2012.

This project is a good example of a larger nourishment effort where a longer reach of shore is needed to place a sufficient volume of sediment to withstand wave forces at a very-high-wave-energy sites. Nourishment above MHHW was an important design decision. Relatively fine-grained sediment was used but it matched native sediment well. Vegetation planting and structure added by log placement also appeared to contribute to maintaining most of the dune since 2006.

Project performance scoring.

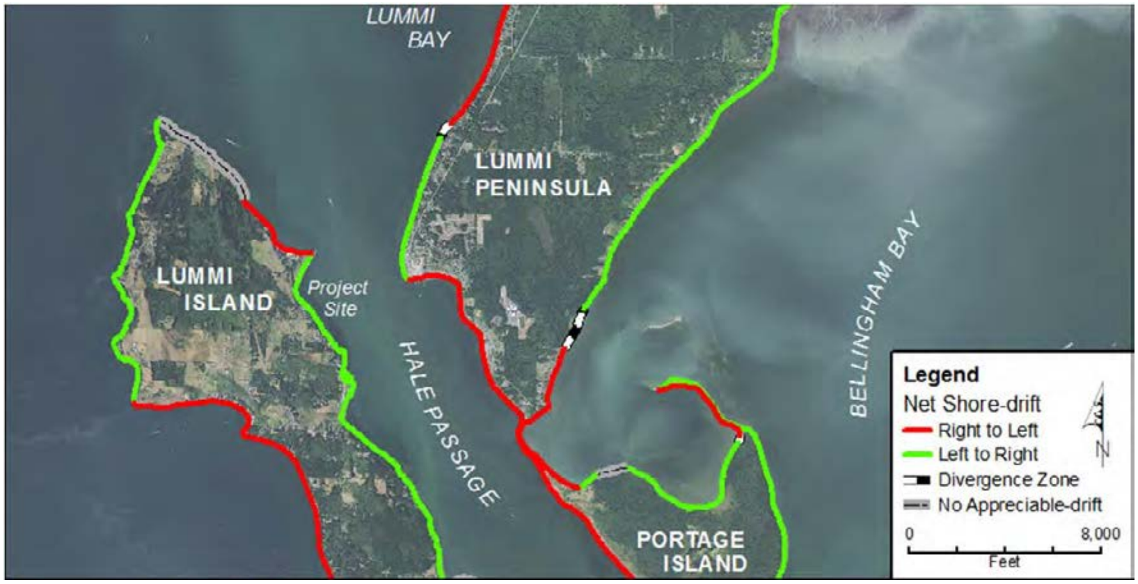
Category	Parameter	Rating	Score	Rationale
Benefits	Effectively mitigated landward erosion	Med	4	Much of the dune has prevented erosion and overwash of the properties, although the northwestern end has experience significant erosion
	Sediment volume augmented	Low	1	Placed sediment was not intended to provide beach nourishment for transport off-site
	Input/exchange of LWD, detritus	Med	2	The structure does not hinder alongshore transport of LWD and detritus
	Backshore vegetation enhanced	High	3	The dune was extensively planted with backshore vegetation
	Marine riparian vegetation enhanced	None	0	No marine riparian planting was included in the project design
	Low-cost and simple installation	Med	2	The project had a moderate cost due to the complexity of berm log placements
Impacts	Structures bury backshore & intertidal areas	None	0	No backshore areas were converted to different use by the project
	Structures impound littoral sediment	None	0	No impediment to littoral transport was installed
	Coarser/steeper beach profiles created	None	0	Beach profiles were not altered by the project
	LWD/detritus recruitment reduced	None	0	Recruitment of detritus has been enhancement by backshore planting
	End erosion adjacent	None	0	The project has had no end effects
	Required maintenance interval	Med	-2	Northwest end of the project required maintenance twice to prevent further erosion of the dune
Design-specific benefits	Enhanced potential spawning habitat for forage fish	Low	1	Sediment was a good match to the already very good potential spawning sediment for forage fish
	Sediment benefits down-drift beaches in process unit	Med	2	Nourishment sediment has been transported to down-drift beaches
Design-specific impacts	Eelgrass beds or other habitats smothered	None	0	No habitats were altered by the project
	Loss of substrate heterogeneity	None	0	Beach sediments have remained similar to pre-project conditions
Total			13	

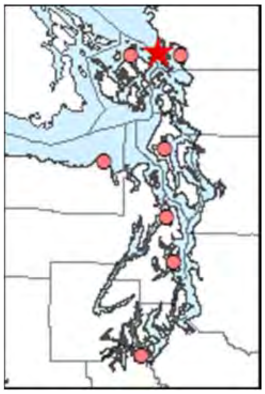
*Scores at double other values (e.g., high=6); all others, none=0, low=1, med=2, high=3

Totaling the above scores, benefits equal +15 points and impacts equal -2 points, for a final combined score of +13.

EAST LUMMI ISLAND – Beach Nourishment (2004)

Waterbody: Hale Passage	Shoretype: Barrier beach	Net shore-drift Cell: WH-4-27	Direction: Northward
Project Elements: Gravel beach nourishment and backshore vegetation, all above MHHW		Objective: Retard coastal erosion near septic drainfield	
Fetch: 15.1 mi SE Wave Energy: Very high Aspect: ESE	MHHW: +8.8 ft MLLW Toe Elev: +9.25 ft MLLW	Land Use: Residential Structure: Septic drainfield Setback: 35 ft Risk Index: 25	Benefit Index: 18 Impact Index: -2 Total BI Index: 16





Project site as red star with dots showing all other beach nourishment projects Sound-wide.

Project Background

This high-wave-energy site consists of a single-family residential property on northeast Lummi Island along western Hale Passage in Whatcom County. The site is on the south flank of a large cuspate foreland (triangular spit). Most of the the drift cell shore consists of Chuckanut Formation sandstone with occasional pockets of sandy and silty glacial deposits. Bluff sediment that once nourished Lane Spit (also called Lummi Point) has diminished both naturally from erosion of the limited volume of unconsolidated sediment and artificially through sediment trapping by shore armor (Bauer 1974). In a report, Bauer (1979) recommended a dense beach nourishment of approximately 12,000 cubic yards (CY) of coarse gravel along 1,600 ft of the south shore of Lane Spit. This nourishment never occurred.

Two segments of a failing wood pile bulkhead located 5 to 10 ft waterward of the OHWM fronted the property. A 25-ft-long segment provided minimal protection to the drainfield and yard. The second 20 ft long bulkhead segment also extended north beyond the property line. Piles typically extended 2.5 ft above the beach, and averaged 0.8 ft in diameter. Erosional end effects caused by the bulkhead segments resulted in approximately 5 ft of horizontal erosion.

The subject property contained a house approximately 65 ft landward of the OHWM. The septic drainfield lay 25 to 35 ft landward of the OHWM. The project was initiated because of concern that the drainfield would become inoperable with continued erosion. Fill was not evident at the erosion scarp or in aerial photo reconnaissance, but some coarse fill soils may have been present. A house on the adjacent and up-drift property lay 28 to 32 ft landward of the OHWM, with a deck within 8 to 12 ft of the OHWM. The house and deck were fronted by a 72 ft long failing low wood pile bulkhead which was causing end erosion on the north end near the subject property.

Southward view of the site prior to implementation. Note failed soldier pile wall in the foreground, along with erosion scarp.

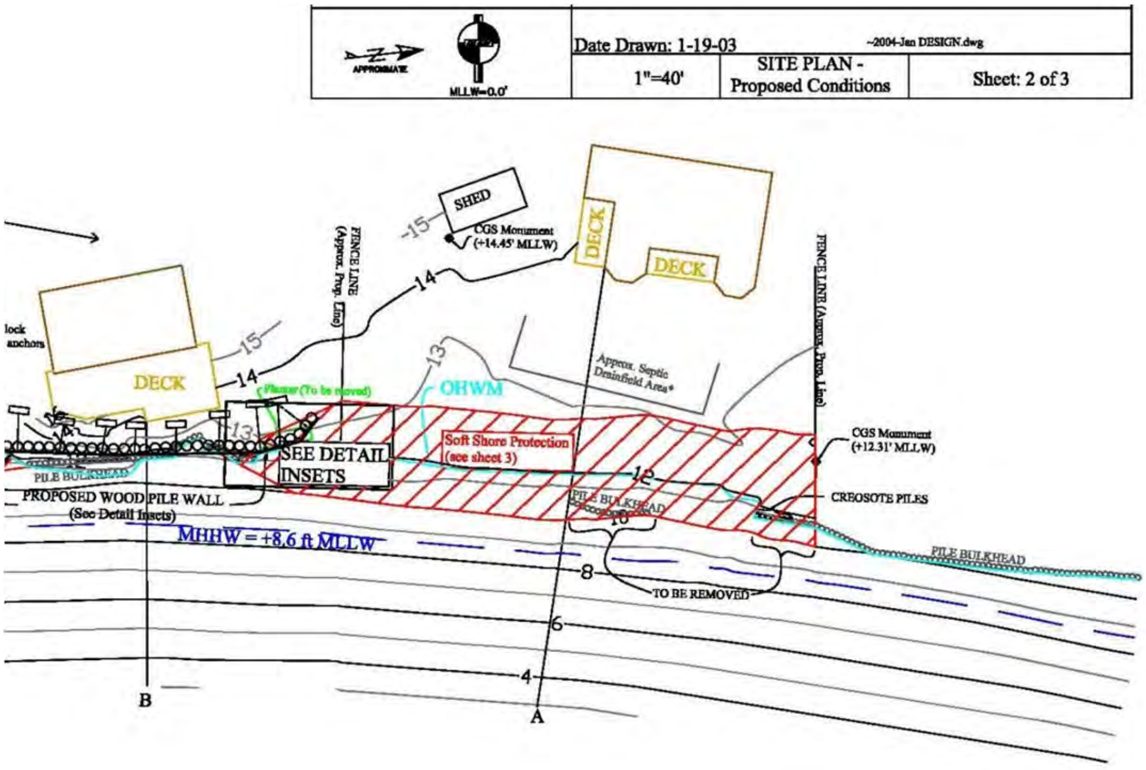
Northward view of the project site prior to implementation.

Design

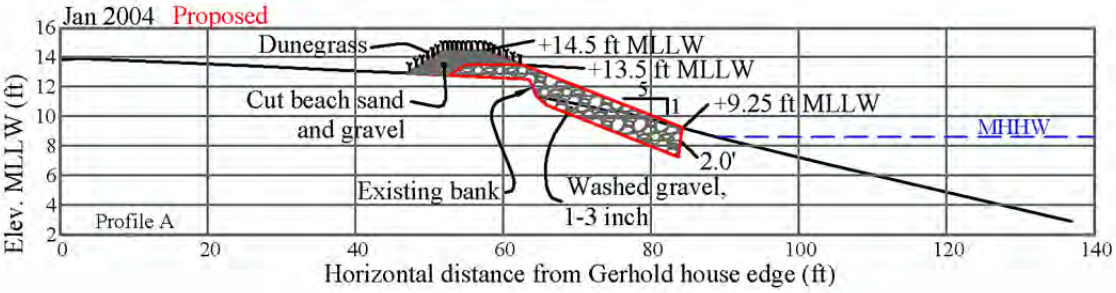
The designers concluded that the site beach would continue to erode if no action was taken (Johannessen 2004). They recommended installing soft shore protection to safeguard the septic drainfield at the subject property and reduce the danger of contamination of marine water. This protection consisted of beach nourishment in the form of an enhanced storm berm. The project also contained a short rock and anchored-log transitional segment at the southern property line, at the north end of the replaced (shorter) wood pile wall on the adjacent property. Only the larger storm berm is assessed here.

The key elements of the design were raising the elevation of the upper beach and “storm berm” and increasing the sediment size to create a higher, more resistant storm berm/backshore area (Johannessen 2004). The entire project was constructed landward of the mean higher high water (MHHW) line, starting at the +9.25 ft MLLW contour or landward of it. Between 1.75 and 2.0 vertical ft of the upper beach sand was first excavated (see Site Plan and Cross Section) and stockpiled. The lower portion of the imported gravel was keyed into the beach in the cut area for additional stability. Washed round rock (1- to 3-inch diameter “drain rock”) was placed in the excavated trench. The imported gravel was 2.0 ft thick vertically and sloped landward at a 5:1 (H:V) slope, extending up to elevation +14 ft MLLW. The total nourishment volume of 252 CY on this property was equivalent to 1.7 CY/ft. The top width of the design berm was 7.5 ft, with the landward side sloped to the existing ground at a 3:1 (H:V) back slope.

The stockpiled beach sand was placed atop the top and landward portion of the gravel protective berm and roughly graded to 1 ft thickness, conforming to the slopes of the gravel berm. Beach logs at the site were stockpiled and placed back on the berm top at the end of construction. Native dunegrass (Elymus mollis) plants in the few existing patches were salvaged and replanted atop the finished berm top. Additional bare-root native dunegrass was then planted atop the sand and gravel shortly after construction to augment, through its root strength, the stability of the constructed protective berm.



Project design drawing (courtesy Coastal Geologic Services, Inc.).



Project design cross section (courtesy Coastal Geologic Services, Inc.).

Current Conditions

Technique condition - The gravel berm remained in place in good condition at the time of the site visit. Dense dunegrass vegetation has provided stability to the berm, and no evidence of overwash was seen. The driftwood accumulation waterward of the berm appeared similar in density and width to the up-drift reference beach. Surface change analysis in AutoCAD between the preproject survey and the 2012 survey revealed that the majority of the storm berm area was 1.5 to 2.0 ft higher, with maximum elevation gain of 3.26 ft.

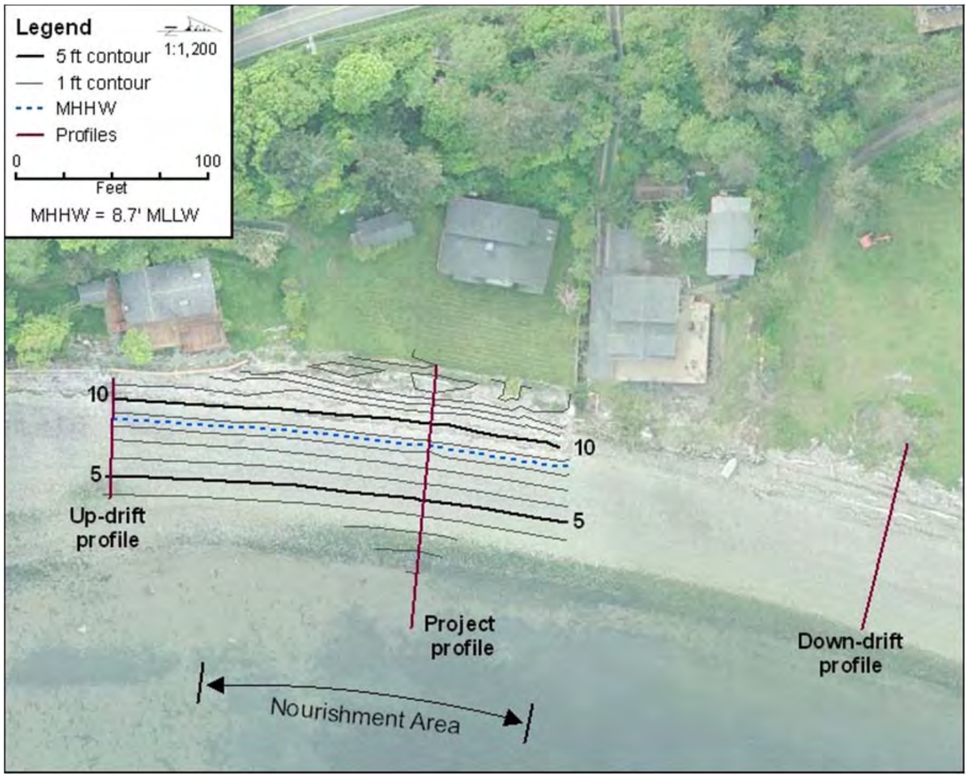
Upland threats - The nourished berm appeared to provide the uplands at the site with adequate protection from erosion.

Beach characteristics - The beach waterward of the project was in good condition, with no visible transition between up- and down-drift reference beaches.

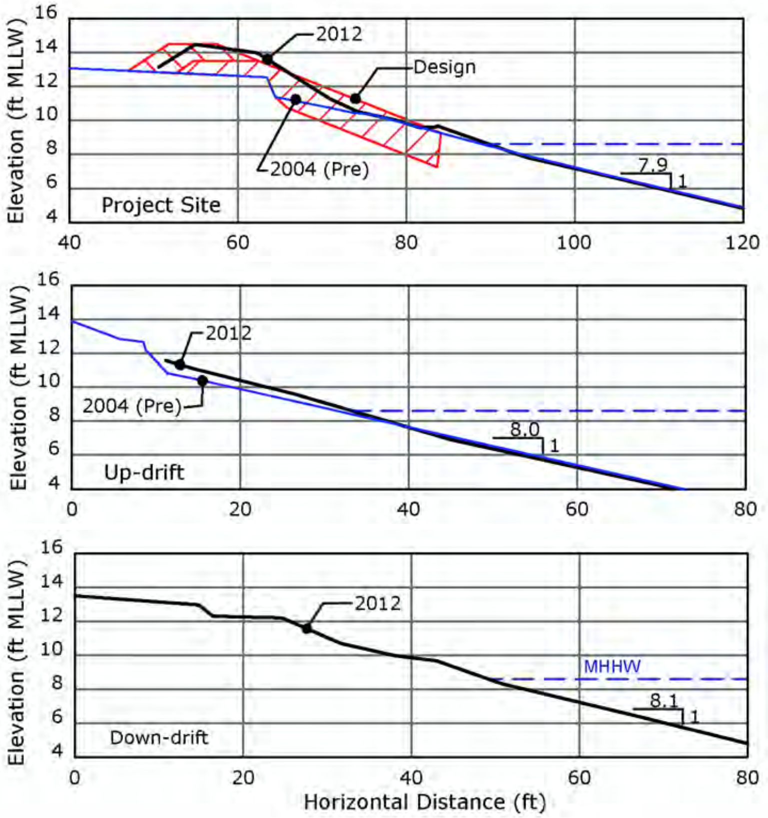
Adjacent shores - The adjacent up-drift shore contained a short stretch of soldier pile bulkhead before transitioning to an unprotected, no-bank shore. Overwash deposits were apparent on the no-bank portion. The down-drift shore contained a soldier pile bulkhead, constructed at the same time as the nourishment project, which extended slightly farther waterward than the toe of the berm.

Westward view of project site in 2012. Note thick dunegrass growing on constructed berm.

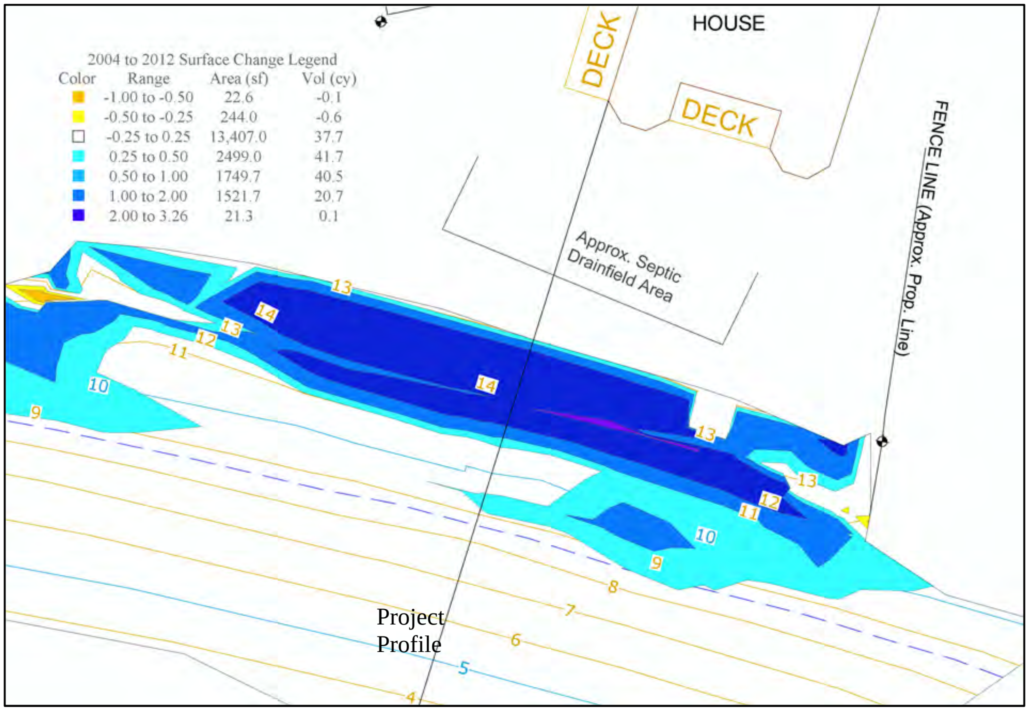
Eastward view of project site in 2012.



Topographic map of conditions during the 2012 site visit.



Beach profiles from monitoring and the 2012 site visit.



Surface Change map of the site between as-built (2004) and 2012 conditions.

Comparison of beach surface sediment at project and adjacent sites.

Location	Backshore	Difference	Upper Intertidal	Difference
Up-drift	COARSE PEBBLE, sand	finer	SAND, coarse pebble, medium pebble	same
Project Site	COARSE PEBBLE, cobble	-	SAND, coarse pebble, medium pebble	-
Down-drift	SAND, coarse pebble	similar	SAND, coarse pebble, medium pebble	same

Performance

Beach nourishment in the form of an enhanced storm berm has performed very well since installation in 2004. A summary of performance follows:

- The gravel storm berm has persisted for the 8 years since installation and has maintained the crest at approximately +14 ft MLLW, slightly more than 5 ft above local MHHW.
- The large majority of coarse gravel placed in the berm, which was cut into existing sediment from the waterward side, appeared to have made the beach more resistant to erosion during storms.
- The recreated setback from the septic drainfield to the OHWM has persisted, without maintenance, since installation.
- The 1 to 3 inch diameter "drain rock" gravel appeared to have been well sized for elevations above MHHW in this very-high-wave-energy environment.
- Dunegrass planted for the project has proliferated, adding some resistance to erosion during storms and augmenting the input of organic material.

Beach profiling, photos, and observations over time revealed that the crest of the enhanced storm berm has not lowered and it has not been overtopped. The lower portion of the storm berm face has lowered slightly due to waves reworking sediment in this area, with what appeared to be some of this gravel forming a higher active berm crest near the waterward edge of the nourishment area. Native beach sediment excavated from the toe of the nourishment area was placed slightly more landward than the design called for and has remained in place with no evidence of overwash since installation. The upper intertidal beach slope at the project site (7.9:1) was slightly steeper than adjacent areas (8.0:1 and 8.1:1). Keeping the sediment a foot or more above local MHHW and selecting the appropriate gravel size appeared to have been important design elements. This type of backshore storm berm installation is usually only possible at no-bank shores (as opposed to bluff sites) as a moderate amount of space is required for installation of a storm berm far enough landward and of high enough elevation to function well and persist without periodic maintenance.

Project performance scoring.

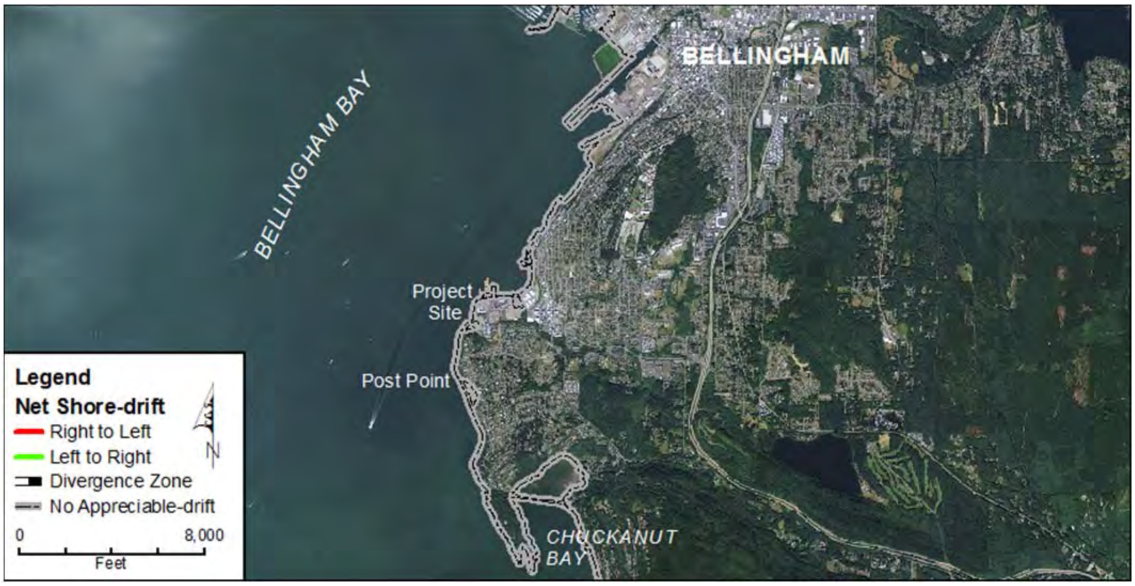
Category	Parameter	Rating	Score	Rationale
Benefits	Effectively mitigated landward erosion*	High	6	No loss of uplands to erosion
	Sediment volume augmented	Med	2	Moderate volume of beach nourishment added
	Input/exchange of LWD, detritus	Med	2	Free alongshore exchange of LWD/detritus
	Backshore vegetation enhanced	High	3	Dense dunegrass on berm
	Marine riparian vegetation enhanced	None	0	No marine riparian planting
	Low-cost and simple installation	High	3	Very low cost of installation
Impacts	Structures bury backshore & intertidal areas	Low	-1	Backshore modified and made more coarse
	Structures impound littoral sediment	None	0	No impact; no-bank site
	Coarser/steeper beach profiles created	Low	-1	Beach slope does not differ from reference beach
	LWD/detritus recruitment reduced	None	0	Broad drift-log zone at project site
	End erosion adjacent (one or both ends); and erosion is greater than adjacent reference areas	None	0	No end erosion
	Required maintenance interval	None	0	None to date; none envisioned for 15 years or more
Design-specific benefits	Enhanced potential spawning habitat for forage fish	None	0	The upper intertidal area was increased with appropriate sediment size
	Sediment benefits down-drift beaches in process unit	Med	2	Minor sediment transport off-site
Design-specific impacts	Eelgrass beds or other habitats smothered	None	0	No offshore sediment transport
	Loss of substrate heterogeneity	None	0	Intertidal and active beach similar to reference beach
Total			+16	

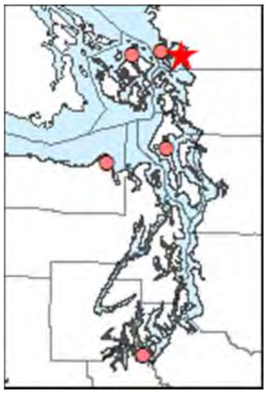
*Scores at double other values (e.g., high=6); all others, none=0, low=1, med=2, high=3.

Totaling the above scores, benefits equal +18 points and impacts equal -2 points, for a final combined score of +16.

MARINE PARK – Beach Nourishment (2004)

Waterbody: Bellingham Bay	Shoretype: Artificial	Net Shore-drift Cell: NAD	Direction: NAD
Project Elements: Bulkhead removal, gravel beach nourishment, sand backshore, and 2 drift sills		Objective: Removal of hazard to park users, recreation and habitat beach creation	
Fetch: 6.6 mi SW Wave Energy: Moderate Aspect: W	Land Use: City Park MHHW: +8.5 ft MLLW Toe Elev: +1–3 ft MLLW	Structure: Park facilities, railroad Setback: 60 ft Risk Index: 15	Benefit Index: 13 Impact Index: -6 Total BI Index: 7





Project site as red star with dots showing all other beach nourishment projects Sound-wide.

Project Background

Marine Park is a heavily used waterfront park in the Fairhaven District of Bellingham, Washington. The site is within an artificial shore that was modified by fill and a BNSF railroad revetment. The shore was part of an old shipyard launch site and had been filled and later armored with a rock revetment. Because the park lies within an extensive area of no appreciable net shore-drift (NAD), it was considered for creation of a pocket beach. Moderate wave exposure and an orientation contrary to the predominant wave direction made it a challenge to design a sustainable beach plan.

The undesigned rubble and debris "revetment" was failing and had become a safety hazard in this heavily used park and impacts to nearshore habitats had recently become a concern. This led to development of a soft shore protection and beach-enhancement approach for much of the park shore. The Marine Park beach-enhancement project was completed as part of a larger Bellingham Bay pilot habitat-restoration effort beginning in 1999. The Whatcom County Marine Resource Committee (MRC) also recommended a soft shore protection approach in 2000.

A design team hired by the Port of Bellingham in 2001–2002 developed plans for removing the failing revetment and constructing a gravel beach. A rock revetment was required in the very narrow northern portion of the park where fill extended into deeper water. The gravel beach was constructed in October to early November 2004. During winter 2007–2008, the City replaced the secondary outfall for the Post Point Wastewater Treatment Plant, which runs under the enhanced beach at Marine Park. The new outfall was run under the waterward portion of the north drift sill, which was rebuilt in February 2008.

Looking north in 2000. Revetment consisted of boulder and concrete debris dumped on the shoreline.

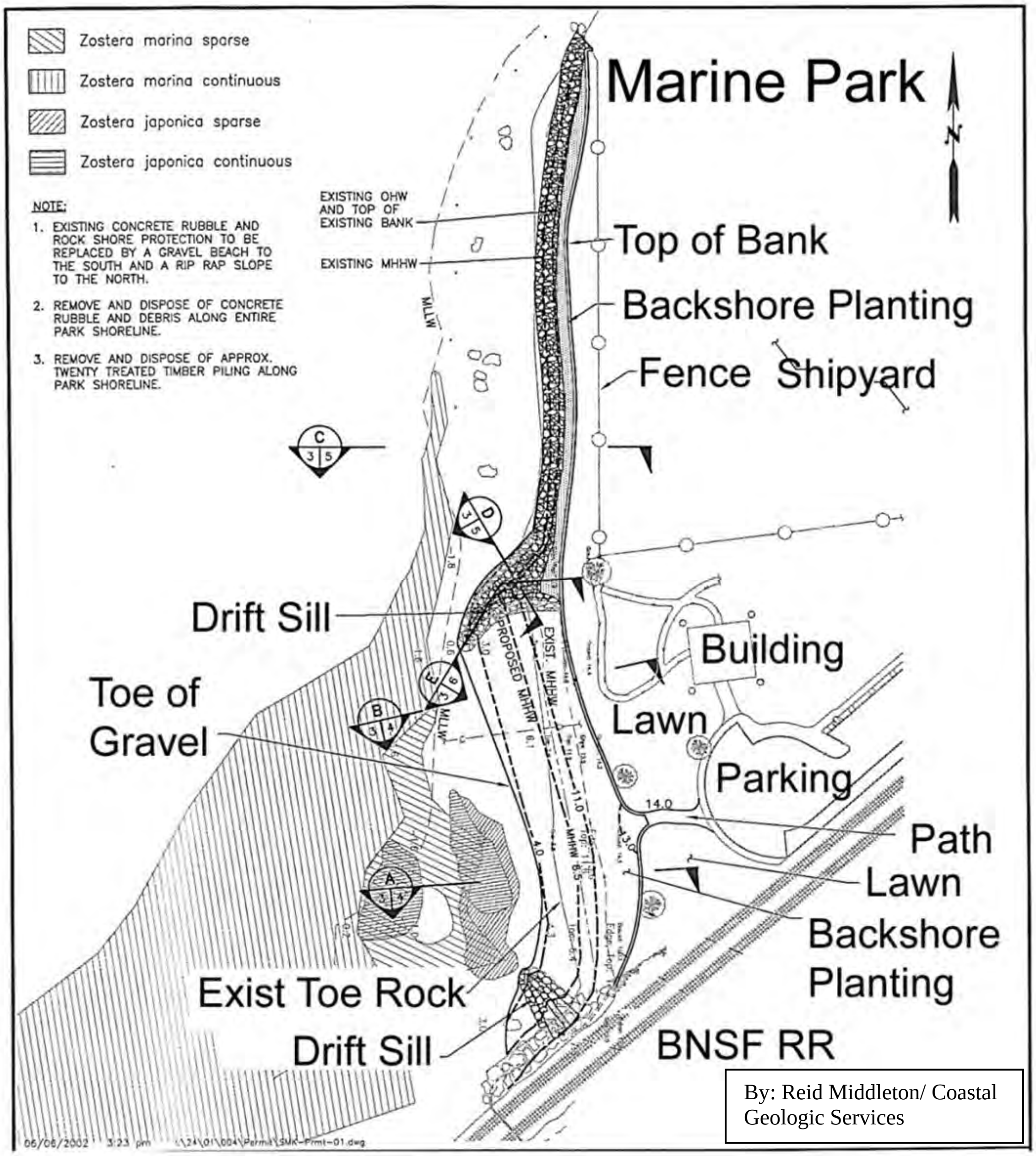
Revetment looking north. Note erosion behind the rock due to wave overtopping. Lighter-colored rock was a more recent addition in response to continued erosion.

Design

- Rock revetment previously extended for the entire length of Marine Park and onto neighboring properties, including the BNSF railway to the south. The revetment consisted of rock, concrete slabs, and debris ranging in size from 1 to 8 ft. Revetment material was apparently placed as it became available. Placement was loose and irregular, lacked geotextile filter fabric, and was not keyed into the beach substate.
- Revetment, associated debris, and fill were removed from 300 ft of the park in 2004, and a gravel beach was installed in their place. Approximately 1,400 CY of rock, concrete, and asphalt debris and 1,200 CY of fill from the beach were first removed from the site. Seventy tons of derelict creosoted wood piles were removed from the intertidal. A new revetment was constructed to a modern design along a very narrow 400-ft-long strip of park property extending to the north waterward of the shipyard, where the fill adjacent to deep water precluded other options.
- Two drift sills (low rock groins) were installed at either end of the project. The southern drift sill was 50 ft long, as measured from the toe of the BNSF revetment, with a crest elevation approximately 1 ft above the finished beach grade. The northern down-drift sill, much larger at 80 ft long, also crested at 1 ft above finished beach grade. The northern drift sill curved to the southwest to create a more contained pocket beach and to maintain a buffer away from native eelgrass (*Zostera marina*). The drift sills were designed to keep a minimum of 20 ft of separation between native eelgrass and the structures, and 10 ft of separation between the nonnative Japanese eelgrass (*Zostera japonica*) and the sills.The sills had a 2:1 side slope.
- Beach enhancement consisted of importing 2,548 CY of washed, rounded gravel. The gravel for the beach consisted of a blend of $^{1}/_{8}$ -inch “pea gravel”, ¾-inch and $1^{7}/_{8}$-inch “drain rock”, and 2-inch-plus cobble, along with 431 CY of coarse sand in the backshore. Density of gravel and sand combined was quite high at 10 CY/ft. The gravel beach extended down to between +2 and +4 ft MLLW and up to a broad sand-covered backshore area. Gravel was placed on the beach starting at +2 ft MLLW on the northern end and down to +4.0 ft MLLW at the southern end. Gravel was placed between 3 and 4 ft thick across the surface after fill was removed to the design grade. Grading to a finished 6:1 slope was accomplished with a bulldozer at low tides at night in November 2004. The gravel beach design resembled conditions found at reference beaches in the vicinity.
- A coarse sand backshore was created above +11.0 ft MLLW and extended as high as +13.5 ft MLLW, with a design slope of 14:1.
- The native backshore planting portion of the restoration design was not fully developed or implemented. Nonnative landscaping was installed in a very small area near retained nonnative trees.
- A minor volume of renourishment sediment was added to the south end of the beach above MHHW three times after March 2006 under direction of the Port of Bellingham, although advice received indicated that the need for this could be avoided by reducing the southern lawn area and adjusting the beach to face the predominant waves as originally intended.

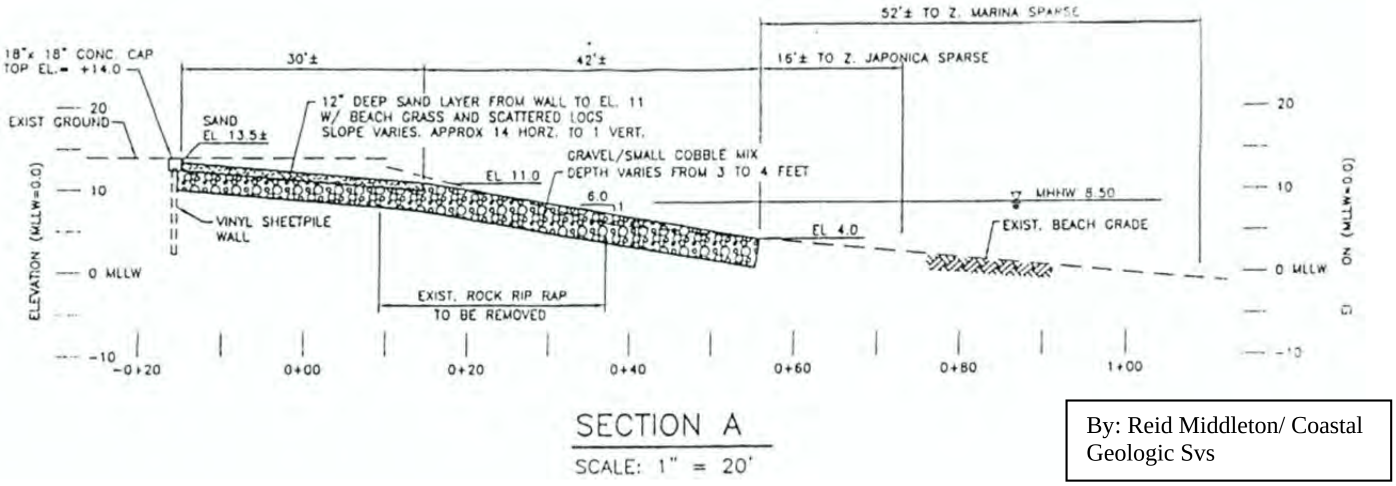

Looking north toward construction of north drift sill and limit of excavation of fill and debris in late October 2004.


Looking north toward intial grading and placement of gravel between drift sills in early November 2004.



By: Reid Middleton/ Coastal Geologic Services

Project design drawing.



By: Reid Middleton/ Coastal Geologic Svs

Project design cross section.

Current Conditions

Technique condition - Large storms in the winter of 2005–2006 adjusted the initial plan form of the beach in the first 2 years after implementation. Since then, the beach has remained fairly stable, with the exception of minor erosion in the far south end and accretion in the north end. The southern end of the beach was not built as far landward as initially recommended or as later recommended for resloping. Instead, there has been minor periodic renourishment above MHHW and a small amount of rock recently placed at the southern property line to prevent further loss of lawn. The project area beach has become more fine grained over time, resulting in a more relaxed slope than originally designed and minor waterward movement of the beach toe in its north-central portion.

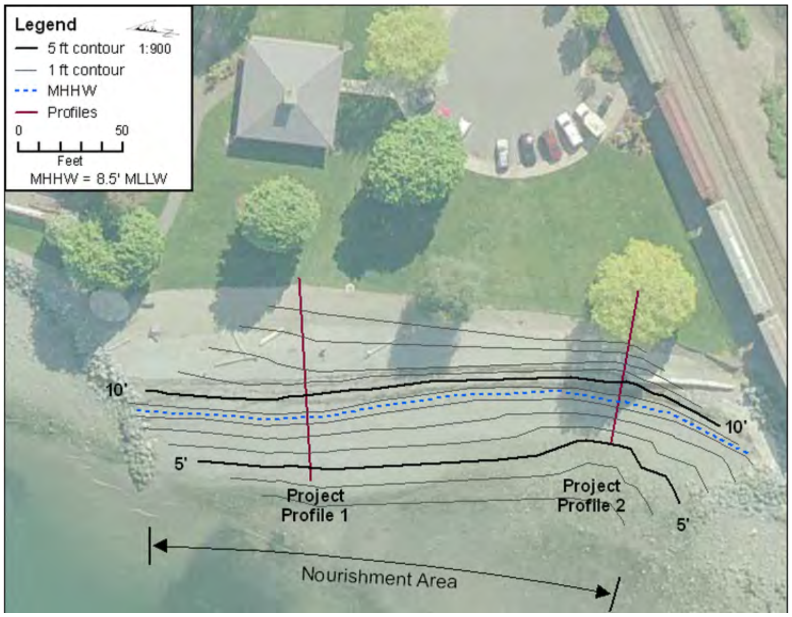
Upland threats - All park infrastructure is far enough landward to avoid damage from coastal erosion.

Beach characteristics - Beach sediment was dominated by medium to coarse pebble nourishment, but has become mixed with sandy backshore sediment, sand from the low-tide terrace, and shell hash. This has resulted in a beach suitable for forage fish spawning under most conditions (Penttila 2010 pers. comm.).

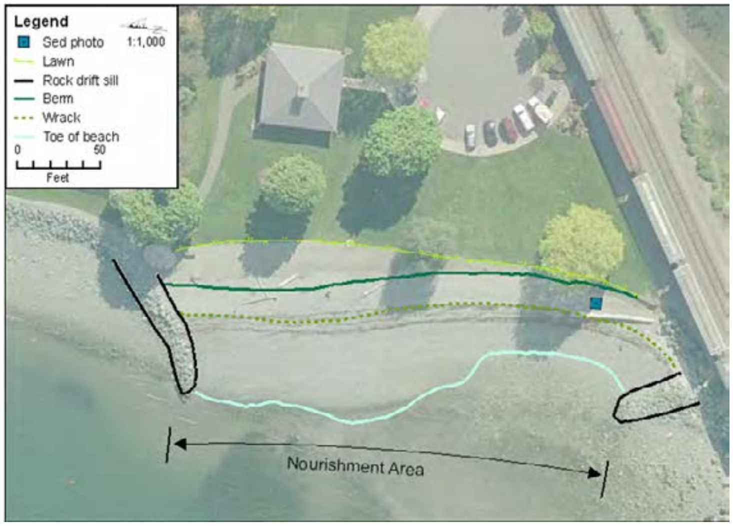
Adjacent shores - Adjacent shores are all modified with rock revetments. The reach south of the park beach has experienced rock-toppling failures and has received additional rock over time from BNSF through side-dumping from the tracks. A rock revetment on the northern park shore that was replaced in 2004 remains in good condition, although rock toppling has occurred in small areas. Beaches that extend only into the mid-upper intertidal were dominated by pebble with boulder and minor pockets of sand both north and south of the park beach.

Upper intertidal beach at the site looking north in 2012. Nourishment gravel dominates, but sand can be seen mixed in the foreground.

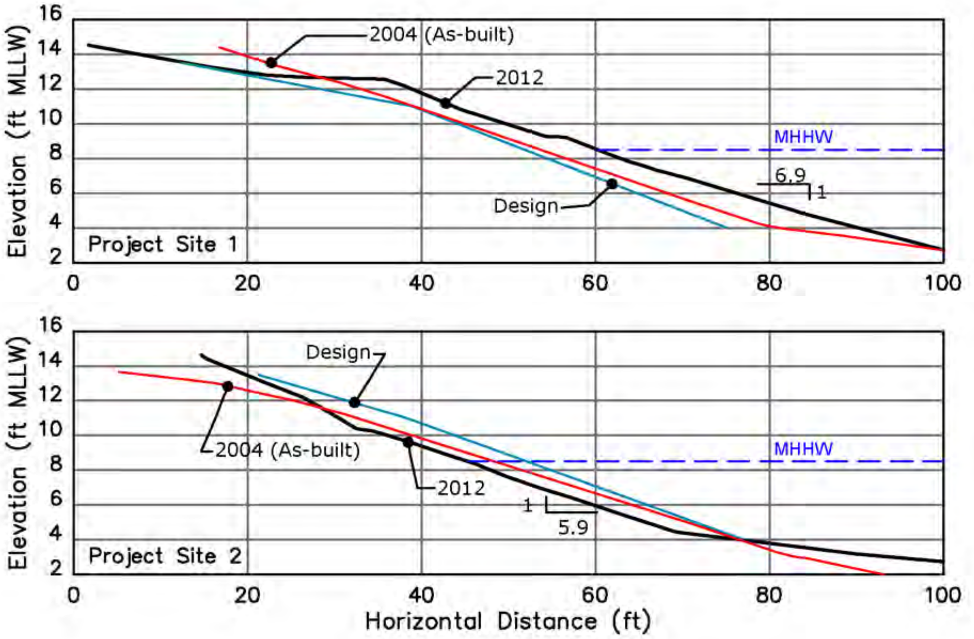
Project site looking south along the BNSF rail causeway in 2012. The southern drift sill (low groin) is in the center of the photo, with a large accumulation of shell hash in the foreground.



Topographic map of conditions during the 2012 site visit.



General beach features mapped during the 2012 site visit.



Beach profiles from monitoring and the 2012 site visit showing comparison to original design.

Comparison of beach surface sediment at project and adjacent sites. n/a indicates the location was not present for sampling.

Location	Backshore	Difference	Upper Intertidal	Difference
Up-drift	n/a	-	SAND, cobble, boulder	coarser
Project site	SAND	-	COARSE PEBBLE, medium pebble, fine pebble	-
Down-drift	n/a	-	COBBLE, boulder	coarser

Performance

Overall the beach nourishment has performed very well since installation in 2004. Accretion has occurred at the north end and some erosion has occurred at the south end; this project provides a clear example of the result of not properly orienting the constructed berm design to the predominant storm waves. Another example of this is Seacrest Park in West Seattle. The original concept for Marine Park included some conversion of upland to beach in the southern portion of the park, but this was not implemented. As a result, the beach has tended to erode in the south end. With the loss of backshore, some large rock was placed to protect the fence at the south property line. Despite some backshore erosion in the south end, the primary goals of improving park safety, providing increased recreation, and habitat enhancement were achieved.

A summary of performance follows:

- Beach nourishment gravel has become “naturalized” with the addition of coarse sand and shell hash from the low tide terrace and the backshore. Starting 5 years after construction, the beach often contained suitable sediment for surf smelt spawning habitat.
- Some sediment has overtopped the gaps in the north drift sill. Drift sills are very difficult to construct with a near-even crest. At this site the fact that the drift sill was half deconstructed during replacement of the wastewater overflow line, then rebuilt during less-than-optimal tide windows may have resulted in additional northward transport.
- Four years of post-project monitoring (CGS 2008) showed that the extensive eelgrass beds on site have not been impacted by the nourishment.
- The park has continued to be highly utilized by the public, has become the most popular paddling launch in the city, and served as the finish line for 500 teams in the Ski-to-Sea relay race.
- Forage fish utilization may be up, but egg density monitoring has not occurred.

Project performance scoring.

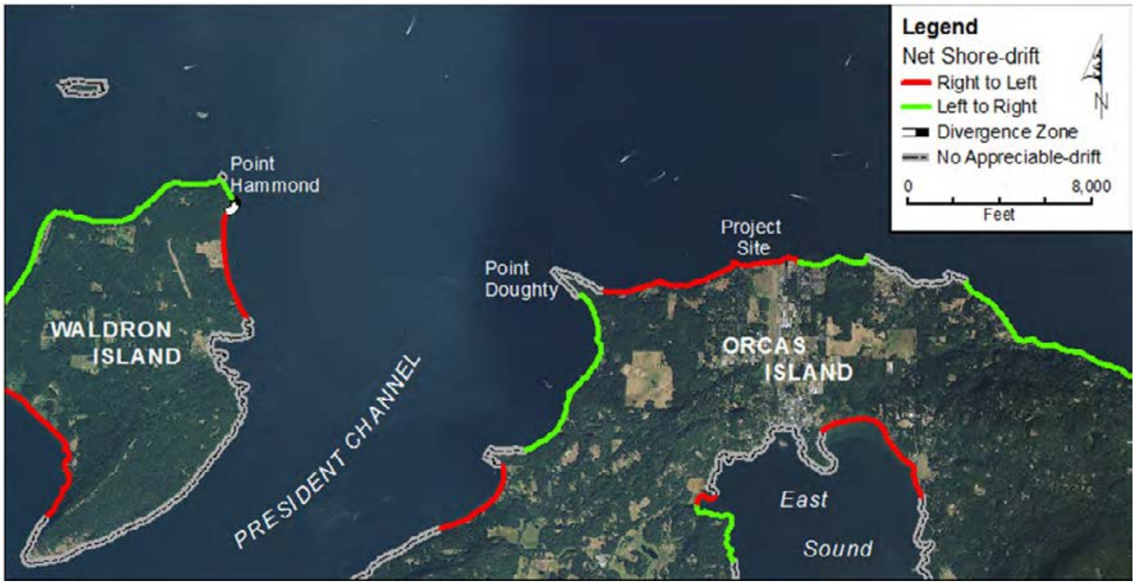
Category	Parameter	Rating	Score	Rationale
Benefits	Effectively mitigated landward erosion*	Med	4	Minor backshore erosion has occurred
	Sediment volume augmented	High	3	Large amount of sediment added
	Input/exchange of LWD, detritus	Low	1	Drift sills trap some LWD and detritus
	Backshore vegetation enhanced	None	0	No backshore planting or natural recruitment
	Marine riparian vegetation enhanced	None	0	No marine riparian planting
	Low-cost and simple installation	None	0	Moderately expensive implementation
Impacts	Structures bury backshore & intertidal areas	None	0	No backshore to bury; new intertidal and backshore created
	Structures impound littoral sediment	Low	-1	Almost no native (littoral) sediment to impound, however drift sills present
	Coarser/steeper beach profiles created	Med	-2	New beach is decidedly steeper and coarser
	LWD/detritus recruitment reduced	None	0	No impact
	End erosion adjacent	None	0	No impact
	Required maintenance interval	High	-3	Several renourishments in absence of allowing southern lawn to erode
Design-specific benefits	Enhanced potential spawning habitat for forage fish	High	3	Upper intertidal provides very good mix of forage fish spawning habitat
	Sediment benefits down-drift beaches in process unit	Med	2	Some nourishment sediment is transported northward
Design-specific impacts	Eelgrass beds or other habitats reduced	None	0	No impacts to eelgrass beds
	Loss of substrate heterogeneity	None	0	Good mix of sediment on beach
Total			7	

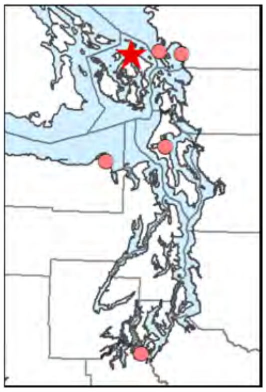
*Scores at double other values (e.g., high=6); all others, none=0, low=1, med=2, high=3

Totaling the above scores, benefits equal +13 points and impacts equal -6 points, for a final combined score of +7.

NORTH ORCAS ISLAND – Beach Nourishment (1992)

Waterbody: Georgia Strait	Shoretype: Barrier beach	Net Shore-drift Cell: OR-1	Direction: Eastward
Project Elements: Gravel beach nourishment with 2 rock drift sills		Objective: Slow landward erosion and remove revetment to improve beach access	
Fetch: 101 mi NW Wave Energy: Very high Aspect: N	Land Use: Residential MHHW: +8.7 ft MLLW Toe Elev: +4.0 ft MLLW	Structure: Houses Setback: 43 ft Risk Index: 25	Benefit Index: 19 Impact Index: -4 Total BI Index: 15





Project site as red star with dots showing all other beach nourishment projects Sound-wide

Project Background

This very high-wave-energy site on northern Orcas Island comprises four adjacent residential properties. A 101 mile northwest fetch from Georgia Strait and the 13 mile northeast fetch exposes the beach to very high-energy waves during northwesterly northeasterly storms. Although mapped as a barrier beach, it functions somewhat like a large pocket beach. Net shore-drift mapping (Johannessen 1992) showed that the larger beach and drift cell experienced cyclical changes in dominant littoral drift direction over a period of a decade or more. Net shore-drift is mapped as eastward, but westward drift occurs in some periods due to large northeasterly windstorms.

Prior to the nourishment project, a rock revetment stretched across the entire four-property site for shore protection. The revetment had become severely damaged in the central and eastern portions of the site, with extensive rock toppling. Erosion landward of the revetment had begun, with scarping and removal of sediment and vegetation. Erosion landward of the revetment was substantial throughout the site during windstorms of winter 1989–1990. The eastern house was very close to the active wave erosion, and had damage and gravel overwash onto the attached deck. Revetment rocks were toppling and sinking into the gravel beach, and owners complained of the lack of a dry beach and of a place to store small boats at high tide. Additionally, older residents and guests had difficulty getting over the revetment.

Cabins at the site were gradually upgraded and enlarged at the same time the revetment was deteriorating. Most owners were long-term owners which made working together on a larger solution to erosion problems a good option. One resident was a long-time park facility planer which also proved to be an important asset to the group for planning and permitting. The project was initiated following storm damage in 1989–1990.

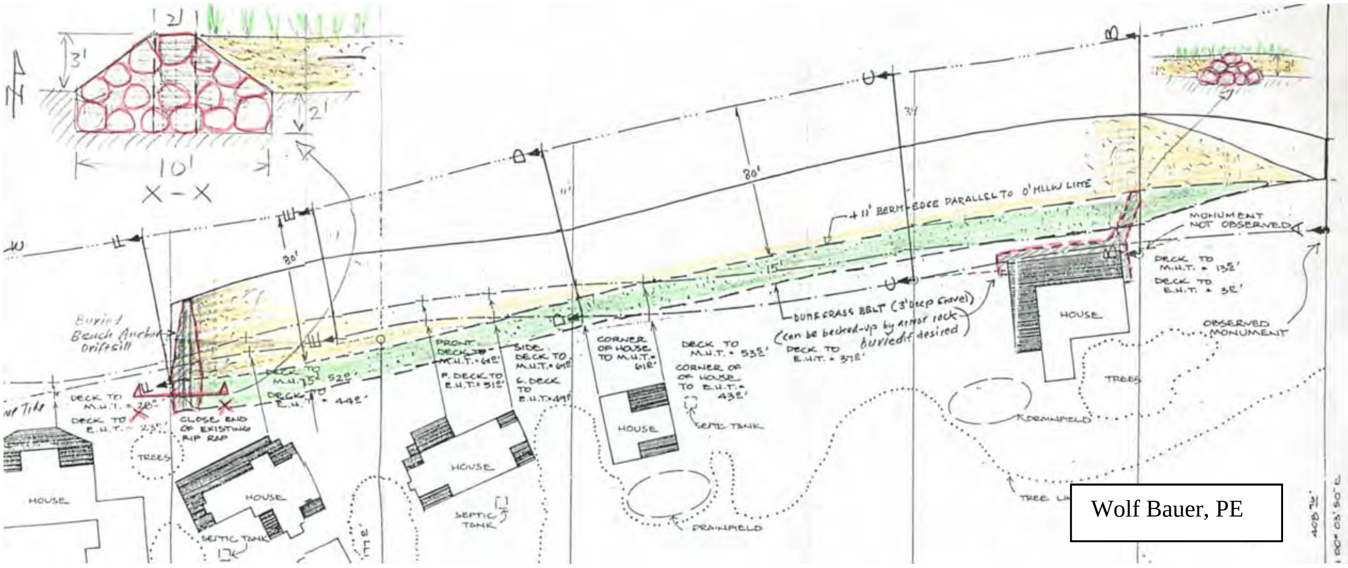
Eastward view from near the middle of the project site prior to implementation. Note largely scattered rock revetment with landward erosion.

Eastward view of the western portion of the project site prior to implementation. Note the higher backshore and intact revetment in this area.

Design

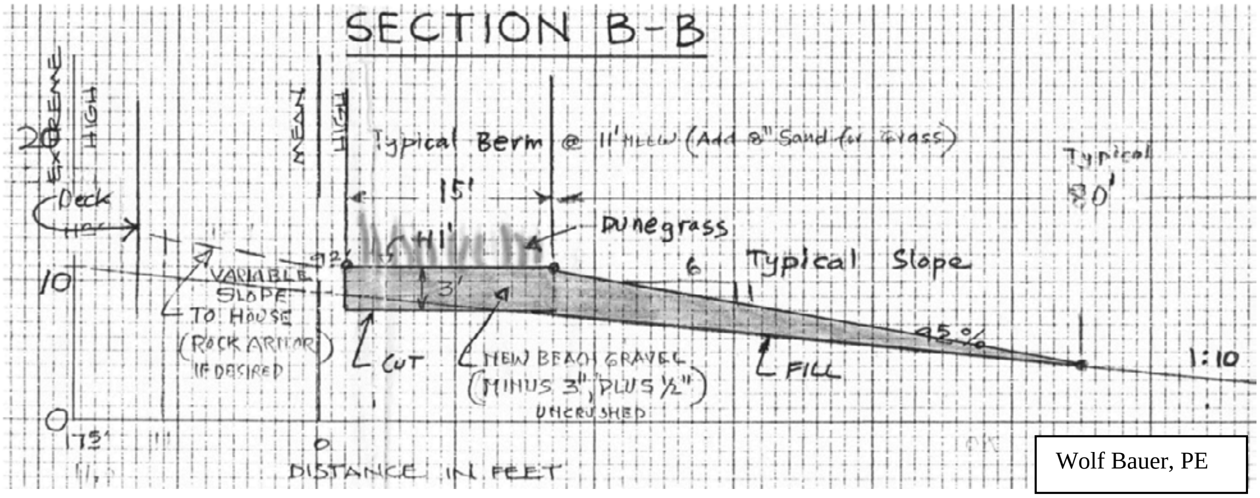
This Wolf Bauer-designed beach nourishment project was intended to allow for removal of a rock revetment and to mitigate for potential beach erosion along 510 ft of barrier beach located on the north shore of Orcas Island. Following removal of the revetment and debris, design drawings called for 2,400 CY of washed gravel (½- to 2-in-diameter “drain rock” from a local source) to be graded across the beachface. There was no initial sediment removal from the beachface, but some of the backshore sand and adjacent soil was removed along with the rock revetment. Many of the rocks were buried in the back of the excavated trench, while others were used for upland landscaping. The gravel was partially contained by two large terminal drift sills composed of 3- to 5-ft-diameter boulders. The eastern sill, which did not extend across the nourished beach width, angled towards the north-northeast, not perpendicular to the trend of the beach. The western drift sill design was for a larger structure that extended approximately 3 ft above preproject grade, with 2 ft of rock burial below preproject grade. The design was similar to the single drift sill placed at North Beach on Samish Island and described by Zelo et al. (2000). The smaller, eastern drift sill included nourishment on the east side, providing added stability to the imported sediment near the eastern house in the project area.

The imported gravel was graded to a 6:1 slope from elevation +4.0 to +11 ft MLLW, which was 2.3 ft above local MHHW. A 15-ft-wide storm berm was constructed landward of the new berm crest. The eastern end of the nourishment area moved the beachface farther waterward as a low-elevation house was very close to the active beach at this end. The project was implemented in December of 1992. Shortly thereafter a large storm naturally regraded the nourishment sediment, transporting sediment onshore and leading to the development of a storm berm, which was present during field surveying in 2012.



Wolf Bauer, PE

Project design drawing.



Wolf Bauer, PE

Project design cross section.

Current Conditions

Technique condition - There has been no backshore erosion or significant flooding since installation in 1992. The nourishment sediment appeared stable, and the beach was broad. Some imported gravel has likely been transported out of the site but apparently was replaced by a greater volume of gravel and sand because the central project profile has risen considerably since the first year of the project. The upper beach and backshore slope were flatter in the project area and steeper in the mid-intertidal compared to the adjacent reference beaches. The down-drift profile area received some nourishment sediment during construction, and profiles indicate it has accreted since. Photos from a 1992 storm right after nourishment showed on-shore gravel transport in the study area, which included minor gravel over the deck on the project area's eastern house. At the same time, significant erosion and minor flooding occurred on adjacent properties outside the project area, causing greater damage. The upper beach in the nourishment area appears to have remained lowered for some years after 1992, while the higher landward storm berm also persisted.

Upland threats - Although several of the houses in the project area are close to the beach, the higher elevation beach and backshore have mitigated previous erosion and storm-wave damage. Owners reported no damage since installation in 1992. The condition of the beach suggested that no maintenance will be needed. This could change if several major storms from the northeast occur as there appears to be a long-term cycle of gross eastward littoral drift, which then reverses to westward.

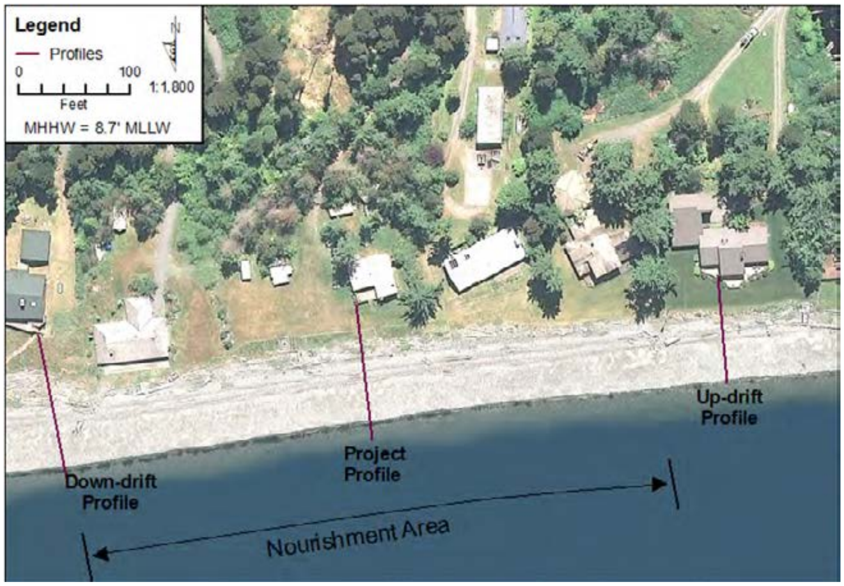
Beach characteristics - The beach elevation appeared to have risen as much as 4 ft in the central project area. Drift sills at each end were almost entirely below grade, indicating that the beach has accreted since the storm soon after nourishment. The area immediately east of the east drift sill was included in the nourishment area, as reflected in the down-drift beach profile. The backshore storm berm here extended up to elevation +12.4 ft MLLW, equal in elevation to the project profile location.

Adjacent shores - No recent erosion of the beach or backshore was observed at adjacent shores; however past erosion and damage occurred after nourishment (as mentioned above). Land at the up-drift area was raised around the houses with fill and this- beach profile differed from the nourished profiles. This western-area beach profile showed a more "natural" storm berm at elevation +11.3 ft MLLW, with a narrow landward-sloping berm top fronting another rise in elevation at the filled uplands that extended up to +13.6 ft MLLW.

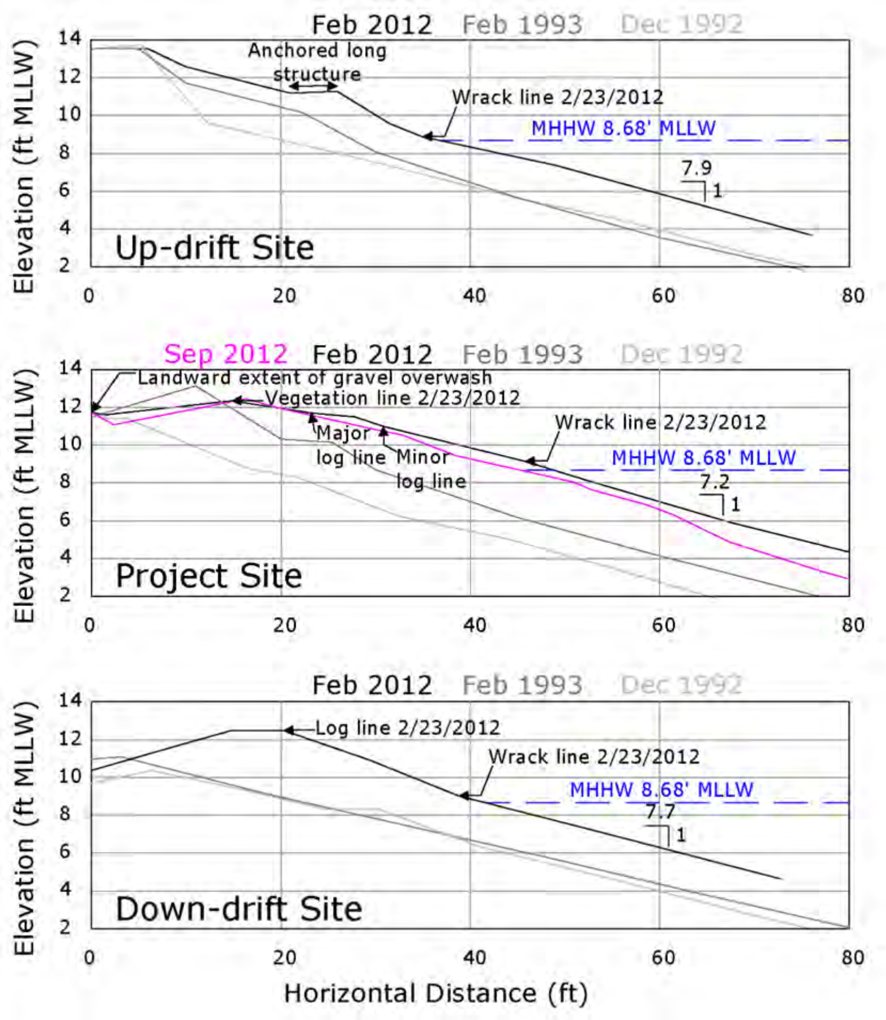
Project site looking up-drift (west) in 2012.

West drift sill looking down-drift (east) towards project, 2012.

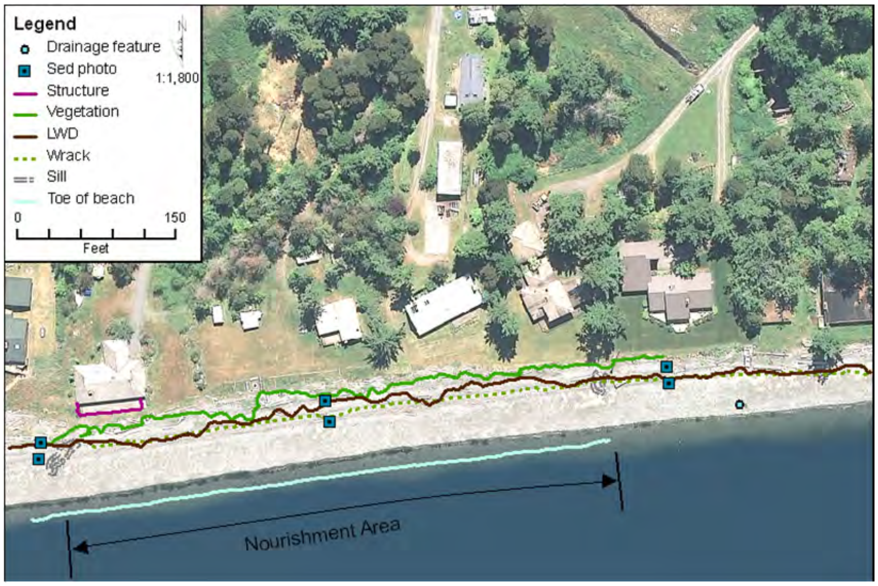
Project area in 2008 with drift sills (at arrows) barely visible on uppermost beach.



Project area showing location of beach profiles.



Beach profiles from pre- and post-project and the 2012 site visits.



General beach features mapped during the 2012 site visit.

Comparison of beach surface sediment at project and adjacent sites.

Location	Backshore	Difference	Upper Intertidal	Difference
Up-drift	COARSE PEBBLE, medium pebble	coarser	COARSE PEBBLE, medium pebble	same
Project site	FINE PEBBLE, medium pebble, coarse pebble	-	COARSE PEBBLE, medium pebble	-
Down-drift	MEDIUM PEBBLE, coarse pebble, fine pebble	similar	FINE PEBBLE, sand, medium pebble	finer

Performance

The four-property beach nourishment project has performed very well at this very-high-wave-energy site. This project seemed to be successful for three reasons:

- The beach was generally swash-aligned beach (which faces the predominant direction of wave attack), thereby limiting alongshore sediment transport.
- The site was a barrier beach, which allowed for adequate room for nourishment landward. This is typically not feasible at a high-bank site unless it is a lower-energy shore and other structural elements such as anchored wood are used.
- The site had an adequate along-shore length because of the cooperation of the four adjacent property owners, allowing nourishment sediment to extend over the majority of the beach profile and have a moderately large nourishment volume and density. This type of project would not have been feasible at a shorter reach in this wave climate.

The project was designed and installed cost-effectively and has not required maintenance, making it an affordable solution for the magnitude of wave energy. The project was inexpensive in part because one owner completed permitting and the local gravel supplier was allowed extra time to produce the desired coarse gravel. The drift sills maintained their structural integrity through major storms. In 2012 the beach was relatively high, and neither sill was exposed more than several inches. No adjacent end erosion was visible in 2012 or in the available photo record. The LWD band and wrack were consistent along-shore with adjacent properties. Backshore dunegrass planting was successful, although not carried out over the full project length. The beach sediment appeared largely natural, with some coarse sand and minor gravel worked into the intertidal area. The overall sediment size, which appeared somewhat coarser than at other beaches in the vicinity, may have altered the site's intertidal habitats somewhat.

It must be noted that the littoral transport regime may shift to a cycle where large volumes of sediment are transported westward, as documented by Johannessen in net shore-drift mapping in 1992. This could dramatically change the beach elevation for some period and result in a lower availability of drift sediment, as marina jetties to the east tend to block some littoral transport.

Project performance scoring.

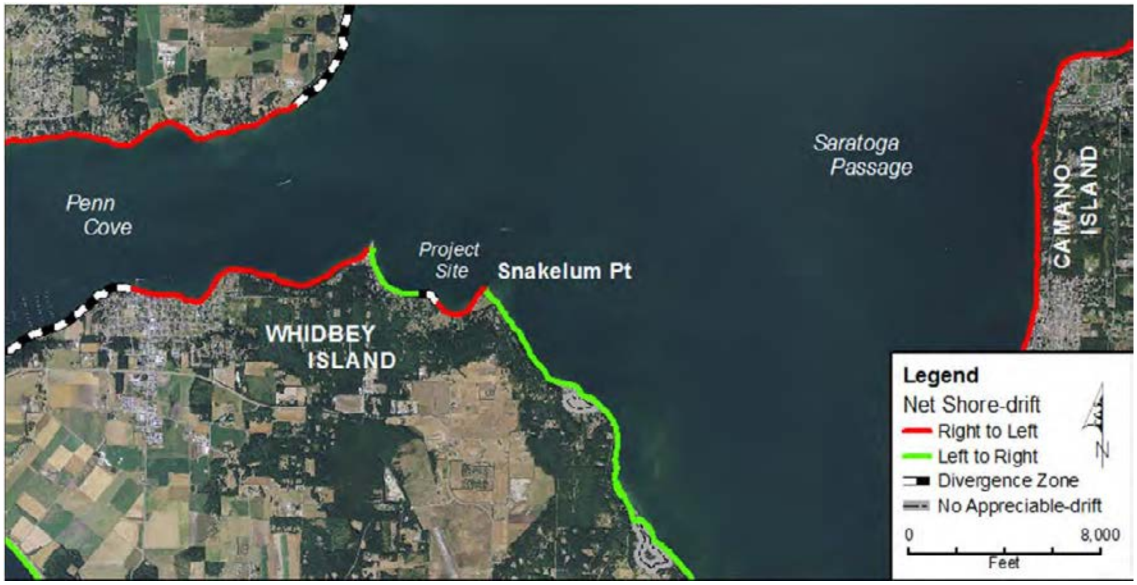
Category	Parameter	Rating	Score	Rationale
Benefits	Effectively mitigated landward erosion*	High	6	No major erosion has occurred since installation
	Sediment volume augmented	High	3	A large quantity of sediment was added to the littoral cell
	Input/exchange of LWD, detritus	Med	2	No alongshore impediment in place
	Backshore vegetation enhanced	Med	2	Extensive dunegrass planting at several parcels has created a dense backshore vegetation community
	Marine riparian vegetation enhanced	None	0	No marine riparian planting was included
	Low-cost and simple installation	High	3	Low cost to implement
Impacts	Structures bury backshore & intertidal areas	None	0	No additional backshore was buried; revetment was removed from backshore
	Structures impound littoral sediment	Low	-1	Drift sills trap some sediment while allowing majority to pass through
	Coarser/steeper beach profiles created	Low	-1	Beach profiles were similar but raised; grain size was sometimes more coarse
	LWD/detritus recruitment reduced	None	0	No impact
	End erosion adjacent	None	0	No end erosion evident
	Required maintenance interval	None	0	No maintenance has been conducted or required
Design-specific benefits	Enhanced potential spawning habitat for forage fish	Low	1	Additional upper beach uncovered, but grain size used was coarser than forage fish typically use
	Sediment benefits down-drift beaches in process unit	Med	2	Some nourishment sediment appeared to have been transported to adjacent beaches
Design-specific impacts	Eelgrass beds or other habitats smothered	Low	-1	Some habitats altered but no loss of eelgrass area identified
	Loss of substrate heterogeneity	Low	-1	Nourishment grain size distribution was low
Total			15	

*Scores at double other values (e.g., high=6); all others, none=0, low=1, med=2, high=3

Totaling the above scores, benefits equal +19 points and impacts equal -4 points, for a final combined score of 15.

SNAKELUM POINT – Beach Nourishment (2002)

Waterbody: Saratoga Passage	Shoretype: Barrier beach	Net Shore-drift Cell: WHid-8a	Direction: Northeastward
Project Elements: Gravel beach nourishment, anchored log, planting		Objective: Retard coastal erosion near septic drainfield	
Fetch: 12.7 mi NE Wave Energy: Moderate Aspect: NW	Land Use: Residential MHHW: +11.5 ft MLLW Toe Elev: +13.0 ft MLLW	Structure: Septic drainfield Setback: 50 ft Risk Index: 16	Benefit Index: 20 Impact Index: -1 Total BI Index: 19



Project site as red star with dots showing all other beach nourishment projects Sound-wide.

Project Background

This barrier beach site on the eastern shore of Whidbey Island lies on the northwest, lower wave-energy side of a cuspate foreland (triangular spit). The property is in a short drift cell with a limited volume of littoral transport. The drift cell originates from high bluffs about a half mile to the west. Drift terminates near the end of the cuspate foreland approximately 300 ft northeast of the property. The area appears to have some amount of short-term littoral drift reversal.

Erosion at the property was clearly exacerbated by a vertical wooden bulkhead constructed over the upper beach immediately down-drift (east) of the site. The bulkhead had a 90° corner located 18 ft from the erosional scarp. This caused the site to experience end effects (due to wave refraction) around the wooden bulkhead during times of southeast to northeast winds. After the soft shore project had been in place for several years, the adjacent wooden bulkhead was replaced with a rockery wall.

A single-family home lies on the landward portion of the small residential lot, with a septic drainfield in the yard waterward of the house. Coastal erosion during high-tide windstorms has caused an erosional scarp to progress landward. This placed the OHWM so near the drainfield that its function and continued usage were threatened. There was no option to move the house or drainfield due to the limited lot size and important cultural resources throughout the area. The area on the far side of the local road is all wetlands and was off limits for relocating a drainfield.

Northeastward view of the project site prior to implementation in 2002.

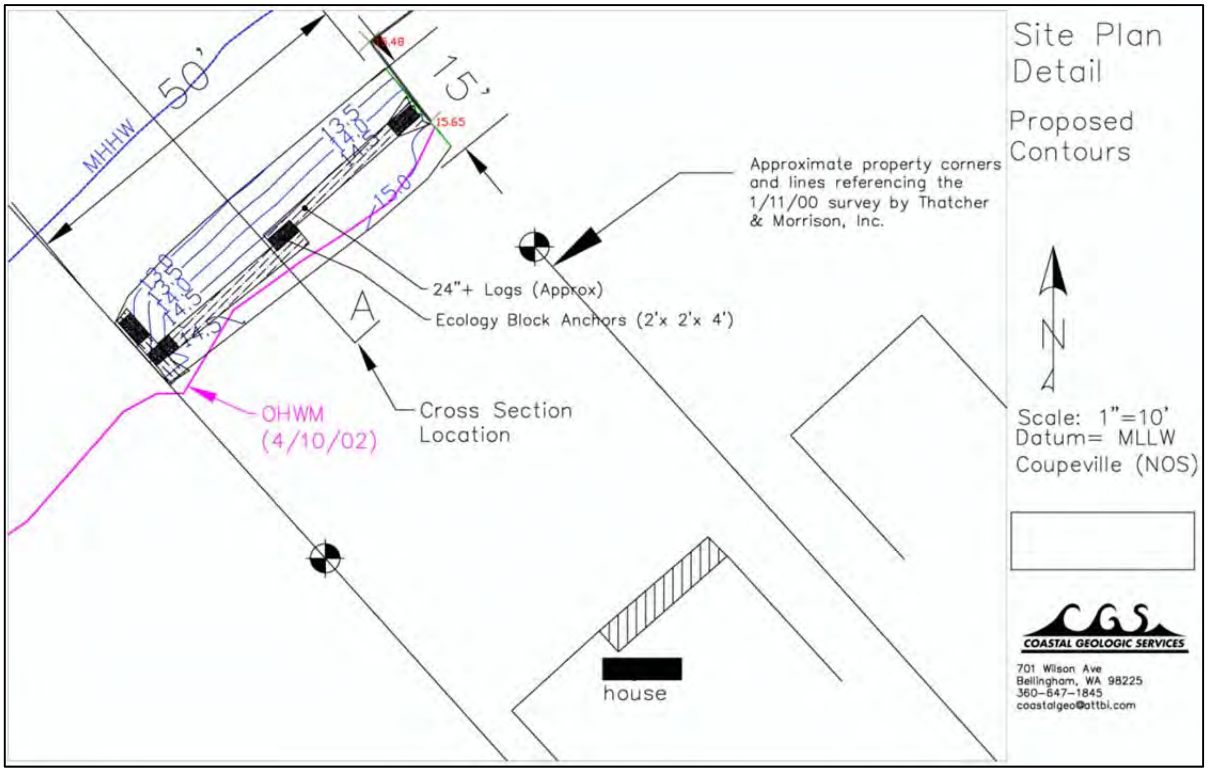
Southwestward view prior to implementation in 2002. Note the large offset of the adjacent wooden bulkhead.

Design

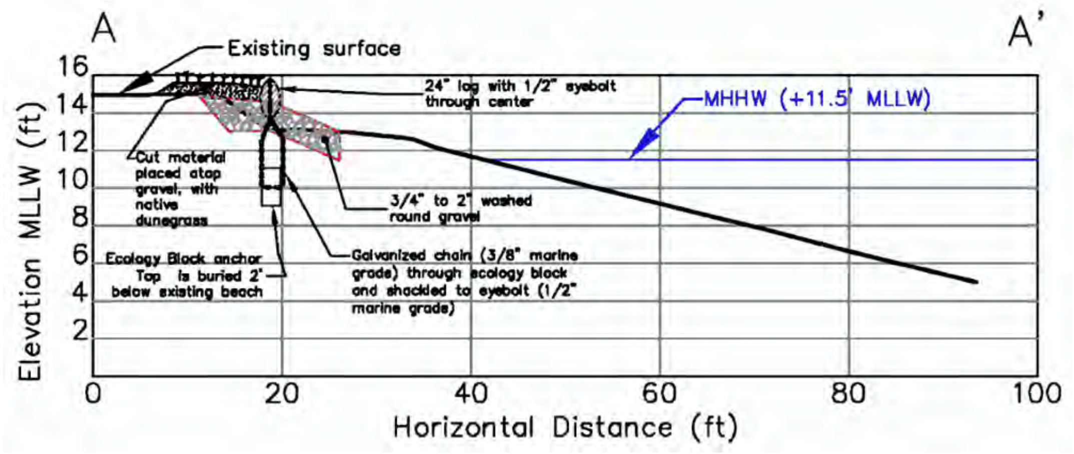
The design was intended to create a more robust storm berm, which included one row of large logs and dunegrass planting. This involved raising the elevation of the uppermost beach waterward of the eroded very low bank and increasing the sediment size to create a higher, more erosion-resistant storm berm in the backshore area. Up to 1.5 vertical ft of the upper beach and yard from a roughly 15-ft-wide area were first excavated and stockpiled. This included an average of 3 to 4 ft of lawn across the width of the property. The lower portion of the imported gravel was keyed into the beach in the cut area, adding to its stability. Washed round rock (¾- to 2-inch drain rock, 75% of which was 1¾ inch) was placed into the excavated area. The imported gravel was to be 1.5 to 2.0 ft thick vertically and extend up to elevation +15.0 ft MLLW.

The design then relied on 2 of the largest available logs. The longest (50 ft) was keyed into the imported gravel to a depth slightly more than one-third of the log's diameter. Ecology-block anchors (drilled through the center) were used to secure the logs with ⅜-in marine-grade galvanized lashing chain through two ½-in marine-grade eye bolts installed through both ends of the log. Galvanized 4-in staples secured the chain to the logs.

Cut native sediment was then placed atop the landward portion of the enhanced storm berm and roughly graded. Exotic species such as English ivy were removed and native dunegrass (*Elymus mollis*) was planted atop the storm berm landward of the log shortly after construction to augment stability of the berm.



Project design drawing.



Project design cross section.

Current Conditions

Technique Condition – The project elements remained in place in good condition at the time of the field visit. The coarse nourishment gravel remained buried beneath 0.2 to 0.5 ft of sandy, native sediment, which had accreted over the gravel several years after installation. The logs used as transition to the backshore and on the up-drift end of the backshore remained firmly in place.

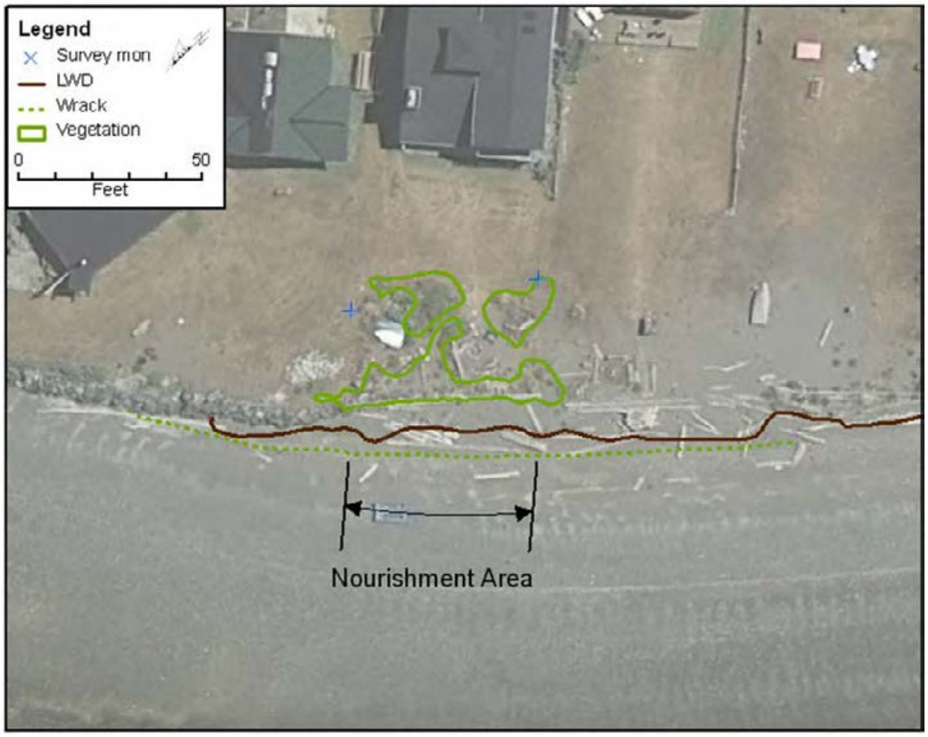
Upland Threats – The septic drainfield and required setback from OHWM were protected without any apparent loss (as evidenced by periodic visits over the 10 years of the project) of placed gravel, sandy sediment placed landward of the shore-parallel logs, or anchored logs. Enhanced backshore vegetation has helped stabilize occasional wind-blown sand.

Beach Characteristics – The upper intertidal beach slope was 8.4:1, slightly less steep than before the project. (The site was surveyed 3 times in all.) The beach comprised sand and fine pebble in the upper intertidal and sand with coarse pebble in the backshore. Alongshore contours were smooth and not altered by the project except landward of the long anchored log.

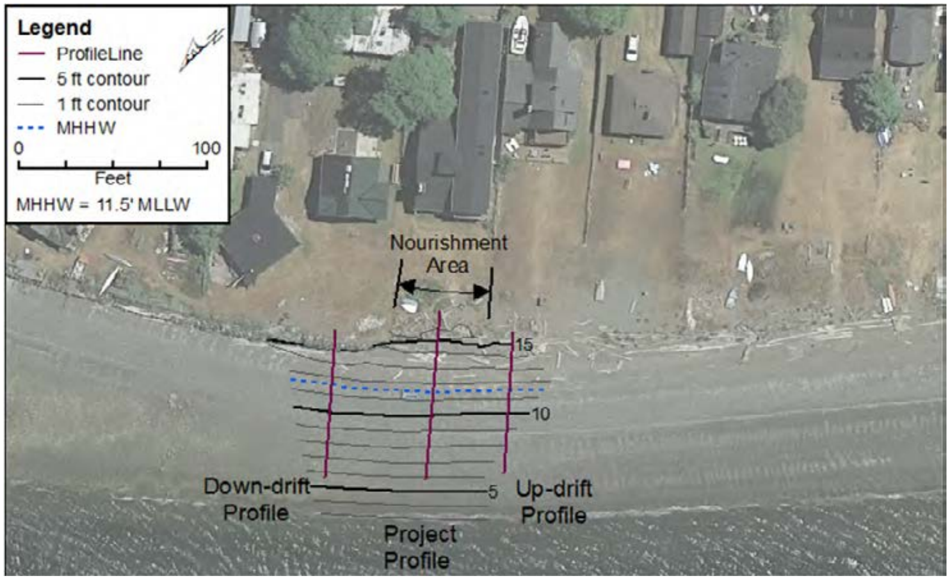
Adjacent Shores – The up-drift shore consisted of beach sediment very similar to that of the project site, although hand excavations showed that the subsurface sediment in the backshore was much finer than the coarse nourishment sediment below grade. The beaches on both sides of the project had similar slopes everywhere except just above MHHW at the project where beach slope was slightly less steep than the median slope of the adjacent profiles. The sown-drift beach had accreted since the as-built survey 10 years prior, and also had a lower overall slope. Therefore, the beach slope progressively decreased in the direction of net shore-drift as often occurs.

Project looking down-drift (northeast) in 2012. Note dunegrass growing in the backshore and sandy upper beach sediment.

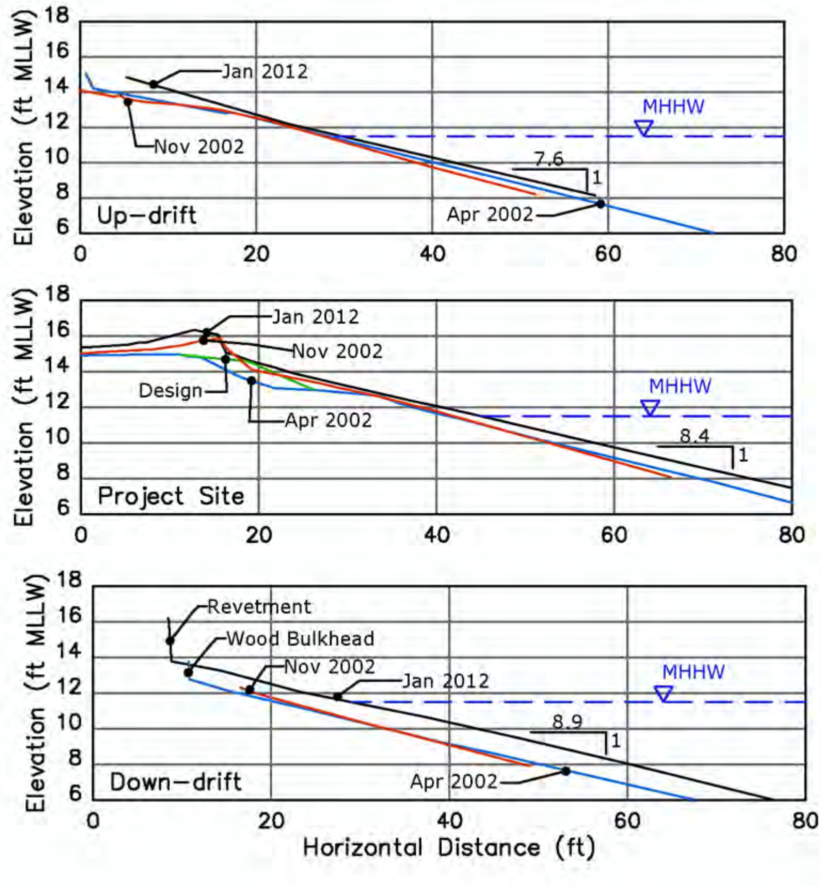
Project site looking up-drift in 2012.



General beach features mapped during the 2012 site visit.



Project site map with profile locations.



Beach profiles from pre- and post-project and the 2012 site visit.

Comparison of beach surface sediment at project and adjacent sites. Sediments in the adjacent shores appear similar to those at the project site, particularly in the upper intertidal. n/a indicates the location was not present for sampling.

Location	Backshore	Difference	Upper Intertidal	Difference
Up-drift	SAND, coarse pebble	Same	SAND, fine pebble	same
Project Site	SAND, coarse pebble	-	SAND, fine pebble	-
Down-drift	n/a	-	SAND, fine pebble	same

Performance

This small-footprint and relatively low-cost soft shore protection project accomplished the goal of minimizing coastal erosion and allowing for the continued safe use of the existing septic drainfield. Because both cultural and wetland resources constrained use of the site, there was no option to move the drainfield. The project area beach profile shows that the entire measured profile width in 2012 was either higher or at the same elevation as the design and the as-built survey (from Nov. 2002). The upper beach at the project site has accreted sand, which may be independent from the soft shore protection project and has only affected the habitat and not structural elements.

Project elements critical to the success of this project included the following:

- The placement location of the gravel storm berm was key. If the berm had been placed farther waterward it would have been hit by storm waves much more frequently and would not have maintained enough elevation to dampen incoming waves at the highest water levels. The effective berm placement allowed the area landward to be suitable for development of dense dunegrass cover.
- The use of two large logs augmented the stability of the project but was not nearly as urgent as the gravel nourishment.
- The native dunegrass planted on the landward portion of the berm within the salvaged gravelly sand is an important element for bolstering this area in times of very high water levels.

Project performance scoring.

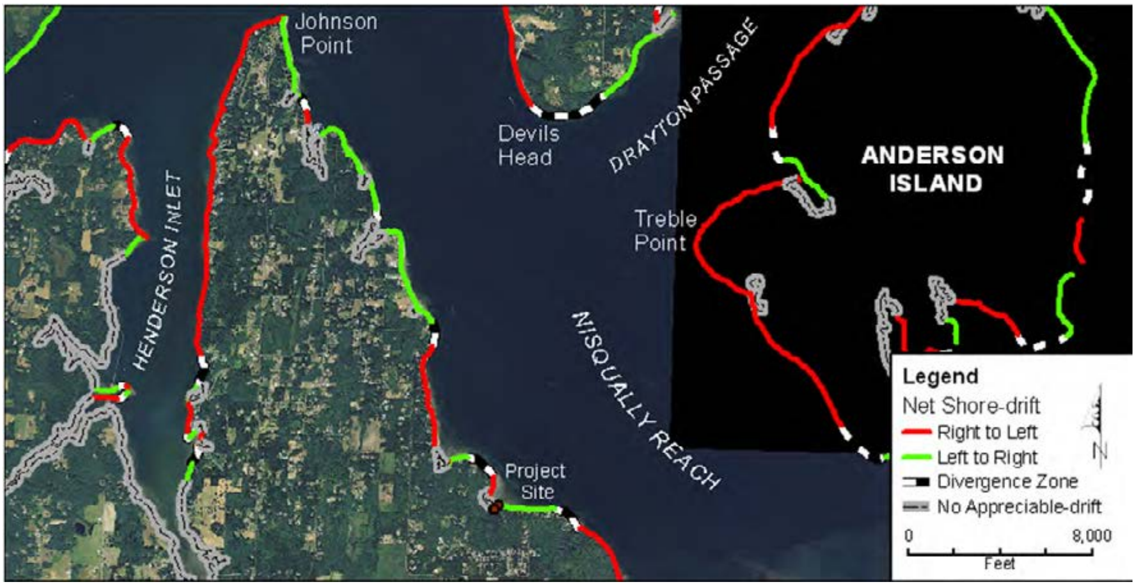
Category	Parameter	Rating	Score	Rationale
Benefits	Effectively mitigated landward erosion*	High	6	No evidence of landward erosion
	Sediment volume augmented	Med	2	Moderate volume of beach nourishment added
	Input/exchange of LWD, detritus	Med	2	Free alongshore exchange of LWD/detritus
	Backshore vegetation enhanced	Med	2	Large but patchy dunegrass vegetation planted in the backshore
	Marine riparian vegetation enhanced	None	0	No marine riparian recruitment
	Low-cost and simple installation	High	3	Very low cost of installation
Impacts	Structures bury backshore & intertidal areas	Low	-1	Backshore modified and coarsened
	Structures impound littoral sediment	None	0	No impact; no-bank site
	Coarser/steeper beach profiles created	None	0	Beach slope does not differ from up-drift reference beach
	LWD/detritus recruitment reduced	None	0	Broad drift-log zone at project zone
	End erosion adjacent	None	0	No end erosion
	Required maintenance interval	None	0	None to date; none envisioned for 15 years or more
Design-specific benefits	Enhanced potential spawning habitat for forage fish	High	3	The upper intertidal area was increased with appropriate sediment size
	Sediment benefits down-drift beaches in process unit	Med	2	Minor sediment transport off-site
Design-specific impacts	Eelgrass beds or other habitats smothered	None	0	No apparent offshore sediment impacts
	Loss of substrate heterogeneity	None	0	Intertidal sediment similar to up-drift reference beach
Total			19	

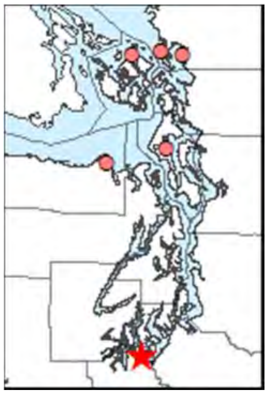
*Scores at double other values (e.g., high=6); for all others none=0, low=1, med=2, high=3

Totaling the above scores, benefits equal +20 points and impacts equal -1 point, for a final combined score of +19.

TOLMIE STATE PARK – Beach Nourishment (1973)

Waterbody: Nisqually Reach	Shoretype: Barrier beach	Net Shore-drift Cell: TH-2-3	Direction: Westward
Project Elements: Gravel nourishment of the upper beachface		Objective: Restore sediment at eroding spit to protect adjacent barrier estuary	
Fetch: 6 mi NW Wave energy: Medium Aspect: North	Land Use: State Park MHHW: +14.0 ft MLLW Toe Elev: +9.5 ft MLLW	Structure: None Setback: n/a Risk Index: 6	Benefit Index: 17 Impact Index: -6 Total BI Index: 11





Project site as red star with dots showing all other beach nourishment projects Sound-wide.

Project Background

The project site sits at the end of a short drift cell in south Puget Sound that terminates at a sand and gravel spit within Tolmie State Park. The spit protects a barrier estuary of high habitat value fed by several small streams flowing through forested uplands. Potential impacts to the estuary from overwash, breaching, or significant erosion of the spit were of concern when a project was considered in the early 1970s.

The site lies within one end of a short (0.6 mi long) drift cell, so sediment supply is naturally limited. Residential development with associated sore modifications up-drift of the park significantly impacted the already-limited sediment supply for the spit. The spit was slowly eroding when Washington State Parks acquired the property. A bulkhead constructed over the beach to create a parking lot at the base of the spit had effectively blocked much of the upper-beach littoral transport to the spit. As the spit narrowed it became more susceptible to erosion and potential breaching through overwash or rollover processes, where sediment is washed over the top of the barrier spit during storms. The project, initiated for habitat reasons, was the first Wolf Bauer beach-enhancement design implemented in Puget Sound.

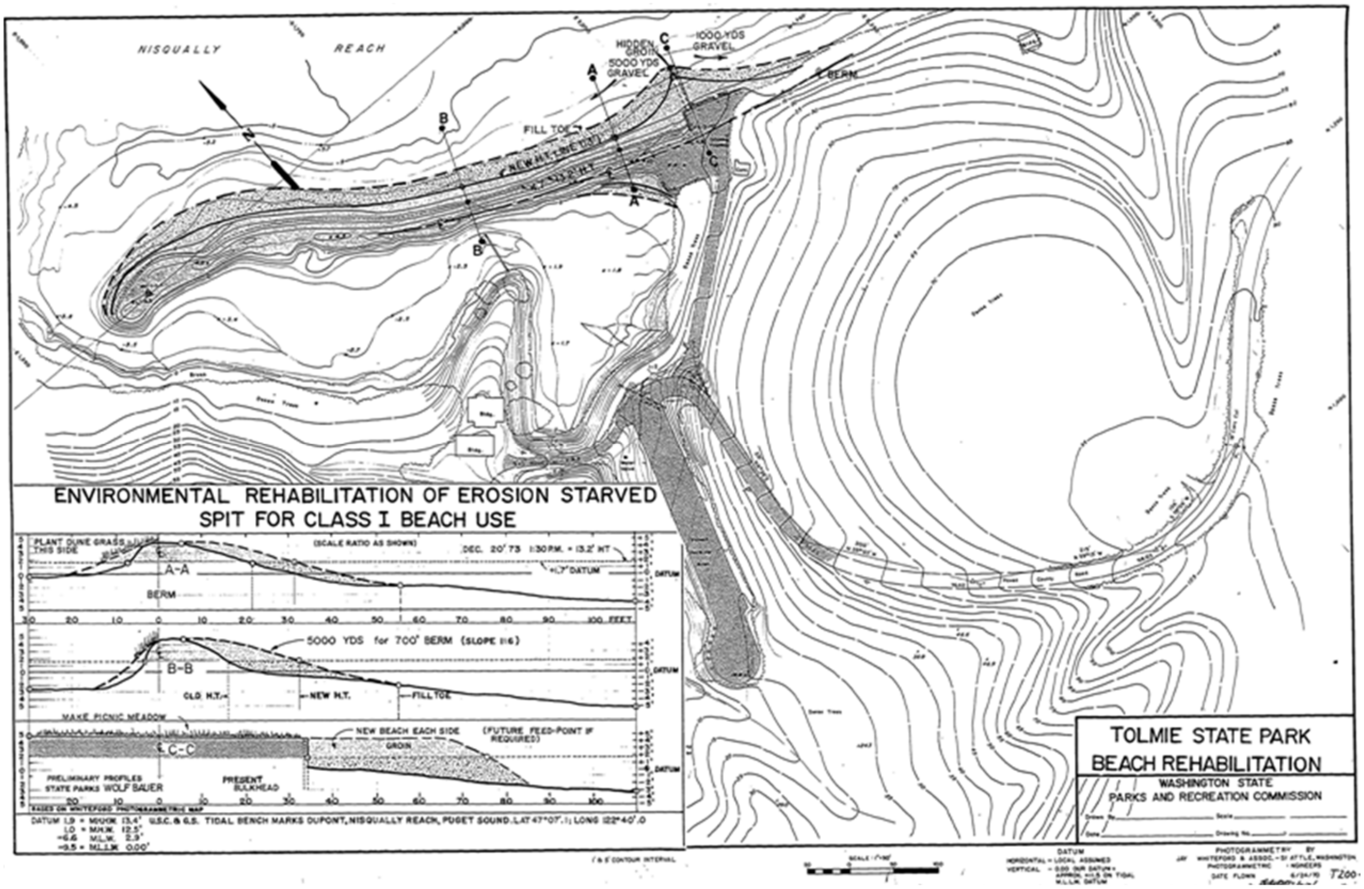
The spit at Tolmie State Park prior to beach nourishment. The old parking lot and bulkhead can be seen in the background (Wolf Bauer).

Aerial view of Tolmie State Park prior to beach nourishment. The old parking lot can be seen at the left (Wolf Bauer).

Design

The primary objective of the nourishment design was to provide a large quantity of sediment that would be relatively resistant to sediment transport. After the parking lot was removed from the beach, 6,000 CY of coarse gravel was brought in. The bulk of the gravel was to be placed in the vicinity of the removed parking lot on either side of a groin intended to remain hidden under the beach surface. The groin was not constructed, but the gravel was placed to form a large bulge in the shore at the up-drift portion of the spit, which is sometimes called “overfill” in beach nourishment projects. This bulge could still be seen in the oblique aerial photo from May 1977 shown below. Although the project intent was poorly documented, it was assumed that Bauer intended this area to be an overfill for continued nourishment of the spit. That would avoid the need to place renourishment sediment at the site for a number of decades. Additionally, making the beach extend waterward of the pre-exiting bulkhead may have been a goal.

Additional gravel was placed on the waterward side of the spit, with some minor additions to the backshore side but none on top of the spit, presumably to keep from burying all of the vegetation and possibly to ensure that natural overwash processes were not changed. The design called for a beach slope of 6:1 (H:V) for the spit area. Nourishment was originally intended to extend to the end of the spit, but may not have been placed that far. The 1977 photograph appeared to show the nourishment sediment extending only halfway between the bridge and the end of the spit, and shows the large overfill area (below).



Project design drawing by Wolf Bauer.

Oblique aerial photograph from summer 1977 (WA Ecology). Note large nourishment gravel lobe still present along up-drift end of the spit.

Current Conditions

Technique condition – The majority of beach nourishment appeared to have remained within its original footprint except in the broad nourishment bulge area. Scattered gravel was left on the low-tide terrace within what appeared to be the beach feed area. Overall the project appeared to have performed quite well, having accomplished the goal of maintaining the spit for nearly 40 years.

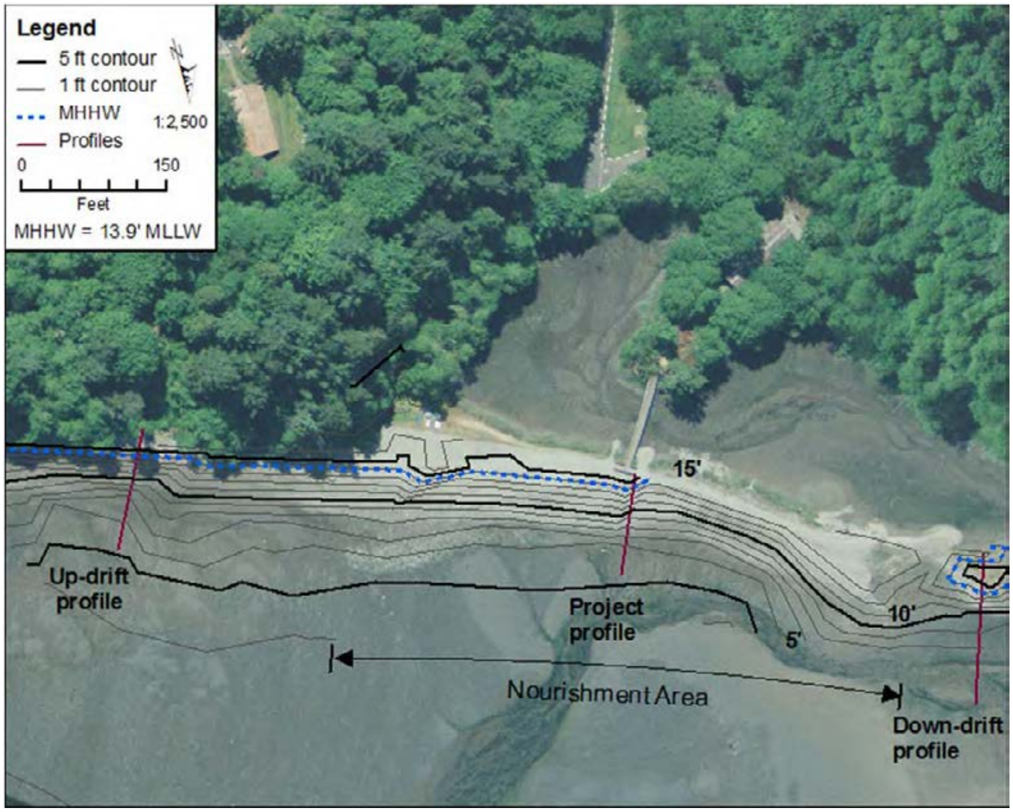
Upland threats – No threats to the park uplands were apparent during the time of the site visit. The nourished spit provides adequate protection from direct wave attack, and even the bridge footing on the spit is in little danger of being undermined.

Beach characteristics – The beach at the project site is relatively coarse, both for the region and for being at the end of a drift cell. A large amount of sand has become entrained with the gravel over the years and resulted in a lower slope than originally designed.

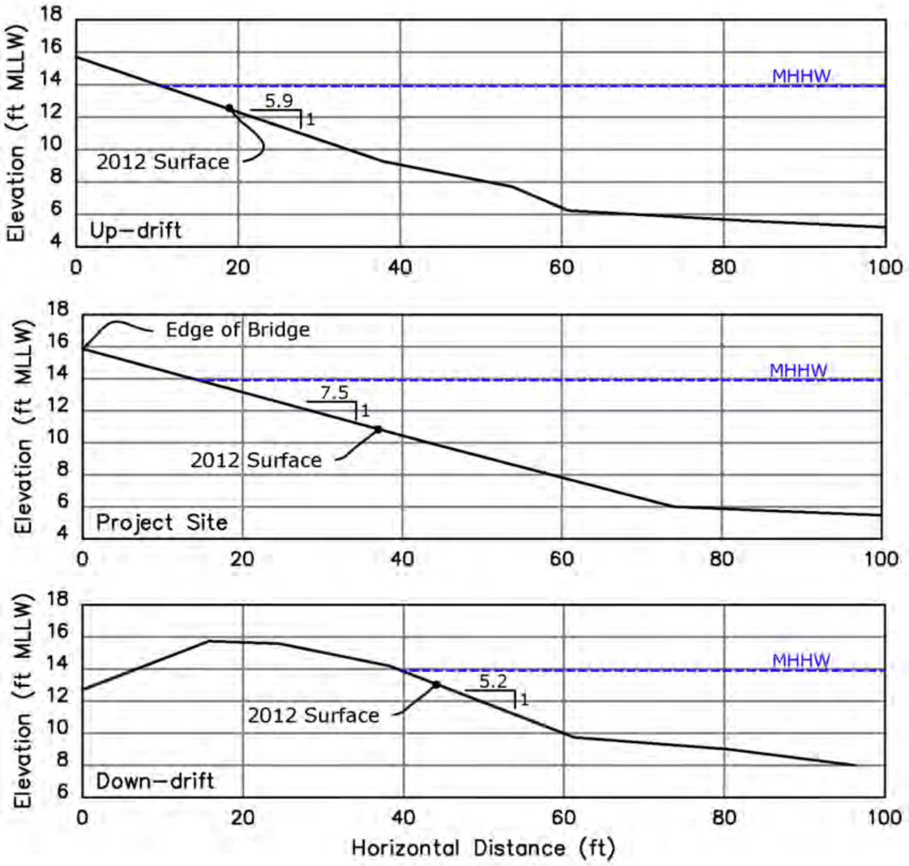
Adjacent shores – The up-drift shore transitions to a high bank in the eastern portion of the park shoreline. The beach sediment was somewhat finer than that within the project site, although the slope was steeper at approximately 6:1 (H:V). Wave-induced erosion at the toe of the bank was evident during the site visit, with some exposed soil and several trees that had fallen to the beach.

Nourishment area looking west toward the end of the spit, 2012.

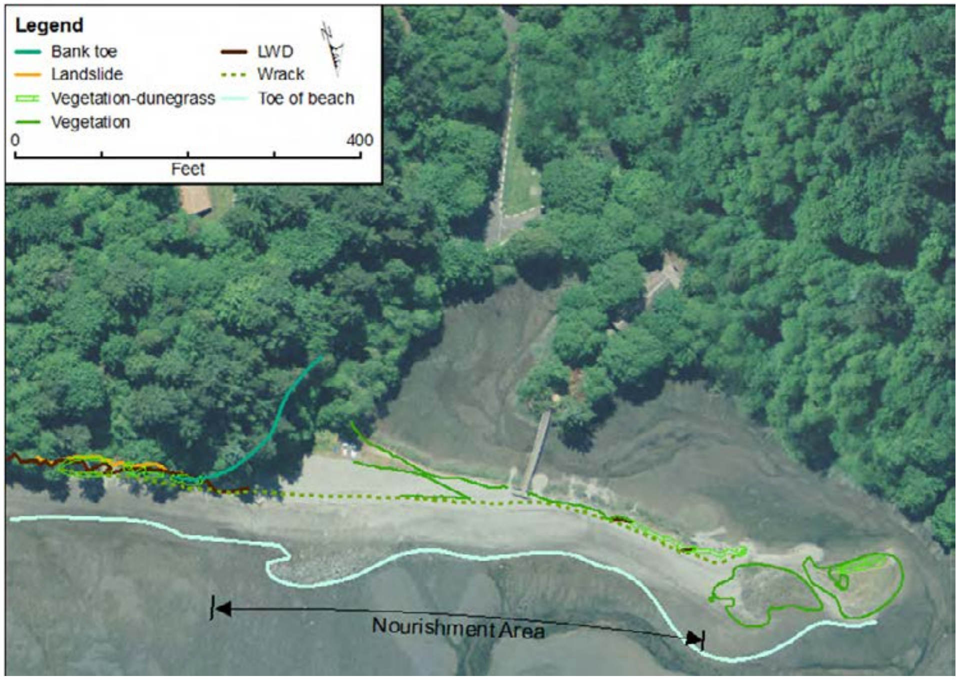
Nourishment area looking east from spit in 2012.



Topographic map of conditions during the 2012 site visit.



Beach profiles from the 2012 site visit.



General beach features mapped during the 2012 site visit.

Comparison of beach surface sediment at project and adjacent sites.

Location	Backshore	Difference	Upper Intertidal	Difference
Up-drift	SAND, granule	finer	SAND, medium pebble, coarse pebble	finer
Project site	SAND, medium pebble, coarse pebble	-	COARSE PEBBLE, medium pebble, fine pebble	-
Down-drift	SAND, medium pebble, coarse pebble	same	COARSE PEBBLE, medium pebble, sand	similar

Performance

The primary project objective of maintaining the spit at the park was effectively accomplished over the very long life of the nourishment. The buried groin did not appear to be required, and its omission had not affected the longevity of the sediment within the spit. Omitting the groin also eliminated the likely exposure of the groin and down drift erosion over time, as well as the burial of intertidal area. Important factors that made this project successful over time included the following:

- The relatively low wave-energy of the site was critical for long-term performance.
- The use of “overfill” or the addition of excess nourishment sediment on the up-drift end of the project resulted in no need for maintenance for 40 years.
- The grain size of the material selected, coarser than typical for the area, enabled it to resist sediment transport.

There are trade-offs with the use of overfill—the temporary burial of the lower intertidal with gravel and displacement of some amount of habitat was scored as a small negative impact below. The coarser gravel used at this site that helped with longevity also altered previous habitats. The spit down-drift of the bulk of nourishment appeared to remain stable, with a large community of saltmarsh plants growing around and atop the spit terminus. Overwash deposits were seen during the site visit, showing that waves continue to be able to overtop the spit and allow natural barrier beach processes to continue, although the spit effectively stops waves from reaching the park uplands. This overwash was not a negative impact to the shoreform or the ecology, and this approach of not raising the elevation of the backshore differed from other typical gravel nourishment projects in Puget Sound where the general goals were erosion control and reducing wave energy in the backshore.

Project performance scoring.

Category	Parameter	Rank	Score	Rationale
Benefits	Effectively mitigated landward erosion*	High	6	The spit has remained dynamically stable and the estuary has continued to function well
	Sediment volume augmented	High	3	A large volume of sediment was placed in the upper intertidal and backshore
	Input/exchange of LWD, detritus	Med	2	Alongshore and cross-shore transport unhindered
	Backshore vegetation enhanced	Med	2	Backshore elevation and vegetation maintained
	Marine riparian vegetation enhanced	None	0	No marine riparian enhancement in the project
	Low-cost and simple installation	Med	2	Installation was likely of moderate cost and complexity
Impacts	Structures bury backshore & intertidal areas	None	0	Structure did not convert any beach or backshore through burial
	Structures impound littoral sediment	None	0	Structure does not impede sediment transport
	Coarser/steeper beach profiles created	Med	-2	Nourishment sediment was coarser than the native beach and likely had steeper profiles
	LWD/detritus recruitment reduced	None	0	No impact
	Adjacent end erosion	None	0	The project has not impacted the adjacent shores
	Required maintenance interval	None	0	No maintenance has been required for 40 years
Design-specific benefits	Enhanced potential spawning habitat for forage fish	Low	0	Beach elevation has been maintained within forage fish spawning elevations, but the nourishment was much coarser than the preferred sediment sizes
	Sediment benefited down-drift beaches in process unit	Med	2	Nourishment sediment has been transported down-drift to sustain the remainder of the spit at the park
Design-specific impacts	Eelgrass beds or other habitats smothered	Med	-2	Overfill covered lower intertidal and nourishment made alterations to habitats in the backshore
	Loss of substrate heterogeneity	Med	-2	The nourishment sediment had a narrow grain size and was coarser than the up-drift sediment
Total			11	

*Scores at double other values (e.g., high=6): all others, none=0, low=1, med=2, high=3

Totaling the above scores, benefits equal +17 points and impacts equal -6 points, for a final combined score of +11.

BIRCH POINT – Large Wood Placement (2000)

Waterbody: Georgia Strait	Shoretype: Bluffed-backed beach	Net Shore-drift Cell: WH-2-4	Direction: Northward to Semiahmoo Spit
Project Elements: Large anchored logs, minor cobble nourishment and backshore planting		Objective: Retard erosion of bluff toe waterward of house that was exacerbated by up-drift gabion bulkhead	
Fetch: 33.5 mi WSW Wave Energy: Very high Aspect: W	Land Use: Residential MHHW: +9.2 ft MLLW Toe Elev: +7.6 ft MLLW	Structure: Single-family home Setback: 60 ft Risk Index: 28	Benefit Index: 13 Impact Index: -6 Total BI Index: 7

Project site as red star with dots showing all other large wood projects Sound-wide.

Project Background

This site is at the toe of an approximately 80-ft-high bluff in a very high wave-energy regime. The site has a single-family residence, patio, shed, driveway, and tram to the beach and has experienced bluff instability and bluff-face recession since site development. Shallow debris-flow landsliding has occurred periodically. Bluff geology comprises compact glacial diamict (glaciomarine drift) overlaying less dense sand, silt, gravelly sand, and sandy gravel. The bluff face has a moderate amount of seepage emanating from different elevations, with the greatest amount of seepage in the mid-bluff face where gravel lenses are perched above fine-grained deposits.

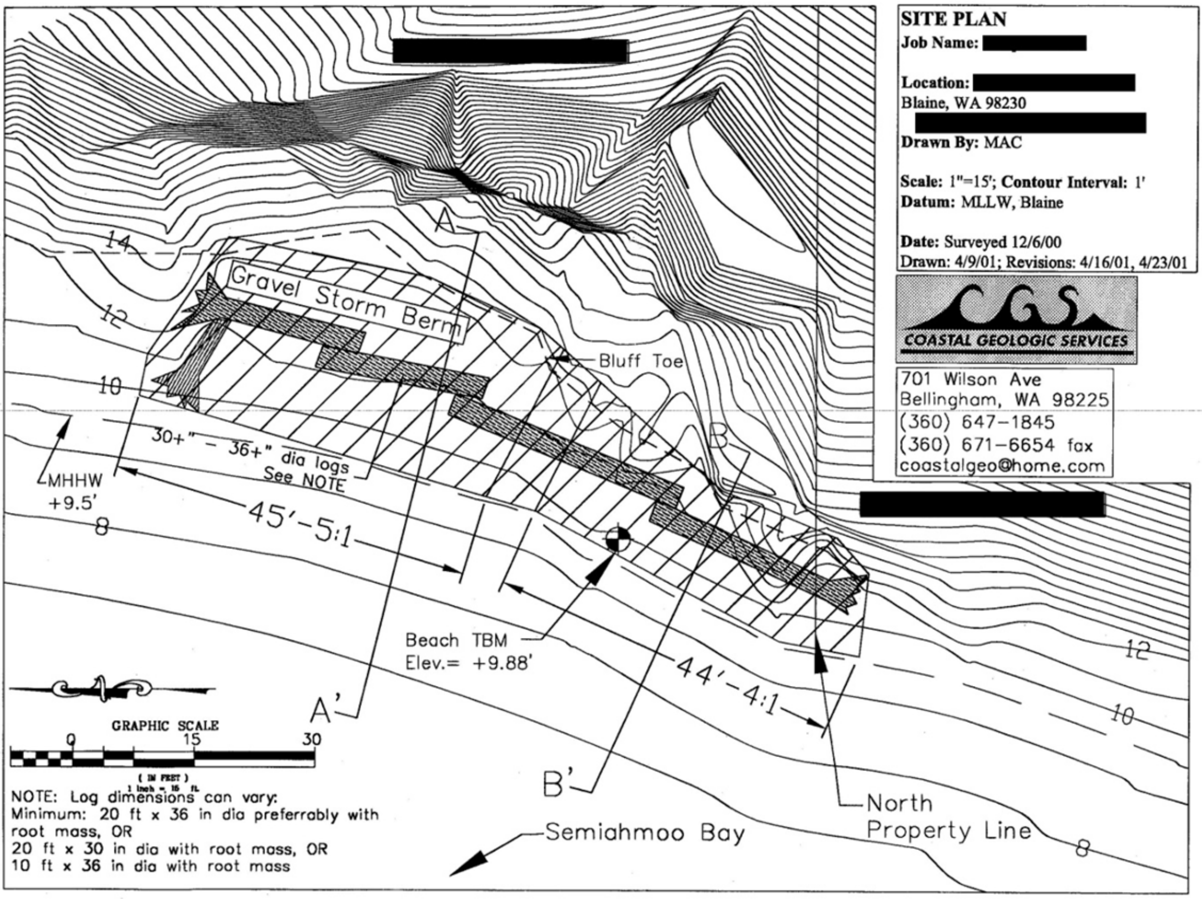
The property owner had tried unsuccessfully to stabilize the bluff through surface-water drainage and revegetation. The seepage could not easily be collected within the limited number of horizontal drains, and Mugo pines and other species used to revegetate the steep bluff face were lost to landslides in the 1990s. A plan to install geofoam blocks beneath Geoweb® (interconnected polystyrene cells filled with soil, sand, or other material) atop the bluff face was rejected by Whatcom County in 1996. Gabion baskets were installed prior to 1994 and were causing bluff toe erosion at the down-drift (northern) end of up to 20 ft horizontally. Erosion propagated upslope for a considerable distance and created a moderate-sized backshore area where none existed before. This made room to install an experimental project of anchored large logs immediately north of a bulkhead-removal assessment area (assessed separately in this document). The large wood project was presented as experimental because of the very high energy level of the site. It was not expected to be fully successful, but the owner saw it as the only option at the time.

Bluff face devoid of vegetation adjacent to gabion baskets (right). Person for scale above boulders.

Natural recruitment of large woody debris (LWD) in the eroded backshore area north of gabion-basket bulkhead.

Design

- Removal of the gabion-basket bulkhead was carried out by legal agreement with Whatcom County and completed from land by cutting open and removing gabions and leaving cobble on the beach. Cobble had been harvested from the beach originally, and it was simply redistributed back onto the beach (see bulkhead-removal case study for Birch Point in this document).
- For shore protection, the already severely eroded northernmost removal area had seven large logs anchored and a cobble storm berm constructed by barge access. This treatment was termed experimental due to the high wave-energy at the site, but was nonetheless pursued by the owners, who had tried other options without success and felt they did not have another available to them.
- Nine recently cut Douglas fir logs without attached root masses, of sound wood and diameters of 24 to 29 in, were set approximately 75% buried into cobble. The logs were acquired at a reasonable price because they had nails in them and were not suitable for milling. Logs were placed in pairs—note the original drawing showed single logs—side by side with the landward of each pair of logs set slightly higher. The 3 pairs of logs were secured parallel to the bluff toe. The final log was a short one set across-shore at the northern, down-drift end of the project area to help keep placed cobble from transporting northward too rapidly.
- Anchors were buried ecology blocks (concrete blocks measuring 2 ft by 2 ft by 4 ft and cast with holes through their centers) set at least 2.5 ft below the original upper beach grade. Half-inch, double-dipped, marine-grade galvanized lashing chain was run through the center of the ecology blocks and secured to logs with very large (6-in) galvanized staples, with generally three staples used per log end.
- Cobble-sized rounded gravel (2 in and larger in diameter, generally 2–5 in) was placed around the buried ecology blocks and logs to form an enhanced storm berm. The design relied on both raising the elevation of the uppermost beach waterward of the bank and increasing the sediment size in the upper beach to match the larger cobbles at the site. The slope of the cobble surface was 4:1 in the narrower southern end and 5:1 in the broader northern end. Beach sediment excavated to bury the ecology blocks and logs was placed on the landward side of the logs above the cobble.
- Native dunegrass (*Elymus mollis*) was planted landward of the anchored logs in sandy gravel (sediment excavated from initial keying in of cobble) using bare-root shoots, which were very successful.



SITE PLAN
Job Name: [redacted]
Location: [redacted]
Blaine, WA 98230
[redacted]
Drawn By: MAC
Scale: 1"=15'; **Contour Interval:** 1'
Datum: MLLW, Blaine
Date: Surveyed 12/6/00
Drawn: 4/9/01; Revisions: 4/16/01, 4/23/01

701 Wilson Ave
Bellingham, WA 98225
(360) 647–1845
(360) 671–6654 fax
coastalgeo@home.com

NOTE: Log dimensions can vary:
Minimum: 20 ft x 36 in dia preferrably with root mass, OR
20 ft x 30 in dia with root mass, OR
10 ft x 36 in dia with root mass

Project design drawing.

Current Conditions

Technique condition - The LWD structure was in moderately good condition at the time of the site visit. One pair of logs had loose anchor chain; these were located where the beach had lowered the most, near the north end of the bulkhead-removal area that lay within the south end of the anchored log project. Some smaller pieces of LWD had accumulated around the structure. About half of the imported cobble nourishment had persisted well with some of the higher elevation cobble removed from the waterward portion of the placement area.

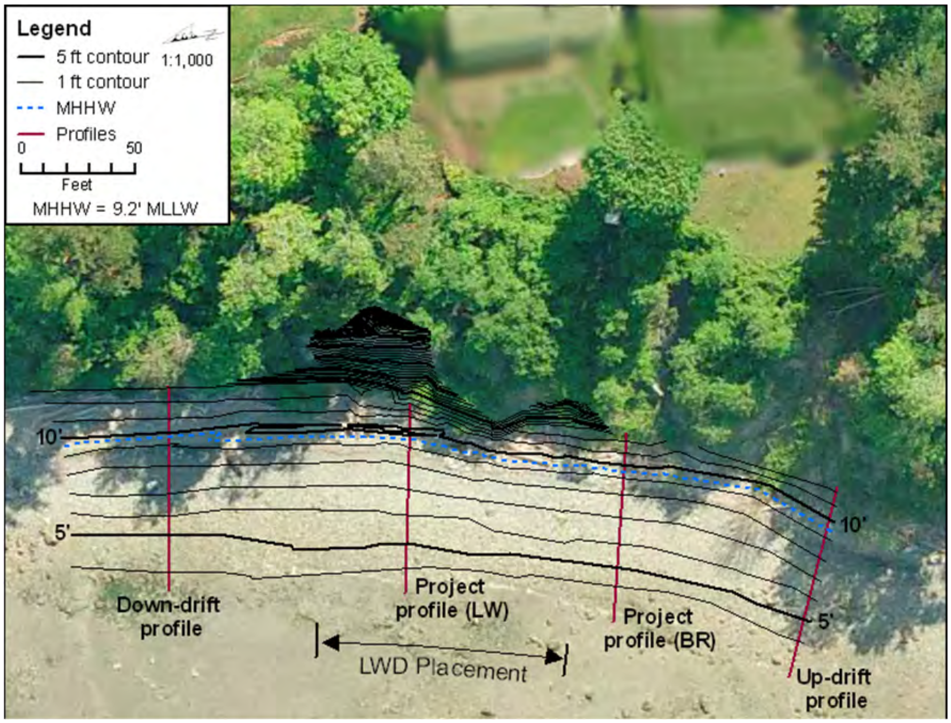
Upland threats - The site showed some signs of bluff toe erosion, recent landsliding, and area-wide beach lowering during the 2000–2006 monitoring period and through 2012. The logs have been overtopped by storm waves, and moderate toe erosion was evident even in the more landward portion of the bluff toe. The lowest setback distance was from the tram, south of the project area. The bluff there continued to slump from midslope, likely due to toe erosion and unstable slope conditions resulting from stratigraphy and discharge of perched groundwater.

Beach characteristics - A band of LWD averaging 2 to 6 ft wide extended along much of the project area shore. Beach substrate has been highly variable spatially and temporally at both the project and adjacent sites, but since the large wood treatment the project and surrounding area beach substrates have become similar.

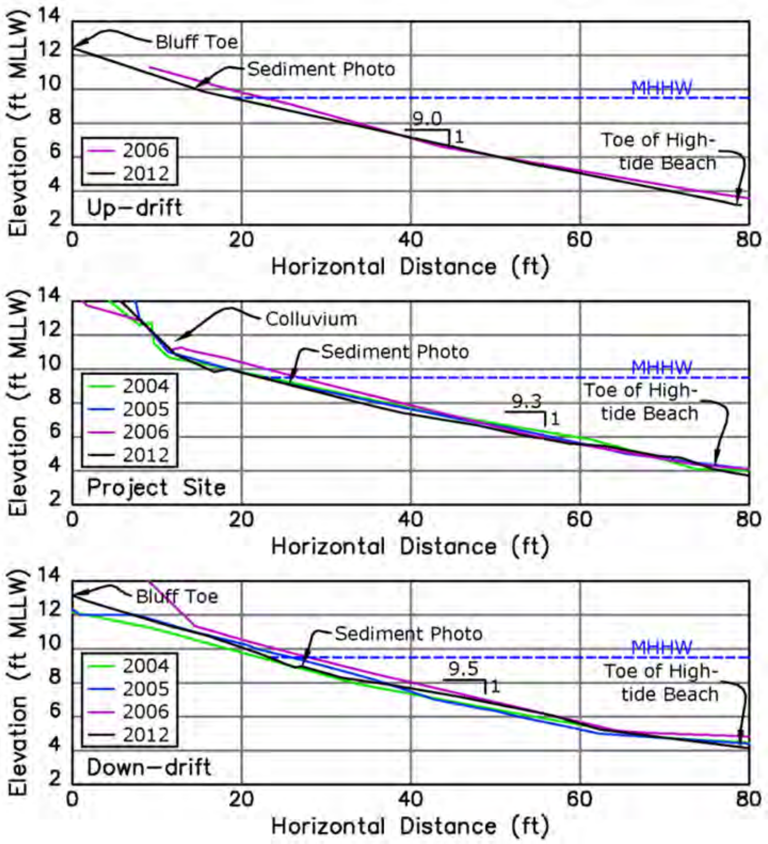
Adjacent shores - The up-drift shore had a small berm of coarse gravel with cobble. The down-drift shore had very little backshore, with active erosion and several landslide events since 2000.


Project site looking onshore in 2012. Two pairs of anchored logs are visible along with some chain, as are relatively recent landslides.

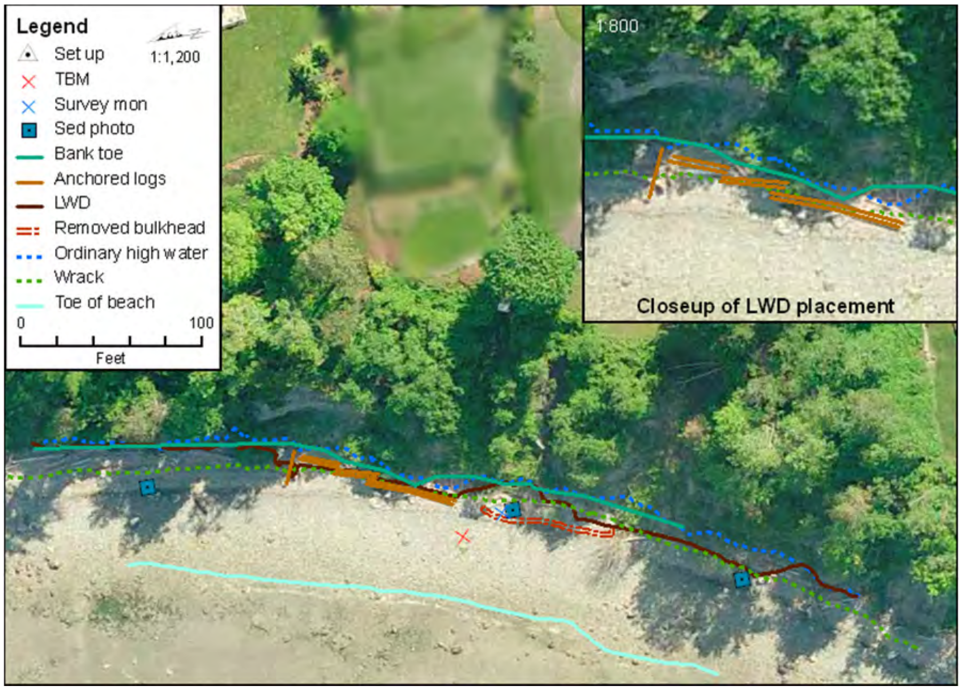

Project site looking down-drift in 2012. Note anchored logs and large accumulation of LWD landward of logs. Boulders were present prior to the project.



Topographic map of conditions during the 2012 site visit.



Beach profiles from monitoring and the 2012 site visit.



General beach features mapped during the 2012 site visit.

Comparison of beach surface sediment at project and adjacent sites. n/a indicates the location was not present for sampling.

Location	Backshore	Difference	Upper intertidal	Difference
Up-drift	n/a	-	SAND, medium pebble, fine pebble	finer
Project site	n/a	-	MEDIUM PEBBLE, sand, cobble	-
Down-drift	MEDIUM PEBBLE, cobble	-	SAND, granule, fine pebble	finer

Performance

This LWD placement slowed erosion somewhat but has not prevented bluff toe erosion or subsequent landslides. The project required minor maintenance within several years, which may have been unavoidable given site conditions. This site is exposed to considerable fetch, and perched water in the bluff appears to contribute to local bluff recession. Maintenance nourishment of 50 CY of coarse gravel and adjustment of anchored logs were required after 2 years, and additional maintenance will likely be required in the future. During maintenance, one pair of logs was unburied, resecured, and repositioned at a lower elevation.

Overall performance conclusions include:

- Bluff-erosion rates were slowed somewhat due to the project as compared to adjacent shores, which have experienced several widespread toe erosion and large landslide events since the project was installed.
- The anchored logs have helped reatain colluvium longer than it would have without the logs in place, providing minor slope buttressing.
- Beach accretion was documented along much of the down-drift shore in monitoring reports.
- Overall, erosion control was moderate at best in this very-high-wave-energy regime, which minimized benefit scores. This site is an example where large wood installation would generally not be advised due the need for maintenance and lack of substantial success. In this case, the landowner was motivated to try this even after informed it was experimental in this setting.

Minor positive elements of the design were the lack of impact on natural processes, low cost, and ease of implementation. Negative scores were associated with required maintenance and the increase in slope of the beachface resulting from installation of coarser sediment at times and minor scour on the waterward side of the anchored logs.

Project performance scoring.

Category	Parameter	Rating	Score	Rationale
Benefits	Effectively mitigated landward erosion*	Low	2	Slowed erosion, but overtopping and localized scour at logs has occurred
	Sediment volume augmented	Low	1	Nourishment was included in the design
	Input/exchange of LWD, detritus	Medium	2	Preserves capacity for alongshore and cross-shore exchange/input
	Backshore vegetation enhanced	Med	2	Almost 10 ft of vegetation enhanced
	Marine riparian vegetation enhanced	None	0	Marine riparian not enhanced and has been subject to periodic toe erosion and landslides
	Low-cost and simple installation	High	3	Cost was moderate (<$100/ft) and installation simple
Impacts	Structures bury backshore & intertidal areas	Low	-1	Width of disturbance of backshore/intertidal area was 0 to 3 ft
	Structures impound littoral sediment	None	0	Sediment delivery is not impaired
	Coarser/steeper beach profiles created	Low	-1	Current slope is slightly steeper than preproject slope
	LWD/detritus recruitment reduced	None	0	LWD recruitment not impacted, but riparian area was not mature enough to facilitate LWD recruitment
	Adjacent end erosion	Low	-1	Limited end erosion on down-drift end
	Required maintenance interval	Med	-2	Maintenance will likely be required in the near future (10 to 15 years)
Design-specific benefits	Natural material used (minimal hardware)	Low	1	Cables, galvanized staples, and ecology blocks used to anchor LWD
	LWD facilitated fine sediment deposition	Med	2	Finer substrate occurs landward of the LWD structure
Design-specific impacts	Placement causes scour, disturbance	Low	-1	Some scour waterward of the structure
	LWD can become detached or cause damage	None	0	LWD is anchored in place
Total			+7	

*Scores at double other values (e.g. high=6); all others, none=0, low=1, med=2, high=3

Totaling the above scores, benefits equal +13 points and impacts equal -6 points, for a final combined score of +7.

DABOB BAY – Large Wood Placement (2002)

Waterbody: Dabob Bay	Shoretype: Barrier beach	Net Shore-drift Cell: JE-16	Direction: Northward
Project Elements: Large anchored logs, cobble storm berm		Objective: Slow erosion of yard in vicinity of septic drainfield	
Fetch: 13.9 mi SSE Wave Energy: High Aspect: SW	Land Use: Residential MHHW: +11.5 ft MLLW Toe Elev: +12.6 ft MLLW	Structure: House Setback: 65 feet Risk Index: 16	Benefit Index: 14 Impact Index: -2 Total BI Index: 12

Project site as red star with dots showing all other large wood projects Sound-wide.

Project Background

This high-wave-energy residential site is on the east shore of Dabob Bay, adjacent to Hood Canal on the west side of the Toandos (or Coyle) Peninsula. The site is part of a very long net shore-drift cell termed cell JE-16, which originates at the SW end of the Toandos Peninsula and continues past the site to the tip of Long Spit at the north end of Dabob Bay. Natural shore-drift processes occur in this area as development of the shoreline is not extensive. The site has a mixed gravel and sand beach. Before the project, the high-tide beach comprised sediments ranging from medium sand to pebble and cobble.

Camp Discovery Creek reaches the beach area south of the site. The lower reach of the creek channel often runs northward across beach area in the vicinity of the site. Erosion of the high-tide beach in the few years prior to the 2002 project had exposed postglacial peat on the beachface near the northern property line. This suggested that the beachface had experienced significant erosion over recent decades or centuries and has retreated landward over the old marsh area, exposing the peat. The largest change at the beach has been the movement of the mouth of Camp Discovery Creek. The intertidal creek mouth has usually been located a considerable distance north of the site, with the creek channel in the backshore of the site. The landowner stated that there had been approximately three “blowouts” of the creek mouth in the 40 years before 2002. At such times, the creek channel cut directly through the berm immediately south of the site during high flow periods. This occurred soon after the summer of 1994, reportedly when a logging road failure upstream triggered a flood event.

Comparison of the 1994 and 2001 air photos revealed significant recent erosion of the upper beach. It is estimated that the vegetation line, which is also the approximate ordinary high water mark (OHWM), moved landward at least 50 ft between 1994 and 2001, based on quasi-scaled measurements from the images. Additional erosion was evident between 2001 and 2002.

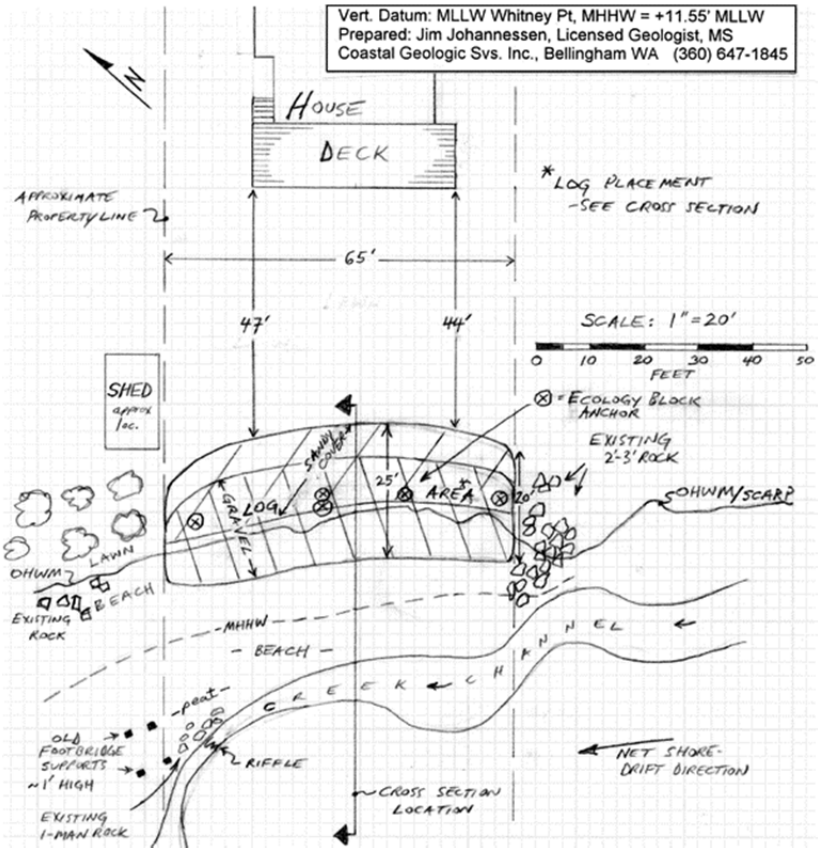
Looking northeast to site in May 2001 prior to construction (Washington State DOE photo).

Looking northwest at site in July 2002 prior to the project. Ecology blocks were recently undercut by the stream and wave attack.

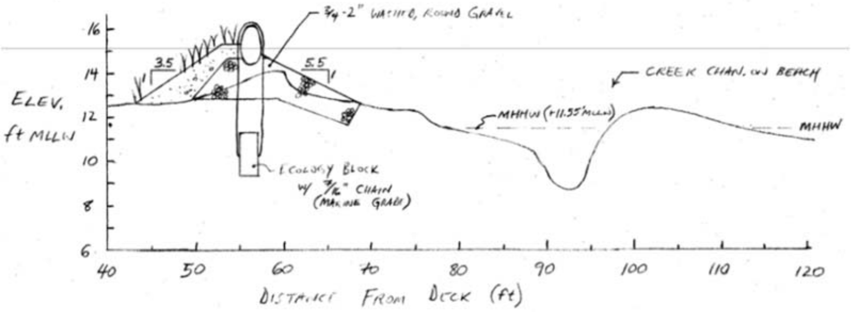
Design

The design was intended to minimize erosion of the low yard area waterward of the house and drainfield that could be caused by coastal erosion or migration of the intertidal creek channel. However, it was understood that if a major storm and flood caused the creek channel to migrate significantly, this shore-protection project could be undermined. The project spanned the full 65-ft width of the property. The design aimed to raise the elevation of the uppermost beach and backshore area near the OHWM and to increase the resiliency of this area. The berm and immediate vicinity were first excavated and five ecology-block anchors (2,500-pound concrete blocks measuring 2 ft by 2 ft by 4 ft) were buried at least 2.5 ft below the surface and several feet landward of the scarp with marine-grade galvanized lashing chain (7/16-in) attached. Imported gravel was placed to form a new, higher berm, leaving the ends of the lashing chain exposed. A combination of 80–100 ft of drift logs from the site and imported logs were placed in the new berm, keyed in to approximately one-third of their diameter. The logs were secured to the ecology block anchors with a complete wrap of the chain around each end of each log. Very large, 4– 6-in-long galvanized staples secured the chain to the logs.

The backshore and upper beach sediment size was altered to a more consistent and well-drained gravel, for a more resistant backshore area. Between 0.75 and 1.0 ft of sand and gravel on the uppermost beach was excavated in a 14- to 18-ft-wide band. The lower portion of the imported gravel was keyed into the beach. Washed and rounded 1.5– 2-in drain rock (60 CY) was placed into and above the excavated area at a 5.5:1 slope, with a new storm-berm crest at approximately +14.7 ft MLLW. The imported gravel was generally 1.25 to 1.75 ft thick vertically. The cut native beach sediment was placed atop the landward portion of the enhanced storm-berm area (see site plan and cross section below). This sediment covered the top of the horizontal storm berm and extended up to 13 to 15 ft landward of the drain rock at a 3.5:1 slope. Native dunegrass (*Elymus mollis*) was then planted atop the sand and gravel storm berm to help stabilize this material during storms.



Project design drawing.



Project design cross section.

Current Conditions

Technique condition – The entire project remained very similar to its original condition. The logs were sound, the hardware had not corroded, and the placed gravel did not appear moved from the original footprint. The beach profile was slightly higher and the logs were slightly farther waterward than the design called for. This may have been due to either the logs being placed there or to settling, but because no as-built conditions were recorded this could not be determined. Vegetation was well established, except in the center of the coarse gravel area. Very young trees were coming in waterward of the berm.

Upland threats – The primary threat at present is coastal flooding, particularly if the mouth of the stream becomes blocked with sediment and overflows its banks. This is unlikely at the project site itself, where the berm was approximately 2 ft above the elevation of the spit, but adjacent shores lacked such a berm.

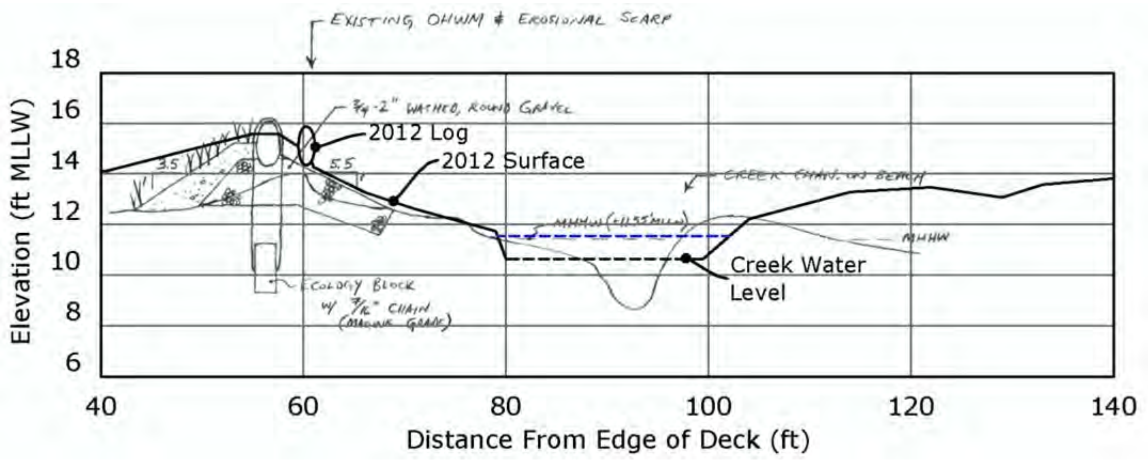
Beach characteristics – The project area was predominately coarse pebble within the placement footprint, but was considerably finer and vegetated outside this area. The spit waterward of the site was more typical of Puget Sound beaches, being sandy with some pebble. Overall, the project berm was considerably steeper than the spit.

Adjacent shores – The up-drift shore was a broad, low-lying area marked by scrub-shrub wetlands and the place where the stream enters the barrier embayment. The bank was somewhat lower than at the project site, but did not show evidence of erosion. The down-drift site was another single-family residential parcel with lawn extending nearly to the water's edge. A loose collection of large rock was seen, which appeared to be a mostly failed revetment.

Project site looking south along shore in 2012 and showing cobble berm and anchored logs, with full gravel cover landward of logs.

Project site looking north along shore in 2012, landward of the creek channel.

Aerial view of project site showing location of beach profile.



Beach profile showing project design and 2012 conditions .

General beach features mapped during the 2012 site visit.

Oblique aerial photo taken 7/11/94 showing the creek extending landward of the beach berm for more than 1,000 ft north. Photos by Washington State Department of Ecology.

Comparison of beach surface sediment at project and adjacent sites. Backshore sediments were documented at the project location landward of the stream channel, and upper intertidal sediments were documented on the waterward side of the channel.

Location	Backshore	Difference	Upper intertidal	Difference
Up-drift	COARSE PEBBLE, medium pebble, sand	finer	SAND, medium pebble, coarse pebble	same
Project site	COARSE PEBBLE	-	SAND, medium pebble, coarse pebble	-
Down-drift	COARSE PEBBLE, medium pebble, sand	finer	SAND, medium pebble, coarse pebble	same

Performance

The anchored logs remained in the same position as when placed in 2002. Cobble and pebble sediment added around and beneath the logs has also remained in place, with very little seen outside the original footprint. Anchoring hardware remained in very good condition, with no signs of rust or damage seen during the site visit. Design performance was characterized by:

- Much of the success of the project may be due to the presence of the long barrier spit that has formed in front of the project site since installation.
- Despite the high wave-energy at the site, the spit has so isolated the project from direct wave attack in most conditions that since installation it may not have been exposed to the full force of wind waves during storms coincident with very high tide.
- Spit formation and reduction is cyclical, however the coarse berm and logs would be expected to provide adequate protection during a period of spit regrowth.

Project performance scoring.

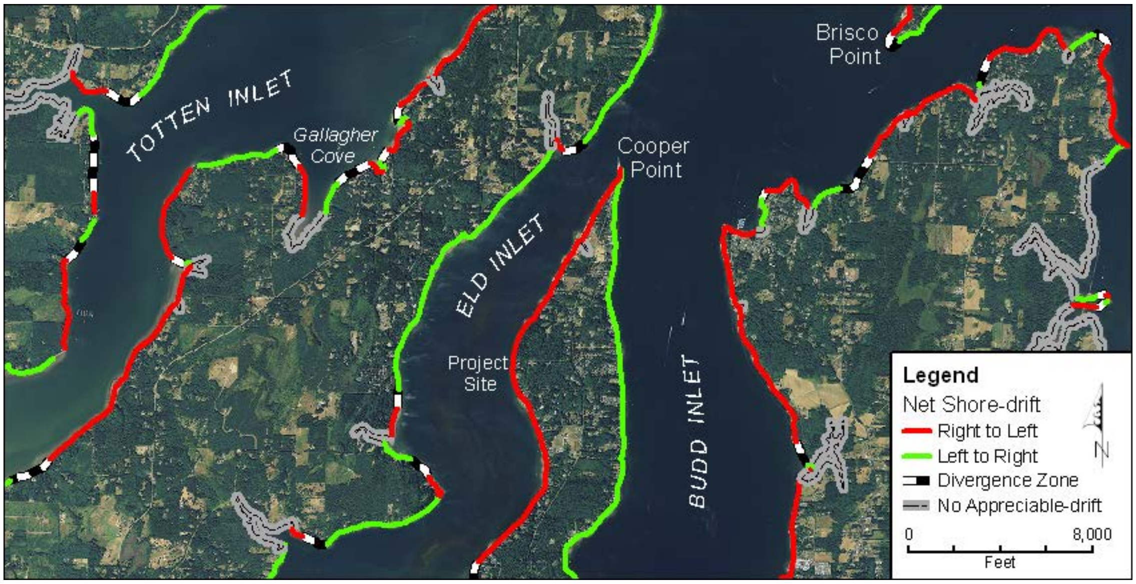
Category	Parameter	Rating	Score	Rationale
Benefits	Effectively mitigated landward erosion*	Med	4	The project remains largely untested due to the growth of the large spit since construction, but no erosion has occurred at the site
	Sediment volume augmented	Low	1	Only a small amount of nourishment sediment was included in the design
	Input/exchange of LWD, detritus	Low	1	Only minor detritus input from backshore vegetation
	Backshore vegetation enhanced	Med	2	The project converted a portion of lawn to vegetated backshore
	Marine riparian vegetation enhanced	None	0	No marine riparian planting was included
	Low-cost and simple installation	High	3	Installation was very low cost and easy to complete with upland access
Impacts	Structures bury backshore & intertidal areas	Low	-1	The coarse gravel prohibits some backshore vegetation from growing
	Structures impound littoral sediment	None	0	No impediment to littoral transport is in place
	Coarser/steeper beach profiles created	Low	-1	The nourishment sediment was moderately coarser than the native sediment
	LWD/detritus recruitment reduced	None	0	No impact
	Adjacent end erosion	None	0	No end erosion was seen during the site visit
	Required maintenance interval	None	0	No maintenance has been required
Design-specific benefits	Natural material used (minimal hardware)	Med	2	The logs matched the appearance of other driftwood in the area
	LWD facilitates fine sediment deposition	Low	1	LWD was too high for sediment deposition except through wind-blown processes
Design-specific impacts	Placement causes scour, disturbance	None	0	No scour or disturbance was seen during the site visit
	LWD can become detached or cause damage	None	0	The anchors and logs appeared well attached and in good shape during the site visit
Total			12	

*Scores at double other values (e.g., high=6); all others, none=0, low=1, med=2, high=3

Totaling the above scores, benefits equal +14 points and impacts equal -2 points, for a final combined score of +12.

EAST ELD INLET – Large Wood Placement (2009)

Waterbody: Eld Inlet	Shoretype: Bluff-backed beach	Net Shore-drift Cell: TH-10-1	Direction: NNE toward Cooper Point
Project Elements: Anchored logs and large boulders		Objective: Slow coastal erosion at residential property	
Fetch: 2.6 mi SSW Wave Energy: Medium Aspect: W	Land Use: Residential MHHW: +14.3 ft MLLW Toe Elev: +16.2 ft MLLW	Structure: House Setback: 110 feet Risk Index: 20	Benefit Index: 14 Impact Index: -5 Total BI Index: 9



- 🟥 Right to Left
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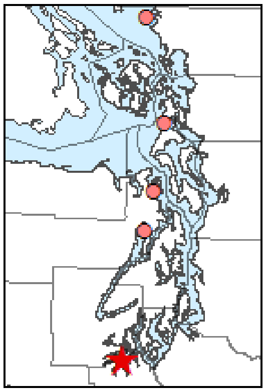
- ▬ Divergence Zone
- ▬ No Appreciable-drift



Project site as red star with dots showing all other large wood projects Sound-wide.

Project Background

The site is located along a 4-mile-long drift cell on the eastern shore of Eld Inlet, in south Puget Sound. The beach contains spawning habitat for surf smelt nearly year-round. The site has medium wave-energy, but is exposed to the southwest with a direct fetch of 2.6 miles and an indirect fetch of approximately twice that length along central Eld Inlet. The bank is composed of glacially compacted, dense pebbly sand that is moderately resistant to erosion.

The single-family residential property sat well back from the beach atop a medium-height bank. The complexity of the bank's slope and shape, however, allowed for several interpretations of the position of the bank crest. Although the house had a small to moderate setback from the crest of the slope, the active slope appeared to be limited to an approximately 15- to 20-ft-high lower bank with an approximately 70-degree slope (from horizontal). Several small slump blocks lay at the toe of the slope in the surrounding area. Most of the bank was well vegetated with a mix of Douglas fir, Pacific madrona, evergreen huckleberry, and other species.

The site is in a relatively unmodified stretch of shore. Wave-induced erosion had produced a near-vertical scarp throughout this stretch of shore that varied between approximately 4 and 10 ft in height. A wooden staircase had been constructed in a portion of the property where the bank toe erosion scarp was lowest. Subsequent windstorms had begun to erode the area around the stairs, hindering access to the beach for the landowner. The owners had several other objectives, including removing 70 ft of creosoted railroad ties on the pathway and protecting large shoreline trees, a Pacific Madrone and four Douglas fir. They did not desire to construct a bulkhead and were very interested in an approach that utilized more natural material such as logs.

Project site before large wood treatment (2006). Photo courtesy of site owner.

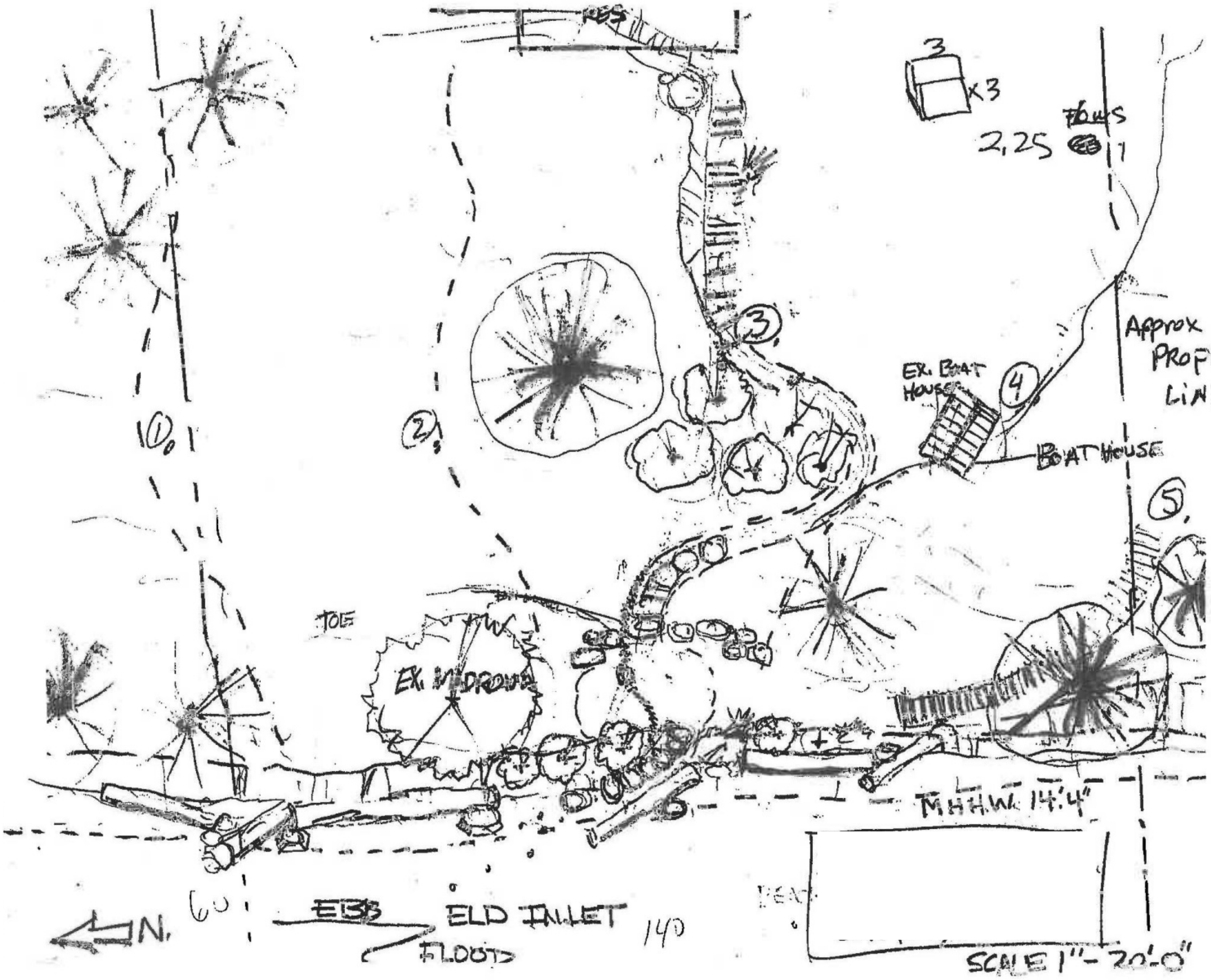
Oblique aerial photo shows old treated wooden steps (arrow) installed in the 1970s.

Design

This large wood placement project was designed to reduce erosion at this bluff-backed beach along the east shore of Eld Inlet. The project involved placement of approximately eight 25-ft-long-logs at the eroded bank toe with fieldstone and cable anchors. Field reconnaissance revealed that about 15 logs and root masses had been installed. There is almost no documentation of the project design details, other than a hand drawn sketch that served as a site plan. Log-placement locations were drawn on the site plan with most but not all logs above MHHW. Rock steps were placed crossing the lowermost portion of the bank toe and uppermost beach.

No cross sections are known to exist. Initial anchoring used rebar stakes drilled through each log and driven into the beach. The rebar did not hold, and began to fail within the first year. The logs were subsequently chained in place, although it is currently not known what all of the logs were chained to. Some of the logs were attached to auger anchors driven part way into the beach and underlying dense, pebbly sand deposit. Chains were a mix of galvanized lashing chain, smaller-link ½-in galvanized chain, and old, oversized chain with a large amount of wear and rust.

The logs consisted of old boom logs and mill seconds (with nails); approximately ten boulders were also used. Logs appeared to be a mix of Douglas fir, cedar, and probably other species. Log diameter ranged from approximately 18 to 30 in. In addition, several root masses were acquired for the project. All logs were placed on the beach surface without keying them in or adding sediment. Additional wood has accumulated via upland recruitment and catchment at the up-drift end of the site. The design called for native trees, shrubs, and ground cover at the toe of the slope and among the logs. Plantings in a 20 x 50 ft marine riparian area included (after removal of Scotch broom and other non-natives) shore pine, ocean spray, evergreen huckleberry, red flowering currant, Lyngby's sedge, kinnikinnick, and coastal strawberry. American dunegrass (dune wild-rye) was planted at the backshore and in some of the areas at the toe of the slope and the stone pathway to the beach. Dunegrass was moderately well established in portions of the backshore.



Project design plan. Numbered notes refer to natural drainage areas.

Current Conditions

Technique condition – The logs and root masses appeared to have remained mostly in place, although this required additional anchoring after initial construction. Initial rebar pinning appeared to have been unsuccessful. It appears that a greater number of logs were added than included on the site plan sketch map. The logs placed against the bank toe were stacked one to two high, although the majority of logs on site are laying on beach grade. Boulders placed during construction remained near the bank toe, and appeared to help in recruiting additional driftwood. Logs apparently were not set below beach grade, and wave energy appeared to reach beneath some logs. Marine riparian vegetation was still overhanging the beach within most of the project area, providing a good amount of shading to the uppermost beachface.

Upland threats – Wave overtopping was evident at the site during the field visit. The project did appear to help slow the rate of erosion, but it is unlikely to prevent it entirely, so some loss of the lower bank is likely in the future. However, the house was set back quite far from the beach, and even the small boat house was not in danger. The threat appeared to be to the path and steps.

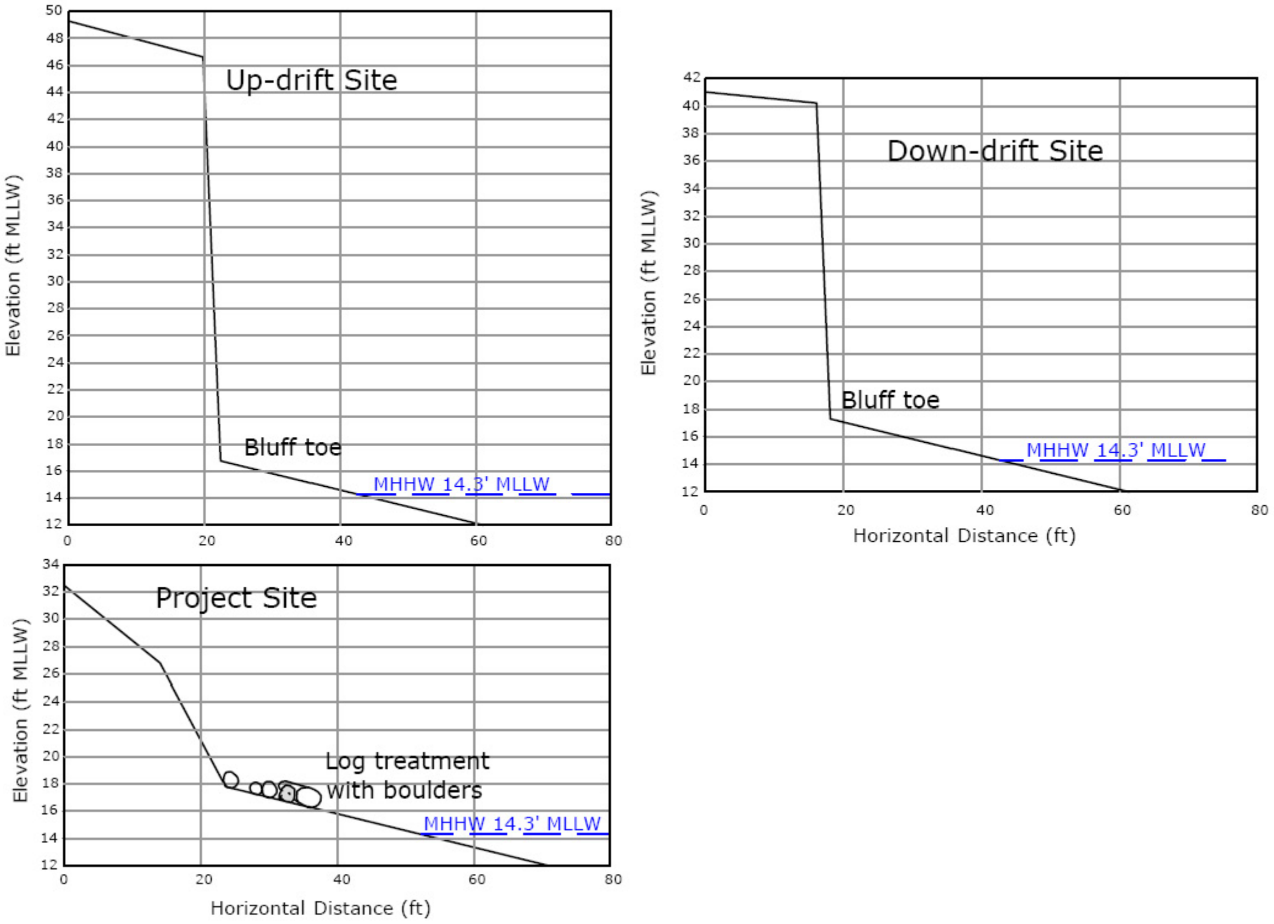
Beach characteristics –As is typical for south Puget Sound beaches, the beach here was quite broad, with a broad mix of sand and pebble. Besides some minor buildup of sediment on the up-drift side of placed logs, the project appeared to have had little effect on the beach at or adjacent to the property. The anchored logs extended up to 18 ft from the bank toe, which was much lower than on surrounding properties. Backshore dunegrass was present in pockets around the logs. Evidence of winter waves reducing the dunegrass cover was noted.

Adjacent shores – The adjacent beaches were very similar in slope and composition to the project site. The up-drift property featured a higher bank, largely unmodified. The down-drift property transitioned back to a high bank that remained unmodified, with minimal large woody debris (LWD) at the time of the site visit.

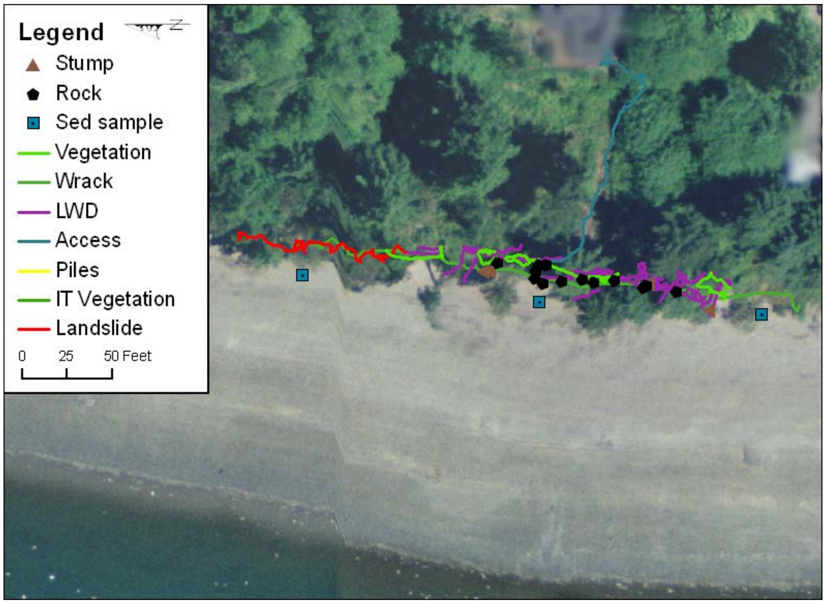
Looking at treatment facing S along beachface in 2012. Note rock steps and logs extending below wrack onto active beach area.

Looking at treatment facing NE along beachface in 2012. Note upright placement of root masses and generally well-vegetated bank.

Aerial view of the project site showing location of cross sections.



Beach profiles showing 2012 conditions.



General beach features mapped during the 2012 site visit.

Comparison of beach surface sediment at project and adjacent sites. n/a indicates the location was not present for sampling.

Location	Backshore	Difference	Upper intertidal	Difference
Up-drift	n/a	-	MEDIUM PEBBLE, coarse pebble	coarser
Project site	n/a	-	MEDIUM PEBBLE, sand	-
Down-drift	n/a	-	MEDIUM PEBBLE, sand	same

Performance

The project as a whole appeared to mostly achieve the intended effect of preventing most wave energy from reaching the bank toe. While the logs placed at the toe of the slope had a decidedly “placed” look, the additional large rock and root masses helped provide a more natural appearance. At the time of field assessment, some additional logs were rope-tied, chained, or cabled in place. Some of these may have been recruited logs anchored in place by the owner.

Other conclusions included:

- The initial anchoring using rebar pins driven into the beach failed and was replaced later with an unknown number and size of auger anchors.
- Some of the anchoring hardware appeared inadequate for the medium to long term (e.g., rope or rusty chain), such that some logs may break away to be transported off site. Additionally, waves were getting under some of the logs.
- Dunegrass had become well established among the logs anchored near the bank toe. There was no indication of other plantings, but it is possible that only the dunegrass was able to survive at that elevation with saltwater inundation.
- The logs were providing some protection to allow vegetation to remain on the low bank.
- The project was reportedly low cost and did not involve much excavation.

Project performance scoring.

Category	Parameter	Rating	Score	Rationale
Benefits	Effectively mitigated landward erosion*	Med	4	The project has effectively slowed erosion at the site, although some wave scour is possible
	Sediment volume augmented	None	0	No sediment was placed, and bluff inputs are slowed
	Input/exchange of LWD, detritus	Low	1	The project allows minor additional LWD and detritus input and exchange
	Backshore vegetation enhanced	Med	2	Some backshore planting was included, and has become established at the site
	Marine riparian vegetation enhanced	Low	1	Some marine riparian planting was completed using native species
	Low-cost and simple installation	High	3	The project was reportedly low cost
Impacts	Structures bury backshore & intertidal areas	Low	-1	Small amount of backshore burial occurred
	Structures impound littoral sediment	Low	-1	Small amount of littoral sediment input from moderately low bank
	Coarser/steeper beach profiles created	None	0	The project beach is similar to or finer than adjacent shores
	LWD/detritus recruitment reduced	None	0	The project does not negatively impact LWD/detritus recruitment
	End erosion adjacent (one or both ends); and erosion is greater than adjacent reference areas	None	0	No end erosion was evident during the site visit
	Required maintenance interval	Med	-2	Maintenance has been required, and may be required within 5 years
Design-specific benefits	Natural material used (minimal hardware)	Med	2	Wood used was relatively natural and hardware was minimal, although some extends above grade
	LWD facilitated fine sediment deposition	Low	1	A small amount of fine sediment has accreted among the logs
Design-specific impacts	Placement causes scour, disturbance	None	0	No scour was evident during the site visit
	LWD can become detached or cause damage	Low	-1	Initial anchoring technique was inadequate, and some anchoring hardware may fail within 5 years
Total			9	

*Scores at double other values (e.g., high=6); all others, none=0, low=1, med=2, high=3

Totaling the above scores, benefits equal +14 points and impacts equal -5 points, for a final combined score of 9.

NW WHIDBEY ISLAND – Large Wood Placement (2008)

Waterbody: Strait of Juan de Fuca	Shoretype: Barrier beach	Net Shore-drift Cell: Whid-25	Direction: Northward into Deception Pass
Project Elements: Partially buried, anchored large wood pieces with several boulders placed considerably landward of MHHW		Objective: Place logs and trap additional wood to buffer wave-induced erosion	
Fetch: 68 mi W Wave Energy: Very high Aspect: W	Land Use: Residential MHHW: +7.62 ft MLLW Toe Elev: +10.5 ft MLLW	Structure: House Setback: 48 feet Risk Index: 25	Benefit Index: 13 Impact Index: -1 Total BI Index: 12

Project site as red star with dots showing all other large wood projects

Project Background

The site is located along the northwest shore of Whidbey Island on an extensive barrier beach complex with backshore dunes and swales. The substantial wave (swell) energy from the west in the Strait of Juan de Fuca to which the site is exposed was the fundamental driver of the erosion that led property owners to seek erosion control. This beach is highly dynamic for the Puget Sound region, a fact reflected in large fluctuations in the beach profile and the quantity of large woody debris (LWD). Up to the early 2000s, the site did not appear to suffer persistent long-term erosion but instead experienced cyclical erosion and accretion as evidenced by analysis of historical maps and aerial photos (below).

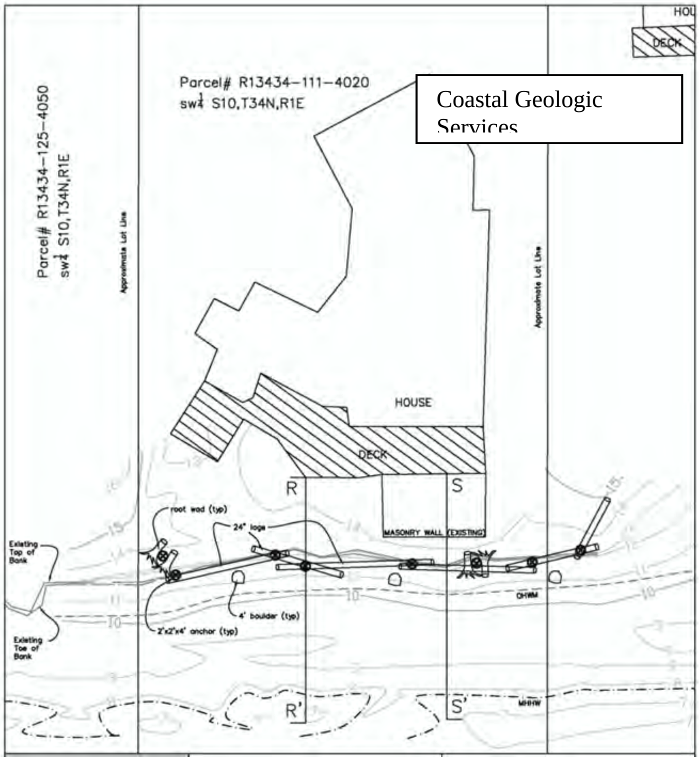
The project site sits near the end of a 14 mi net shore-drift cell exposed to the long fetch of the Strait of Juan de Fuca. The bluffs along much of the cell are comprised of sandy glacial deposits that provide large quantities of sandy sediment to the littoral system, along with large pebble and cobble.

Before construction in 2007, showing low erosional scarp and evidence of recent recession of the backshore scarp.

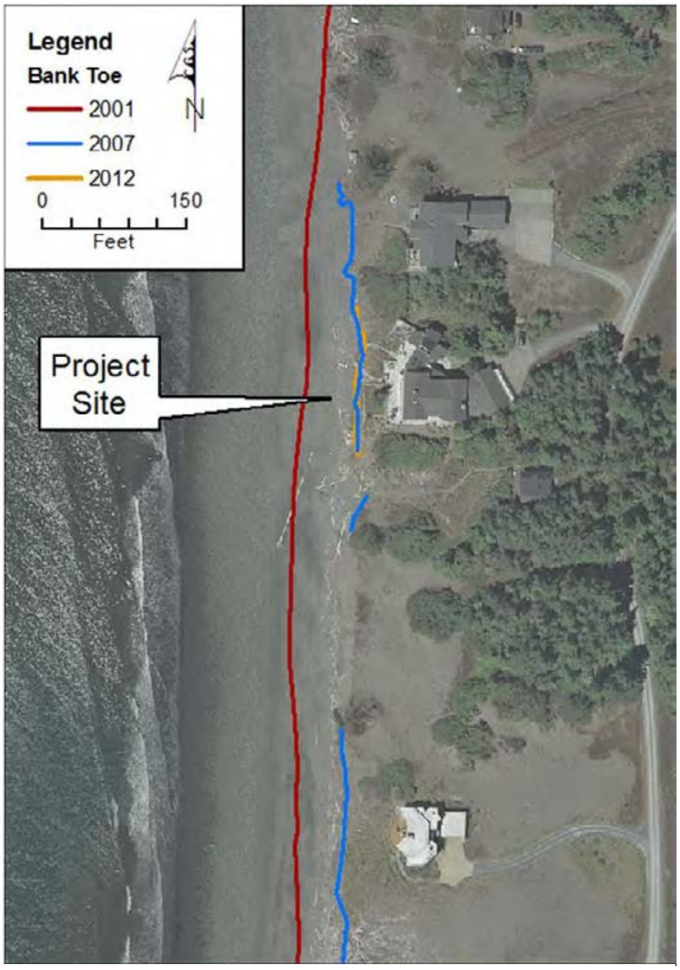
Before construction in 2007, with sand and cobble beach sediment, and minimal drift logs.

Design

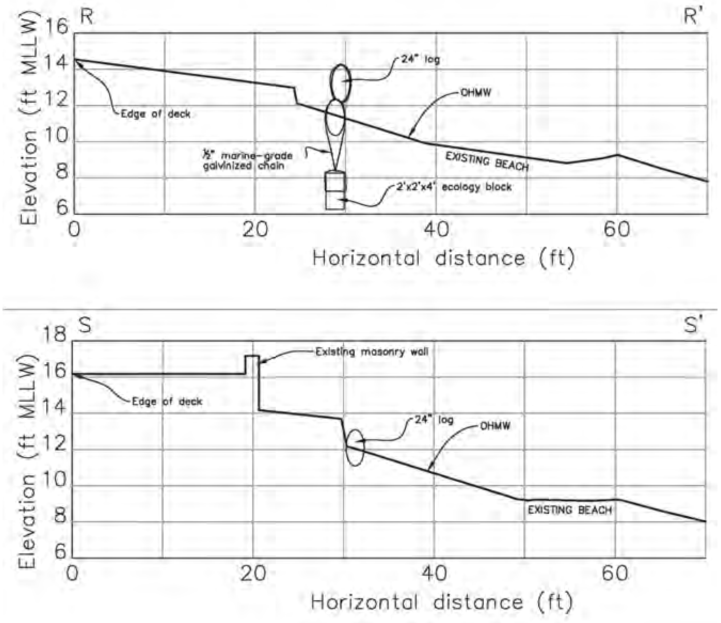
A series of large anchored log pieces were designed to trap additional drift logs, with the overarching objective of enhancing the log zone for erosion control of the no-bank property. The log system was designed and constructed in 2008 to buffer wave attack on the residential property. The design entailed burial of approximately eight concrete ecology blocks to a depth of 4.0–4.5 ft near the low bank at the site with ½ in, marine-grade, galvanized lashing chain run through the center of the blocks. Large logs from the site were then anchored to the blocks using the chain and large galvanized staples, leaving approximately one-third of most logs below existing beach grade. Other logs were inclined as prongs facing up-drift with the waterward ends several feet above beach grade to trap natural logs. Three large boulders were placed several feet waterward of the anchored logs to further aid in LWD recruitment. All work was proposed to take place 7 ft landward of the OHWM. All anchored logs have remained in place, with substantial recruitment of new logs since 2008.



Project design drawing.



Shore-change analysis completed prior to the design, and updated with survey data collected during the 2012 site visit.



Project design cross sections.

Current Conditions

Technique condition – The original anchored logs, which remained in place at the site, have accumulated significant quantities of additional driftwood. Compared to the waterward extent of driftwood preproject, as documented by the 2007 aerial photographs shown below, the driftwood line extended much farther waterward following installation of the anchored logs. This included the northern portion of the project, away from the very large cottonwood tree at the southern end, lower on the upper beach. The project site beach has accreted approximately 2 ft since the preproject survey (without any beach nourishment).

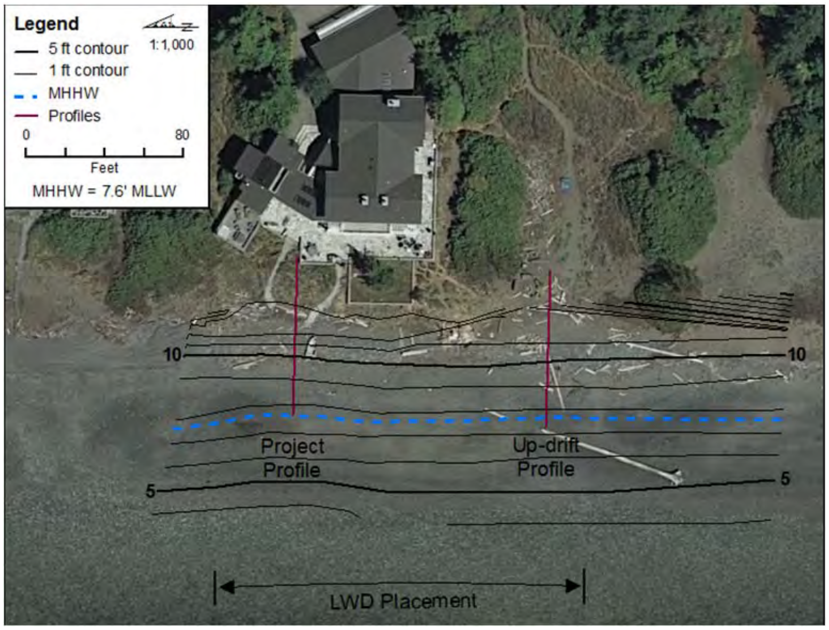
Upland threats – The anchored and accumulated wood and accreted berm provided adequate protection from direct wave attack and overwash at the treatment site. Given the lower elevation, flooding remains an issue during very-high-water-level events.

Beach characteristics – The beach at the project site appeared in good condition, with no transition between the project site and adjacent shores. The high-elevation, natural cobble berm was continuous on the site and on adjacent properties. Upper intertidal sediment, which is highly dynamic over time, was also consistent on and off site. The sediment outside the footprint of the project sediments varied little between up- and down-drift shores.

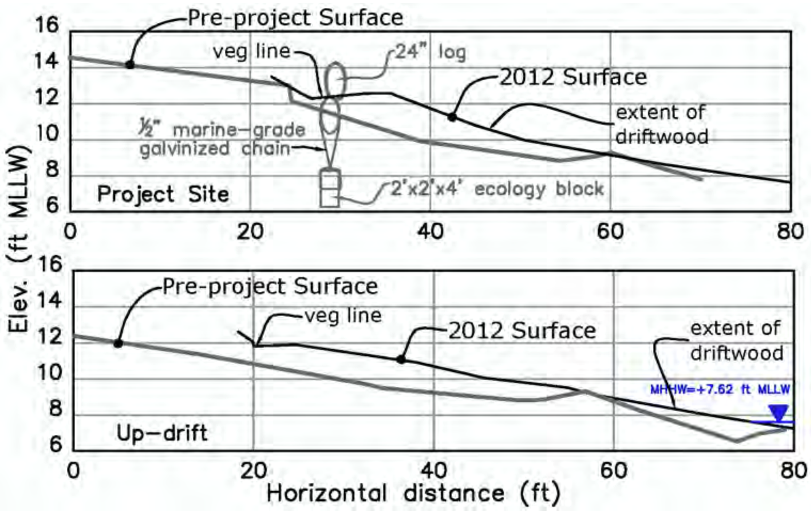
Adjacent shores – The up-drift property has a cabin set back well behind the shore without any armor, which then transitions to an approximately 6-ft-high bank cut into a backshore dune. The down-drift shore is a no-bank site that had experienced similar erosion as at the treatment site prior to the project. A creosoted soldier pile bulkhead was constructed there approximately 20 ft waterward of the backshore and backfilled with beach sediment. The majority of the fill had eroded, leaving the bulkhead, now with piles cut lower, stranded on the beach.

Looking south at northern portion of project site. Note recruited LWD among and up-drift of the anchored logs and placed boulder amid logs.

Looking north at central project site. Logs anchored with one end buried (left and central back), with substantial recruited LWD.



Topographic map of conditions during the 2012 site visit.



Beach profiles showing design and 2012 conditions.

General beach features mapped during the 2012 site visit.

Comparison of beach surface sediment at project and adjacent sites.

Location	Backshore	Difference	Upper intertidal	Difference
Up-drift	COARSE PEBBLE, sand, cobble	coarser	COARSE PEBBLE, sand, cobble	similar
Project site	MEDIUM PEBBLE, cobble	-	COARSE PEBBLE, cobble, sand	-
Down-drift	COARSE PEBBLE, cobble, sand	coarser	COARSE PEBBLE, sand, cobble	similar

Performance

Overall, the project has performed quite well over 4 years, especially given the very high wave-energy at the site. All anchored logs were still in place and all anchoring hardware was in good condition during the site visit. A significant amount of wood has been trapped by the anchored logs and several placed boulders as intended by the design, which included logs placed at angles to the bank. A particularly long log, which had become trapped nearly shore normal (roughly perpendicular to the shoreline), was tied in place and had become a trap for large wood and sediment on the up-drift side. The up-drift beach had accreted as much as 2 ft in elevation above MHHW since before the project, although some of the accretion may be influenced by the movement of cusps alongshore.

Overall conclusions included:

- The wood and cobble berm dampens wave energy and has effectively prevented further erosion of the backshore at the site.
- The postproject driftwood line was much farther waterward than in the 2007 preproject aerial photograph.
- The large quantity of wood at the site has resulted in deposition of pebble and cobble into a relatively high storm berm among the anchored wood. With the periodic nature of erosion and accretion trends in the area, it is possible that the erosion that triggered the project was only short-term, and accretion or stability has been the general trend since. However, the additional recruited wood and sediment appear to provide additional protection from direct wave attack.

Project performance scoring.

Category	Parameter	Rating	Score	Rationale
Benefits	Effectively mitigated landward erosion*	Med	4	The threat of erosion and storm damage has been moderately reduced at the site
	Sediment volume augmented	None	0	No nourishment sediment was included in the original project
	Input/exchange of LWD, detritus	Low	1	The project has partially trapped alongshore transport of LWD and detritus
	Backshore vegetation enhanced	Low	1	Some backshore planting of dunegrass was included in the project, and more vegetation became established
	Marine riparian vegetation enhanced	None	0	No marine riparian planting was included
	Low-cost and simple installation	Med	2	Cost was moderately low due to limited amount of imported material and reasonable land-based access
Impacts	Structures bury backshore & intertidal areas	None	0	Backshore was not buried
	Structures impound littoral sediment	Low	-1	Some upper beach sediment has become impounded by the anchored and recruited wood
	Coarser/steeper beach profiles created	None	0	The upper intertidal beach has not been impacted by the project
	LWD/detritus recruitment reduced	None	0	No LWD recruitment was available preproject
	Adjacent end erosion	None	0	No end effects were seen during the site visit
	Required maintenance interval	None	0	No maintenance has been required or will be required for at least another 5 years
Design-specific benefits	Natural material used (minimal hardware)	Med	2	The wood used matched the native driftwood quite well, but chain was used to a moderate degree
	LWD facilitates fine sediment deposition	High	3	Both pebble and sand have accumulated among and up-drift of the anchored and recruited wood
Design-specific impacts	Placement causes scour, disturbance	None	0	The structure has not caused scour at or adjacent to the project
	LWD can become detached or cause damage	None	0	All of the placed wood appears to be in place
Total			12	

*Scores at double other values (e.g., high=6); all others, none=0, low=1, med=2, high=3

Totaling the above scores, benefits equal +13 points and impacts total -1 point, for a final combined score of +12.

OAK BAY – Large Wood Placement (1999)

Waterbody: Oak Bay	Shoretype: Barrier beach	Net Shore-drift Cell: JE-1	Direction: Northward
Project Elements: Large anchored logs, cobble berm, and vegetation in backshore		Objective: Coastal erosion control at residential site	
Fetch: 20 mi SE Wave Energy: Very high Aspect: E	Land Use: Residential MHHW: +9.37 ft MLLW Toe Elev: +14.3 ft MLLW	Structure: House Setback: 21 ft Risk Index: 30	Benefit Index: 15 Impact Index: -2 Total BI Index: 13

Project site as red star with dots showing all other large wood projects Sound-wide.

Project Background

This high-wave energy site, a residential lot between a road and a barrier beach, contains a small stream with a small restored population of spawning Coho salmon. The project site is semiprotected north of a small headland in a relatively shallow portion of northwest Oak Bay, but still has a considerable fetch to the southeast. The site is near the end of a very long drift cell with northward net shore-drift. Adjacent properties on both sides have vertical concrete bulkheads that have been in place for many years. A very dynamic creek mouth flows across the site's mixed sand and gravel beach. The creek mouth typically runs obliquely across the upper intertidal, generally pushed northward by net shore-drift but sometimes blocked by littoral sediment. During a major storm event on New Year's Eve 1996–1997, the road culvert on the landward side of the house became blocked by debris, and the creek ran over the road and scoured out the old channel. This reach of the creek was replanted, with some rock added at grade, several years before the soft shore protection project.

The soft protection project was installed after Jefferson County and the Washington Department of Fish and Wildlife issued violation notices that included an order for removal of a small unpermitted rockery wall. The rockery wall covered portions of the backshore and restricted the mouth of the small Coho-bearing stream. Upon its removal, the landowner was not allowed to install a concrete wall as desired, but was allowed to install a soft shore protection project to slow coastal erosion of the very small yard protecting the deck and house. The project was constructed in 2000 with land-based equipment. No as-built or project monitoring occurred other than periodic photo monitoring.

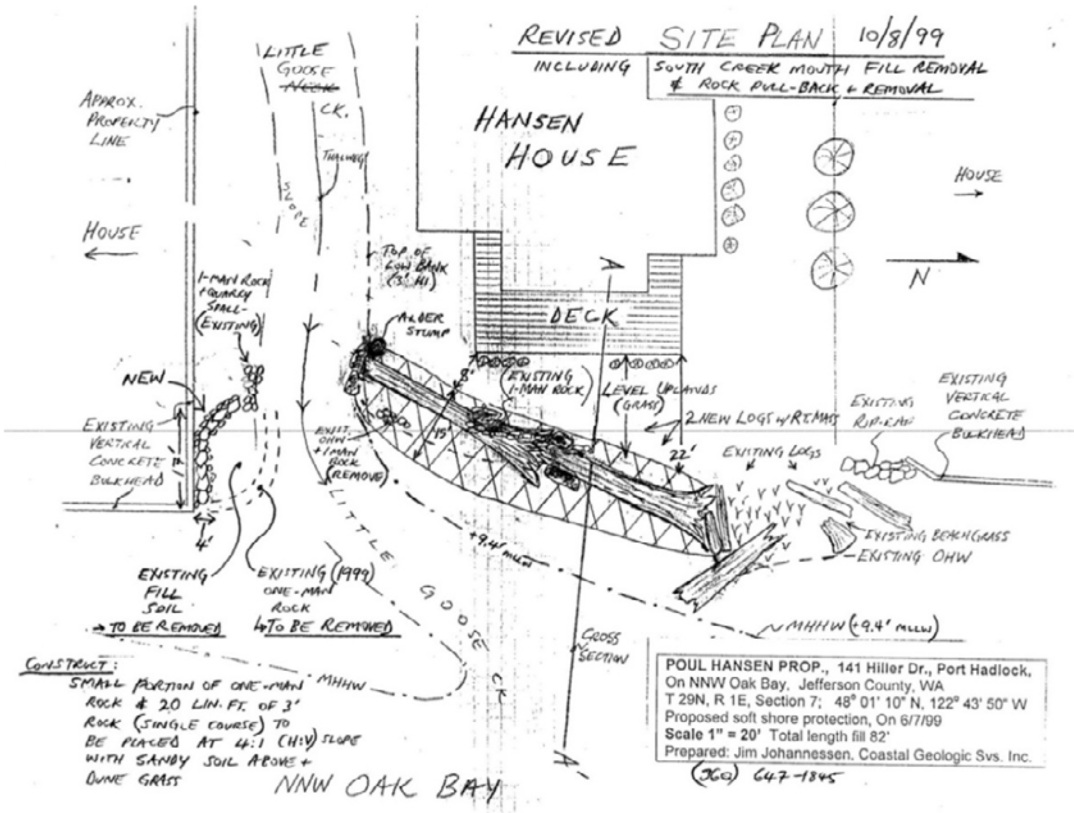
Site before removal of small rockery and installation of treatment in 1998. Note constricted creek and backshore encroachment.

Site prior to development in 1977, seen in lower right with creek crossing berm.

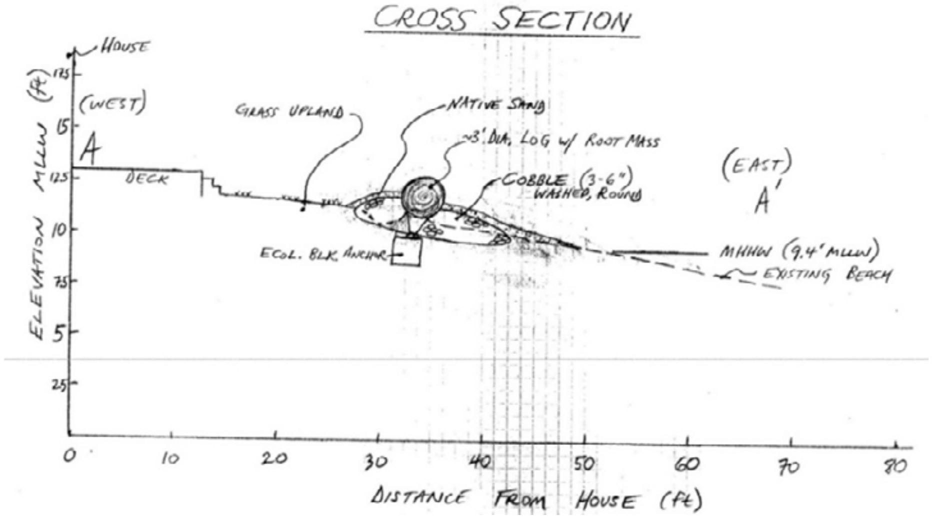
Design

The intent of the project design was to provide an environmentally acceptable shore protection structure to minimize storm-wave erosion of the small yard area and single-family residence. The project consisted of placing two very large logs with an enhanced cobble storm berm or dune at the point where the old beach transitioned into the rockery and the waterward portion of the yard. The project included placement and anchoring of two logs, approximately 36 in and 24 in in diameter, acquired with permission from the nearby county park beach and towed to the site. Prior to log installation, the small rockery wall was removed and most of the rock was removed from the site.

A 15-ft-wide dune or berm was constructed of cobble (2 in plus round gravel) with a toe generally 1–2 ft above MHHW. This raised the berm elevation approximately 1.5 ft. The two large logs were anchored with ½ in-diameter marine-grade galvanized cable that was passed through holes in the center of buried ecology block (deadman) anchors. Cables were passed around the logs and secured with galvanized staples. Existing logs were also placed approximately half way into the enhanced storm berm area at the time of construction. The logs raised the elevation approximately 1.5 ft higher near the center of the berm. A small amount of rock was retained on site and used to add structure to the small point where the anchored logs met the creek channel and on each side of the creek mouth, including the area adjacent to the neighbor's concrete wall.



Project design drawing.



Project design cross section.

Current Conditions

Technique condition - The anchored logs remained in place, along with most of the placed gravel. Additional drift logs had been placed atop the anchored logs by the owner in recent years to augment the log zone. No other actions had been taken by the owner. Natural drift-log recruitment had also occurred just waterward of the anchored logs. Anchoring hardware weathered well. Both of the large anchored logs, one of which had a small amount of rot upon installation, had areas of rot above beach level. Backshore vegetation, primarily dunegrass, was dense in places.

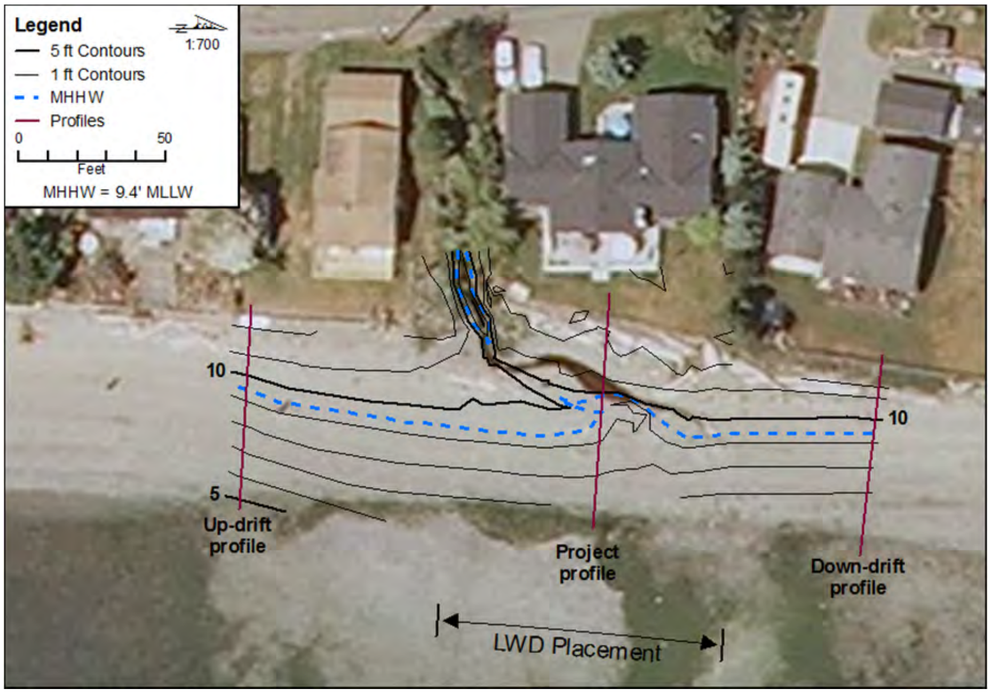
Upland threats – The project appeared to be providing good protection from overtopping and flooding at the site and from migration of the small stream into the deck and yard.

Beach characteristics – The dominant features of the beach at the project site are the stream channel and very small barrier spit that tends to accrete to the north in the direction of net shore-drift. Being near the end of a drift cell, the beach was largely sand with some pebble. The intertidal beach slope at the project area was gentle due to the presence of the small stream delta.

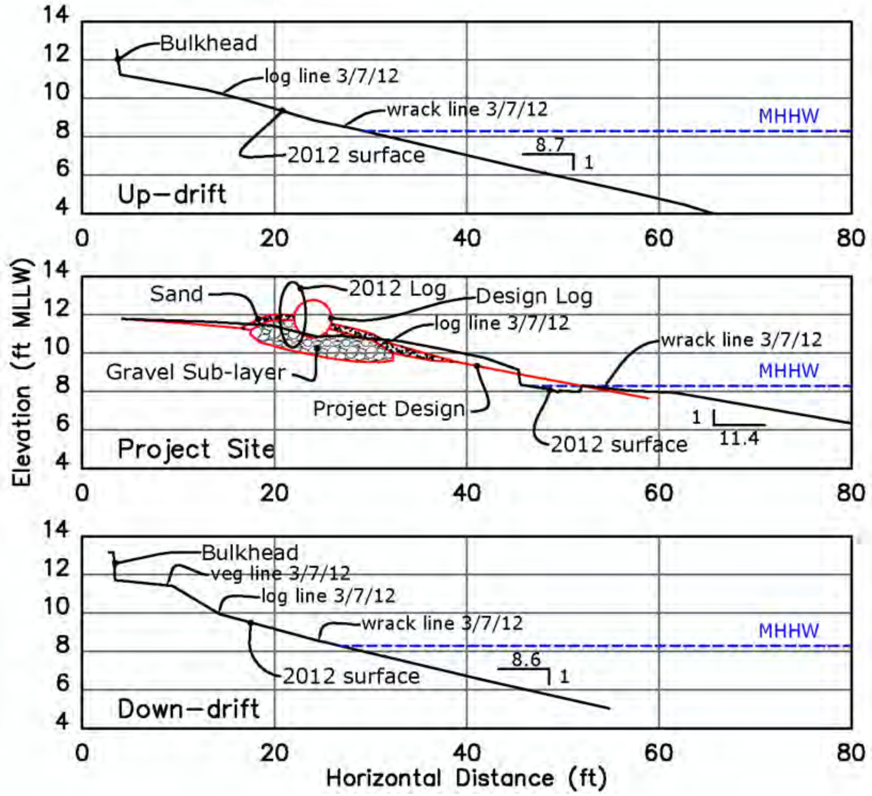
Adjacent shores – The adjacent up- and down-drift shores both contained concrete bulkheads. The beaches were steeper than at the project site, although the presence of the stream channel and delta may be the strongest factor affecting the difference, as the slopes of the adjacent shores were typical of sandy shores in the region at approximately 8.7:1 and 8.6:1.

Looking up-drift in 2012. Placed logs are just landward of the smaller logs atop the berm area.

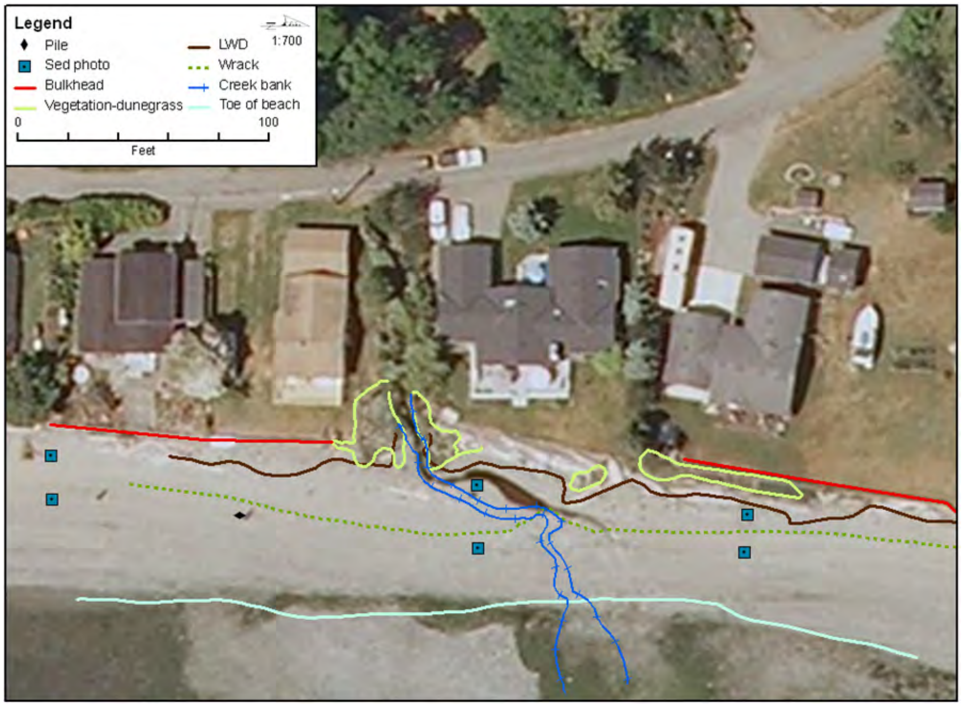
Looking down-drift in 2012. South log is visible behind dunegrass.



Topographic map of conditions during the 2012 site visit.



Beach profiles showing design and 2012 conditions.



General beach features mapped during the 2012 site visit.

Comparison of beach surface sediment at project and adjacent sites.

Location	Backshore	Difference	Upper intertidal	Difference
Up-drift	COARSE PEBBLE, medium pebble, fine pebble	coarser	COARSE PEBBLE, sand, medium pebble	coarser
Project site	MEDIUM PEBBLE, sand, coarse pebble	-	SAND, coarse pebble, medium pebble	-
Down-drift	SAND, fine pebble, medium pebble	finer	SAND, coarse pebble, medium pebble	same

Performance

Overall, the project performed well since installation in late 1999. The hardware appeared sound, although the large logs exhibited some rot. Cables and other hardware used to keep the wood in place showed minor signs of rust but no risk of breakage in the near future. The coarse pebble and cobble placed in the backshore remained in place, although the logs were no longer keyed into the gravel berm. Large and small logs had been recruited naturally on the waterward side of the anchored logs, and several had been pulled over the top of the anchored logs and tied or cabled in place to augment the original anchored wood. The reasons for project success appear to be:

- The partial wave shadow caused by the small headland to the south
- The southeast-facing orientation of the anchored logs
- A shallow subtidal area, which partially dissipates wave attack in the backshore project area
- The use of large logs augmented with coarse gravel, rocks at the south end, and dunegrass planting

The dominant feature at the project site is the stream channel, which trends northward in front of the project. The northward net shore-drift results in the deposition of a small barrier spit in a cycle of growth and breach that creates a very dynamic beachface. Prior to installation, the channel and storm waves tended to cause backshore erosion, which undermined the small riprap that had been placed to prevent erosion before the project. There did not appear to have been any significant erosion of the wood and gravel structure since 1999.

Project performance scoring.

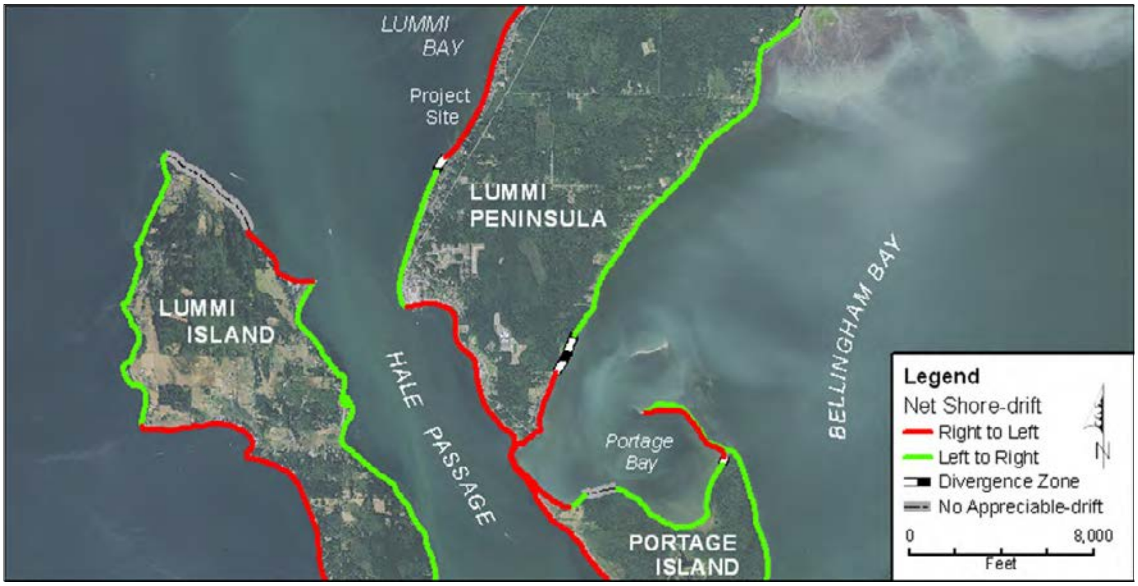
Category	Parameter	Rating	Score	Rationale
Benefits	Effectively mitigated landward erosion*	High	6	No evidence of erosion of the backshore was seen during the site visit
	Sediment volume augmented	Low	1	The design introduced only a small amount of sediment to the beach, as the gravel was meant to stay in place
	Input/exchange of LWD, detritus	Low	1	The project allows alongshore transport of LWD/detritus
	Backshore vegetation enhanced	Med	2	The project included planting of dunegrass among the anchored logs
	Marine riparian vegetation enhanced	None	0	No marine riparian planting was included in the design
	Low-cost and simple installation	Med	2	The project was moderately expensive, largely due to the lack of upland access, which necessitated use of a barge
Impacts	Structures bury backshore & intertidal areas	Low	-1	A small area of backshore was buried by the logs and sediment was coarser than the native substrate
	Structures impound littoral sediment	None	0	No impediment to littoral transport was included
	Coarser/steeper beach profiles created	Low	-1	The backshore was made coarser, but the remainder of the beach was outside the project area
	LWD/detritus recruitment reduced	None	0	The project has not had an impact on LWD/detritus recruitment
	Adjacent end erosion	None	0	No end erosion was seen during the site visit
	Required maintenance interval	None	0	No maintenance has been required or is foreseen for at least the next 5 years
Design-specific benefits	Natural material used (minimal hardware)	Med	2	Natural driftwood from Oak Bay was used in construction
	LWD facilitates fine sediment deposition	Low	1	The anchored and recruited wood facilitates a small amount of sediment deposition
Design-specific impacts	Placement causes scour, disturbance	None	0	No scour was seen during the site visit
	LWD can become detached or cause damage	None	0	The anchors and hardware appeared to be in good condition

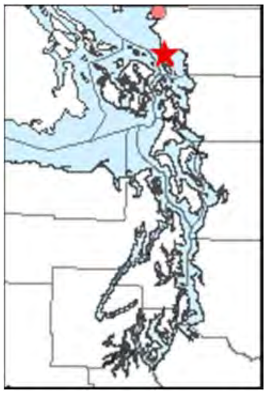
*Scores at double other values (e.g., high=6); all others, none=0, low=1, med=2, high=3

Totaling the above scores, benefits equal +15 points and impacts equal -2 points, for a final combined score of +13.

WEST LUMMI PENINSULA – Reslope and Revegetation (2003)

Waterbody: Hale Passage	Shoretype: Bluff-backed beach	Net Shore-drift Cell: WH-4-11	Direction: Northeast
Project Elements: Regrade bank and install native plants, install small gravel berm and large anchored log		Objective: Stabilize slope	
Fetch: 119 mi NW Wave Energy: Very high Aspect: WNW	Land Use: Residential MHHW: +8.83 ft MLLW Toe Elev: approximately +13 ft MLLW	Structure: Single-family residence Setback: 40 Risk Index: 30	Benefit Index: +13 Impact Index: -3 Total BI Index: 10





Project site as red star with dots showing all other reslope and revegetation projects Sound-wide.

Project Background

This site is in a very-high-wave-energy regime, and hosts a single-family residence on the west shore of the Lummi Peninsula, just north of Hale Passage. Western Geotechnical Consultants, Inc., and Coastal Geologic Services investigated the instability of the marine bank at this site in August 2002. A subsequent geotechnical report that described and assessed the cause of recent slope movement, materials involved, and mitigation of the effects concluded the following:

- A soil slump had occurred on the southern portion of an approximately 50-ft reach of private land with a 15-ft-high marine bank and a slope of 70–80%.
- Slumping caused the base of the slope adjacent to a neighbor's vertical wooden bulkhead to recede 4 to 6 ft.
- Slumping was attributed to end-effect erosion caused by wave refraction concentrating at the end of the bulkhead on the adjacent southern property, along with instability due to low-strength soils on an oversteepened slope.
- It appeared that large drift logs at the base of the bank protected the northern portion of the bank against wave action.

Conditions observed after soil slump and considered while preparing mitigation actions included

- An oversteepened head scarp at the slope crest, with tension cracks landward of the crest. The old stairway was undermined.
- An eroded and oversteepened bank toe, allowing for potential further crest retrogression.
- Bank sediment consisting entirely of silty fine sand to sandy silt.
- Intermittent bank toe erosion that occurred during high-energy northwesterly waves, particularly during storms coinciding with high tides and storm surges.

Project site before treatment in 2002.

Revegetation in progress in 2004.

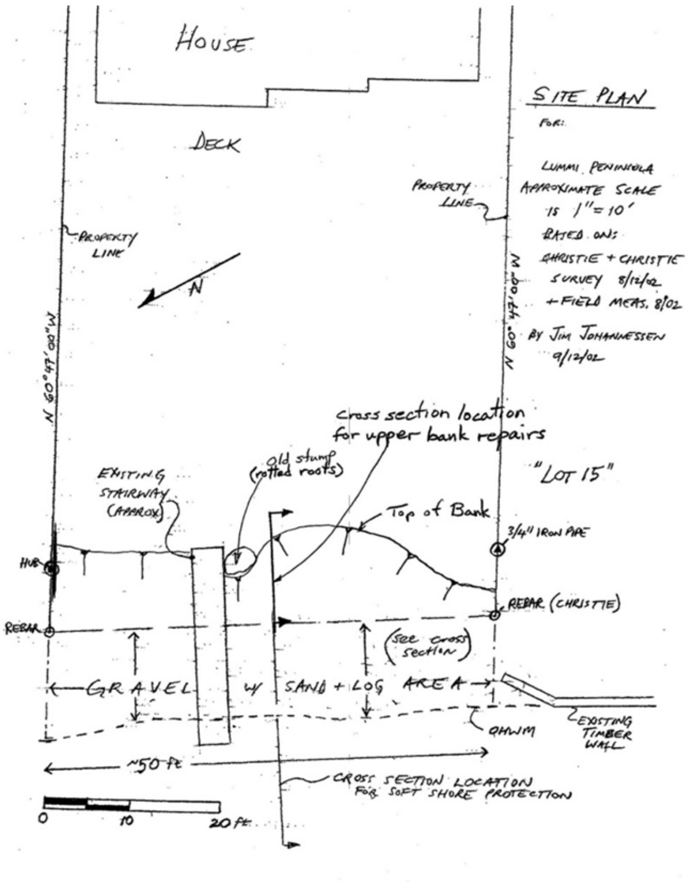
Design

The bank toe at this very-high-energy site was periodically subject to wave attack, causing failure of the approximately 15-ft-high bank and subsequent loss of the yard fronting a single-family residence. The proposed slope reconfiguration and soft shore protection was intended to

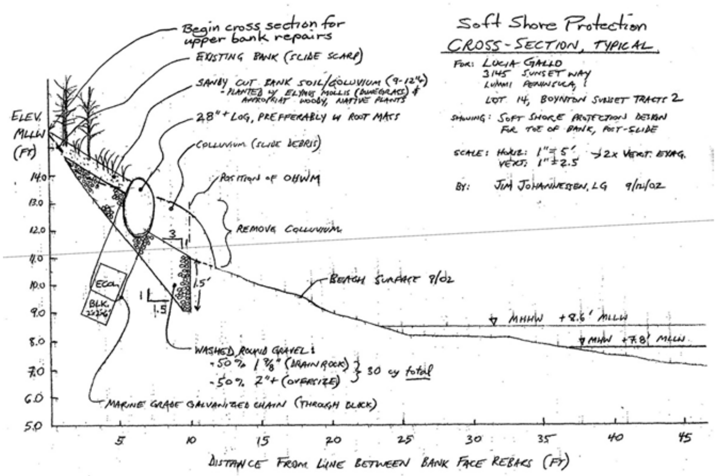
- Protect the bank toe area from wave erosion.
- Protect against end erosion from adjacent bulkheads.
- Mitigate the risk of further bluff crest retreat.
- Stabilize the bank using a design that included regrading and planting the bank face. This also involved removing all Himalayan blackberry and English ivy and planting deep-rooted, native vegetation. Additional stabilization was planned by adding a single anchored log at the toe of the bank along with a small volume of gravel.

The design included pulling the steep bluff crest back 4 to 6 ft and regrading the slope to a ratio of 2:1 (horizontal to vertical). An erosion-control mat was then to be installed over the regraded bank face. Note the optional terrace was not installed on the bank face. The “Bon Terra Straw Fiber Blanket” (SFB 2) was recommended, with 1 in diameter anchor pins installed into the bank face on a 3-ft by 3-ft grid. It is not known if this material was installed. Once the regrading was completed and the soft shore protection was installed, the marine bank was planted with low-growing native vegetation. It was also recommended that trees be planted on the bank to provide for recruitment of woody debris in the future.

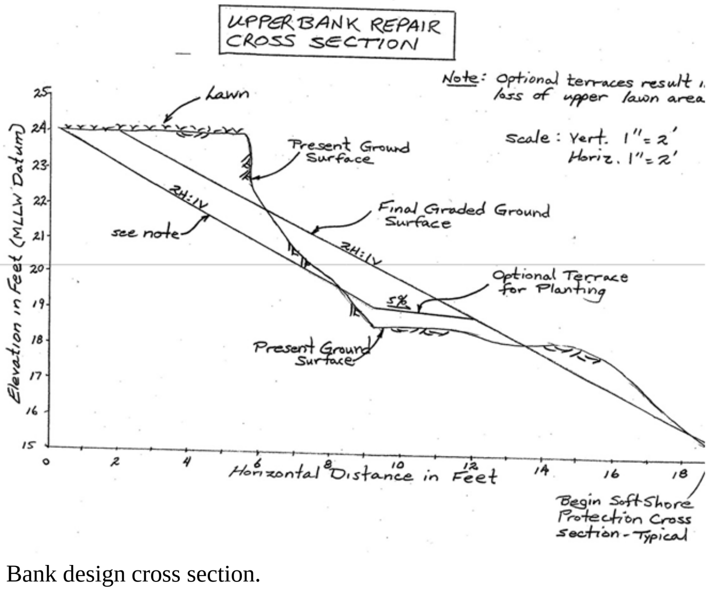
The soft shore protection involved a single log attached by galvanized lashing chain to ecology-block anchors buried under an 8-ft-wide band of ¾–2 in washed rounded gravel. The length of the area to be protected was the full width of the property (approximately 50 ft).



Project design drawing.



Beach design cross section.



Bank design cross section.

Current Conditions

Technique condition – The slope appeared stable, with good vegetation cover dominated by shrubs and groundcovers. Some grasses have naturally established themselves on the slope along with the planted vegetation. The bank appeared to have been graded to a consistent slope that has persisted since installation in 2003.

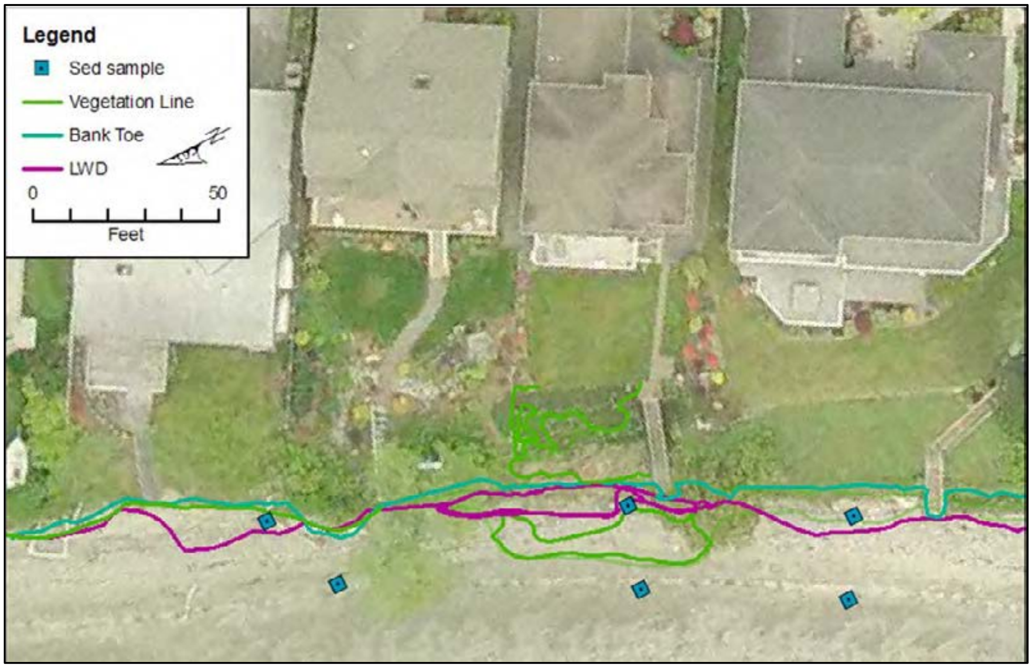
Upland threats – There no longer appeared to be any threat to the structures landward of the top of the slope. No bank crest failures or erosion appeared to have occurred since installation. The staircase appeared stable and has recruited small pieces of driftwood.

Beach characteristics – Beach sediment was dominated by sand with minor pebble in the mid to upper intertidal, and by medium and coarse pebble in the lower beachface and separately in the backshore. The sediment appeared consistent across the project site and adjacent up-drift and down-drift sites except for a broader backshore of coarse pebble on the project site from sediment imported during stabilization work. Dunegrass and wrack from storms had collected here. Before restoration work, this area had been covered with sand.

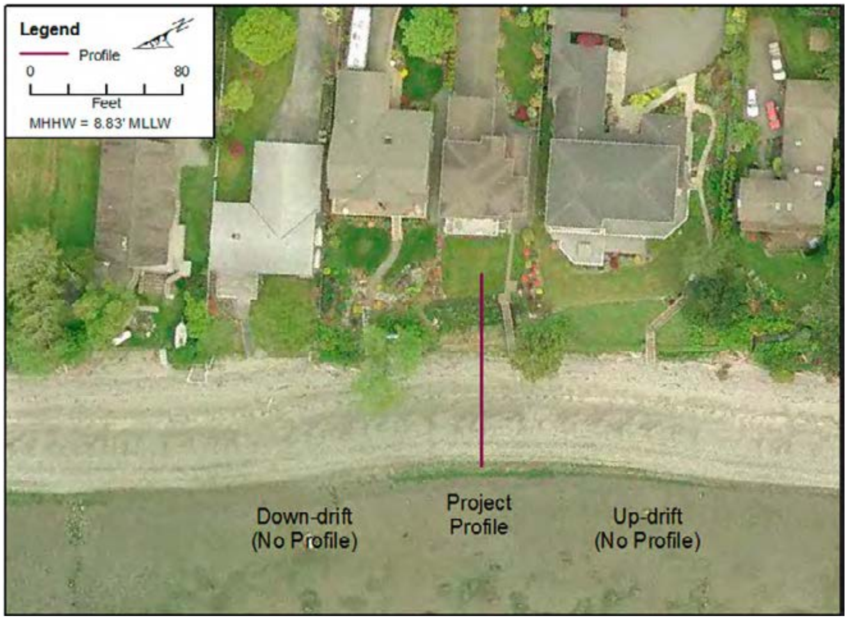
Adjacent shores – Adjacent shores were consistent in morphology and beach characteristics with those of the treatment site. The up-drift shore had a low (approximately 2.5 ft high) concrete bulkhead and a slope covered with ivy. The down-drift shore had no protection and was relatively stable, with native vegetation and only a small area of erosion on the south end of the property.

Revegetated project site in 2012. Note vegetation covering slope, expanded area of dunegrass, and recruited large wood.

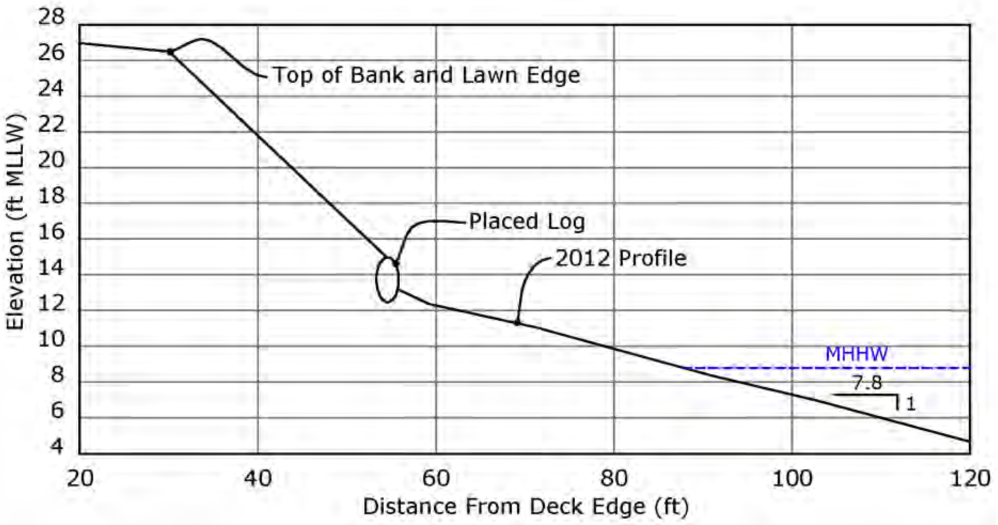
View of bank looking north (down-drift) at revegetated project site in 2012. Groundcovers are more prevalent in foreground; shrubs such as snowberry are dominant in background.



General beach features mapped during the 2012 field visit.



Project site map with profile locations.



Beach profile showing 2012 conditions.

Comparison of beach surface sediment at project and adjacent sites.

Location	Backshore	Difference	Upper intertidal	Difference
Up-drift	COARSE PEBBLE, medium pebble	same	SAND, medium pebble, coarse pebble	similar
Project site	COARSE PEBBLE, medium pebble	-	SAND, coarse pebble, medium pebble	-
Down-drift	COARSE PEBBLE, medium pebble	same	SAND, coarse pebble, medium pebble	similar

Performance

The bank regrading and revegetation project has performed well overall since installation in 2003. No slope failures of any kind and no toe erosion appeared to have occurred since installation; the bank face slope remained uniform and no erosion was observed at the bank toe. Plants were becoming well established with no evidence of significant die-off. The general lack of planted trees limited the potential habitat benefits of recreating a natural marine riparian area and promoting LWD input. The minor gravel nourishment added a small amount of beach-quality sediment that was within the range of sizes present in a large part of the Lummi Peninsula. Backshore vegetation was enhanced, although it was somewhat isolated from the active beach by the single anchored log. The project was intended to limit bank-face recession and therefore reduced somewhat the potential for input of littoral drift sediment in this low-bank site. No known maintenance had been performed to date, although some vegetation maintenance likely occurred. Sale of the property since project installation complicated the process of acquiring full project details. Minor encroachments of English ivy and Himalayan blackberry from the adjacent property could be controlled if addressed promptly.

This project provides a very good example of bank resloping and revegetation. The key to success appeared to have been the low erosion rate, as the incident wave is typically at a very high or very low angle, depending on whether the storm waves are from the predominant storm direction (southwest) or from the longer fetch to the northwest. The very shallow low-tide terrace dampens wave energy to some extent. The site is not prone to excessive seepage, but minor seepage was observed before project installation. Habitat and slope stability could be enhanced by planting additional trees and large shrubs, which did not appear to have been included in the original installation.

Project performance scoring.

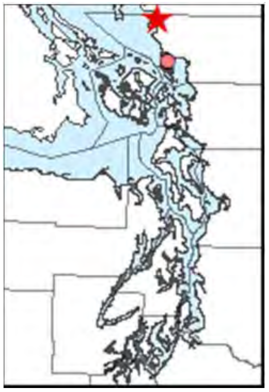
Category	Parameter	Rating	Score	Rationale
Benefits	Effectively mitigated landward erosion*	Med	4	Very effectively managed erosion, although bank-toe elements likely contributed to this
	Sediment volume augmented	Low	1	Minor beach-nourishment gravel added, potential for bluff sediment input
	Input/exchange of LWD, detritus	Low	1	Alongshore exchange is unimpeded but single log slightly reduces cross-shore connectivity
	Backshore vegetation enhanced	Low	1	Small area of dunegrass planting was successful, although landward of single anchored log
	Marine riparian vegetation enhanced	Low	1	Only shrubs planted, with alder recolonizing naturally
	Low-cost and simple installation	Low	1	Cost unknown, but this was likely not a high-cost project
Impacts	Structures bury backshore and intertidal areas	None	0	Reslope/revegetation elements slightly increased available backshore room
	Structures impound littoral sediment	Low	-1	Vegetation has reduced erosion and minor to moderate slope instability
	Coarser/steeper beach profiles	None	0	No changed in beach sediment or profiles observed
	LWD/detritus recruitment reduced	Low	-1	Tree reestablishment will be slow; dominant plantings were shrubs and groundcovers
	Adjacent end erosion	None	0	No end erosion observed
	Required maintenance interval	None	0	No maintenance needs likely for 30 years
Design-specific benefits	Vegetation reestablished without slope failure	Med	2	No slope failures have occurred since installation
	Surface- and groundwater adequately managed	Med	2	Water managed through revegetation, resloping, and surface-water collection system
Design-specific impacts	Slope failure within the project area	None	0	No slope failures have occurred since installation
	Nonnative/invasive vegetation	Low	-1	Minor encroachment of English ivy and Himalayan blackberry from adjacent site
Total			10	

*Scores at double other values (e.g., high=6); all others, none=0, low=1, med=2, high=3

Totaling the above scores, benefits equal +13 points and impacts equal -3 points, for a final combined score of 10.

EAST DRAYTON HARBOR – Reslope and Revegetate (2009)

Waterbody: Drayton Harbor	Shoretype: Open Coastal Inlet	Net Shore-drift Cell: WH-2-2	Direction: Northward to Port of Blaine
Project Elements: Removal of slope modifications and fill, planting native vegetation		Objective: Restore natural bluff vegetation and processes	
Fetch: 2.4 mi SW Wave Energy: Low Aspect: WSW	Land Use: Residential MHHW: +9.4 ft MLLW Toe Elev: +10.1 ft MLLW	Structure: None Setback: N/A Risk Index: 4	Benefit Index: +12 Impact Index: -5 Total BI Index: +7



Project site as red star with dots showing all other reslope and revegetation projects Sound-wide.

Project Background

This site is located in a low-energy protected embayment where a low-relief upland drops to the beach surface along a 15–20 ft high bank. Coastal Geologic Services visited the site on January 11, 2008, to assess beach and bank stability for eventual development of the uplands. The property bank shore, on eastern Drayton Harbor in Blaine, Washington, is 88 ft long and includes 8 ft of utility easement. A shallow depression in the northwest corner of the property contained standing water during the field visit, and reportedly holds water throughout the winter months, although it is dry in summer. Examination of shallow test pits in the uplands showed silty clay with sand, indicating a very low infiltration rate.

Exposed near the base of the bluff was a dense, pebbly clayey silt, characteristic of locally mapped glacial marine drift (GMD). The low permeability and poor drainage of this unit explains the ponded water observed at the surface during winter. Overlying the GMD was a mantle of fill and topsoil of variable thickness up to 3 ft. Slumping of the upper soil layer was evidenced as small scarps, stepped slope topography, and disrupted vegetation. There was no evidence of deep-seated landsliding in the vicinity. Tree root systems provided stability to the slope.

Two large mounds, apparently topsoil scraped from the uplands on the property, were located at the top of the bank. These mounds were thought to decrease slope stability and to damage fine roots of a large cedar and Douglas fir, and possibly those of other trees at the site. Early reports suggested removing the mounds of topsoil and leaving the trees for the stability provided by their root systems. Trees in 2008 included the large cedar and Douglas fir growing at the bank crest, a cherry tree near the bank crest, and an alder on the bank face. Bank face vegetation included salmonberry, willow, alder, Himalayan blackberry, and other shrubby vegetation. Older shrub vegetation on the bank had apparently been repeatedly cut for view maintenance. Measures recommended to improve overall stability were to remove the Himalayan blackberry and to replace it with native vegetation similar to that on adjacent lots. Reports also identified the need to determine the source of drain pipes and manage them appropriately, and noted that waves were undercutting the bank, probably very slowly.

Looking northward along treatment area before treatment. Note trees and debris on the bank and beach.

Bluff before treatment. Note drainage pipes and invasive Himalayan blackberries.

Design

The treatment was to remove concrete and other debris from the bank face, remove invasive plants such as Himalayan blackberries, and plant native vegetation. Fill placed at the crest of the slope prior to 2007 was to be removed. The project was not well documented. A summary of activities from the contractor (shown below) included work in 2008 and spring 2009. Additional maintenance and planting was completed in 2010 to early 2012.

View looking south shortly after cleanup and removal of invasive vegetation and initial planting of native vegetation. Note tension crack at top of slope and slumping of soil and mantle of fill and topsoil.

June 2008 - Bank cleared by English Gardener
All invasive vegetation cut and some grubbed out.
Raked to mudflat.
Driftwood removed and stacked
Overhanging alder and scouler willow cut down
Mulched and irrigation applied for season.
99 plants installed
44 Thimbleberry
50 Salmonberry
40 cubic yards hog fuel applied to bank
Grubbed blackberry and teasel
October 2008 - 100 plants installed
50 Oregon grape top of bank
50 nootka rose top of bank
40 cu yards hog fuel applied
Grubbed blackberry and teasel
March 2009 - 309 plants installed
54 nootka rose
105 thimbleberry
22 evergreen huckleberry
6 Indian plum
1 salal
1 California wax myrtle
50 snowberry
2 red flowering current
50 salmonberry
5 scouler willow
2 sword fern
1 black gooseberry
3 serviceberry
3 ocean spray
3 sitka alder
Grubbed blackberry and other weeds
Irrigated over growing season

February 2012 - 123 plants installed
50 snowberry
30 thimbleberry
10 dunegrass
3 ocean spray
3 pacific crabapple
1 Indian plum
10 low Oregon grape
3 serviceberry
4 red currant
15 evergreen huckleberry
1 red huckleberry
6 scouler willow
6 yards hog fuel applied
Blackberry grubbed
Irrigated for growing season

MAINTENANCE ACTIVITIES
April 2010 - Grubbed blackberry
June 2010
4 yards hog fuel
1 load haul-off brush
Grub blackberry and teasel
September 2010 - Herbicide reed canary grass
September 2011 - Herbicide reed canary grass

Summary of activities provided by the construction contractor.

Current Conditions

Technique condition - The project has experienced mixed success in the survival and proliferation of native plantings; some invasive plants still had a good hold on the bank. Large discarded items (e.g., an aluminum ladder) remained on the slope in some places, and the topsoil fill excavated from the neighbor had not been moved, or at least not fully removed as recommended. Shallow slope instability continued, although trees on the lower part of the slope were still standing (except the cherry, which had been cut down).

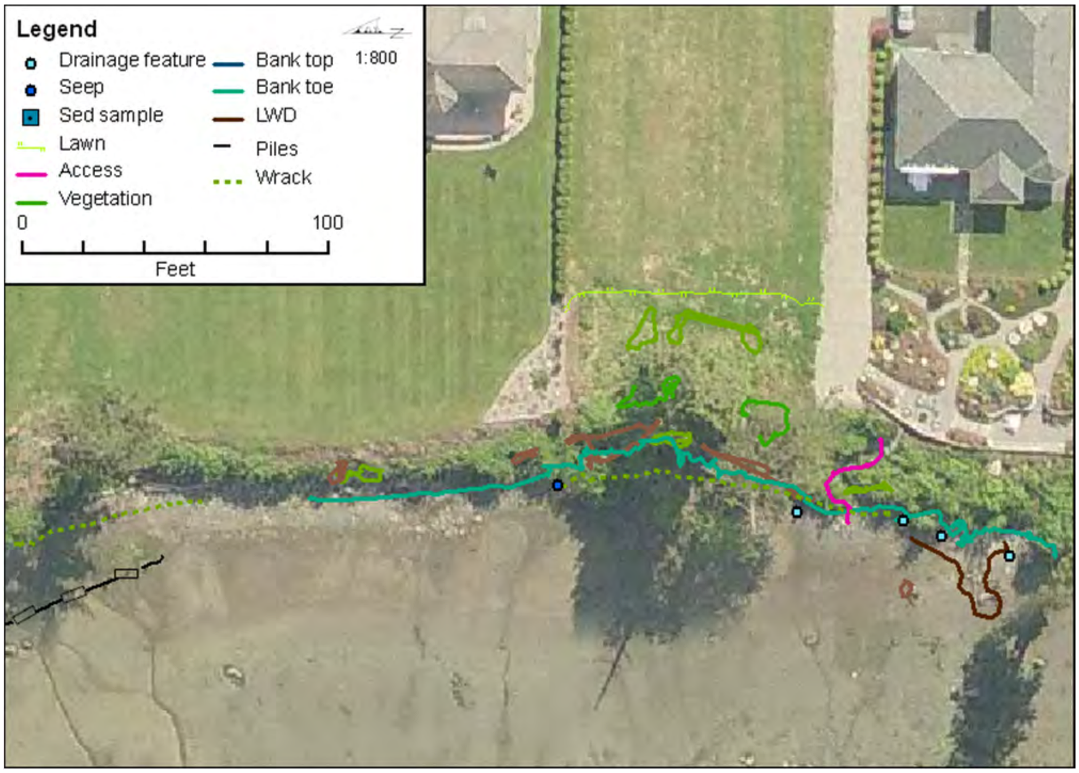
Upland threats - Because there are not yet any structures on the uplands and it is a relatively deep lot, further retreat of the bluff or loss of large trees or shrubs is not a threat to this parcel. Neighboring homes have adequate setbacks, and bluff retreat is relatively slow, minimizing upland threats to this or adjacent properties. Small rotational slumps on the bluff face typical of this sedimentary sequence are associated with saturation of the more permeable unconsolidated surface sediments over dense groundwater-perching GMD.

Beach characteristics - Natural beach substrate along the reach of the treatment area was characterized by either a very thin veneer of sediment, typically less than 2 inches, or one cobble thick on the upper beach. Beach sediment was primarily sand, ranging from coarse to fine. The upper intertidal beach included sand with fine to medium pebble and cobble, likely derived from weathering and erosion of glaciomarine drift exposed at the base of the bluff.

Adjacent shores - Adjacent shores were consistent in morphology and beach characteristics with those of the treatment site, although somewhat steeper due to modifications consisting primarily of broken concrete. The bank in this area was generally very moist, with perched water. Plastic tightline pipes appeared more numerous to the south than along the adjacent property to the north. Adjacent slopes appeared to be less susceptible to shallow slumping, likely because of remaining concrete on the slopes. The concentration of surface water noted during previous visits to the treatment site might point to a cause for the more apparent slumping.

View of treatment area looking northeast. Note fallen cherry tree. Photo taken in spring 2012, so vegetation had not yet leafed out.

Looking south over treatment site where nonnative plants were removed and upper bank was replanted with native plants in 2012.



General beach features mapped during the 2012 site visit.

Comparison of beach surface sediment at project and adjacent sites. n/a indicates the location was not present for sampling.

Location	Backshore	Difference	Upper intertidal	Difference
Up-drift	n/a	-	SAND, medium pebble	similar
Project site	SAND, medium pebble	-	SAND, fine pebble, medium pebble	-
Down-drift	COBBLE, coarse pebble, sand	coarser	SAND	finer

Performance

The East Drayton Harbor revegetation project improved stability to a small degree but did not dramatically improve overall stability. Because the treatment did not include any modification of the bluff slope, scoring of the potential benefits and negative impacts primarily considered vegetation management. This was a different project approach than that used for the West Lummi Peninsula project (also included in this report in the same treatment group), and resulted in a slightly different perspective for evaluation. Slumping of the bluff appears to be a chronic process, and may be a pre-existing condition resulting from groundwater issues and minor toe erosion, or possibly a newer condition resulting from only partial removal of debris on the bluff face or from vegetation management. Both planting activities and tree cutting can contribute to slope movement, and both have occurred on the slope face in recent years, particularly in the lower, southern corner where a deciduous tree was recently cut. Apparent removal of some broken concrete, the continued downward creep of surface soils, and some undercutting at the bank toe are all contributing to sediment input.

Scoring of the treatment at this site included consideration of projected longer term issues. The cost of the treatment was considered to include erosion-control measures and plant installation. With this in mind, benefits were assigned “low” or “medium” scores because of the ongoing slope movement, limited survival rate of some plants, the likely need for replacement, and continuing maintenance costs. This same rationale was reflected in the value given for negative impacts.

Project performance scoring.

Category	Parameter	Rating	Score	Rationale
Benefits	Effectively mitigated landward erosion*	Low	2	Bank recession appears as it if will be slowed but overall success not as high as intended
	Sediment volume augmented	Low	1	No nourishment sediment, but bank instability continued
	Input/exchange of LWD, detritus	Med	2	Some trees planted and existing trees retained
	Backshore vegetation enhanced	None	0	No backshore present at the property beach
	Marine riparian vegetation enhanced	Med	2	Native species planted but few trees were becoming established
	Low-cost and simple installation	Med	2	Project activities were not high cost and mostly labor costs
Impacts	Structures bury backshore & intertidal areas	None	0	No change to beach
	Structures impound littoral sediment	None	0	No impact
	Coarser/steeper beach profiles created	None	0	No change to beach
	LWD/detritus recruitment reduced	None	0	No change to beach system; LWD input not reduced
	Adjacent end erosion	None	0	No end erosion present
	Required maintenance interval	Med	-2	Maintenance needs moderately high in first years but will decrease over time
Design-specific benefits	Vegetation reestablished without slope failure	Low	1	Vegetation establishing but minor recent slumps have occurred
	Surface- and groundwater adequately managed	Med	2	No development at property but drainage control not optimal
Design-specific impacts	Slope failure within the project area	Med	-2	Minor recent slumps have occurred
	Nonnative/invasive vegetation	Low	-1	Minor encroachment of invasives not fully controlled
Total			+7	

*Scores at double other values (e.g., high=6); all others, none=0, low=1, med=2, high=3

Totaling the above scores, benefits equal +12 points and impacts equal -5 points, for a final combined score of 7.

DEER HARBOR POOL – Bulkhead Removal (2008)

Waterbody: Deer Harbor	Shoretype: Rocky Platform	Net Shore-drift Cell: OR-16	Direction: Northward toward the harbor
Project Elements: Bulkhead removal		Objective: Habitat restoration and increased public access	
Fetch: 2 mi SW Wave Energy: Medium Aspect: West	Land Use: Park MHHW: + 7.96 ft MLLW Toe Elev: +5.0 ft MLLW	Structure: Road Setback: 125 ft Risk Index: 8	Benefit Index: 17 Impact Index: -2 Total BI Index: 15

Project Site as red star with dots showing all other bulkhead removal projects Sound- wide.

Project Background

The Kaiser pool was constructed in 1935 within the northeastern portion of Deer Harbor on western Orcas Island. Built from the low bank over the upper intertidal beach, this saltwater pool extended down to +5 ft MLLW. It had not been functioning for a long time. The 1977 aerial photo showed the pool walls still upright, but no water inside the pool. When assessed in 2006, two sections of wall had fallen. Other wall sections were cracked, and the concrete footing was exposed in a number of places.

This portion of Deer Harbor has a sandy beach with a broad lower beachface and low-tide terrace. The net shore-drift rate is reduced by the up-drift marina. The remaining pool walls diverted much of the upper beach sediment transport into the lower beach, a process exacerbated by the pool's location in the lee of a minor rocky point. This sediment otherwise would have "fed" the down-drift beach that extends toward the inner estuary. The pool also interrupted natural saltmarsh vegetation (pickleweed and saltgrass, *Salicornia virginica* and *Distichlis spicata*), which did not grow inside it.

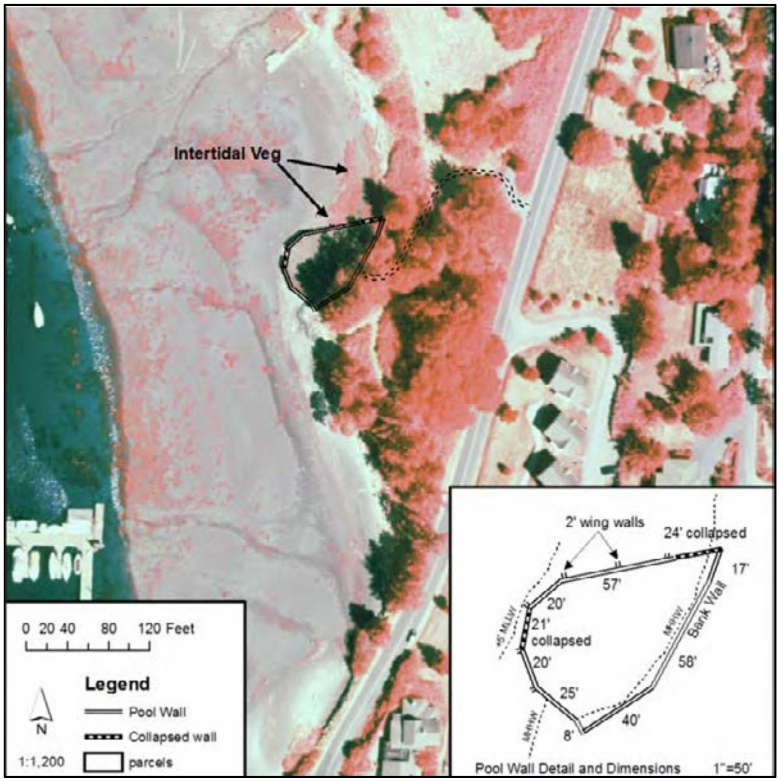
The estuary of nearby Cayou Valley Creek, originally a salmon-bearing stream, has been a restoration target for years. Salmon migration alongshore was impeded by the derelict pool walls during high and mid tides. The derelict pool had a depression open to the south that could trap fish during falling tides. The south end and the remaining footings were higher in elevation than the missing wall sections of the north end. Removal of the pool was recommended in the Soft Shore Blueprint by Coastal Geologic Services (CGS) and Friends of the San Juans in 2006. The San Juan County Land Bank secured funding from the Salmon Recovery Funding Board (SRFB), had a simple removal plan prepared by CGS, and managed the pool removal in 2008 for a total budget of $35,000.

Remains of concrete pool outside pool before removal, looking down-drift in 2006.

Inside of the pool, looking up-drift in 2007.

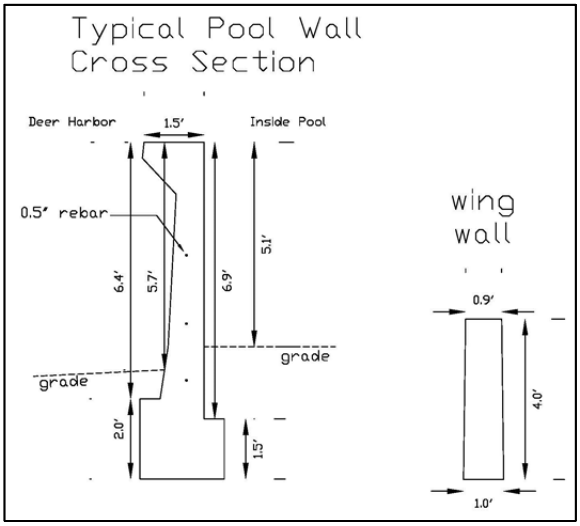
Design

- The pool walls, made of formed concrete, varied in height between 2.0 and 6.3 ft above beach grade. It appeared that the wall contained three ½ in horizontal and vertical rebar with an approximate spacing of 1.5 ft on center. The pool walls extended to +5.0 ft MLLW at the most westerly extent and varied in thickness from a 1.5 ft recurved cap and a 0.7 ft upper wall to just over 1.0 ft at the footing. The concrete footing appeared generally to be 2.0 ft high by 2.1 ft wide.
- Perhaps six short wing walls, largely deteriorated, extended up to 3 ft outboard and waterward of the pool walls.
- The 253 linear feet of wall removed contained approximately 80 CY of concrete. Approximately 20 CY of rock were removed from the low bulkhead along the toe of the bank, but 8 to 15 CY were retained to avoid losing several mature trees.
- Prior to removal, the difference in elevation between the inside and outside of the south pool walls was less than 0.4 ft. The north-central pool walls contained the greatest vertical offset, with the beach up to 2.0 ft higher outside of the pool. Several isolated outcrops of bedrock were found on the beach immediately north of the pool wall, and it was presumed that one or two sections of the pool wall footing were founded directly atop bedrock.
- The landward edge of the old pool (the bank wall) was composed of stacked, angular, two-man rock with a mortar facing. Generally, the concrete mortar facing was 3 ft high and nearly vertical, with a 3 to 4 ft-wide mortar cap. The mortar was generally less than 0.5 ft thick. The bank wall was measured at 98 ft long. Total volume of concrete in the bank wall was calculated at approximately 11 CY and the total volume of rock at 18 CY.
- The pool structure was one of the most obvious derelict structures covering the nearshore in San Juan County at the time. The pool-removal project ranked high in the 2006 enhancement prioritization, partially due to the landscape setting. The site is in an area with intact riparian vegetation and up-drift of an important estuary and large eelgrass beds. The site was also favorable for restoration due to the low to moderate wave energy, minimal hard structures, and potential low-cost benefits to nearshore salmon habitat.
- The rationale for removal was based on restoring 1) alongshore connectivity for juvenile salmon, 2) the saltmarsh band, and 3) net shore-drift processes.
- An excavator and trucks removed the pool in 2008, hauling away debris via a temporary road. Because it would have required a more involved and lengthy federal permitting process, no sediment for beach nourishment was placed in the depression left by removal of the pool walls. In the absence of sediment placement, the beach was given time to adjust to the restored conditions, so saltmarsh vegetation was not replanted. Marine riparian planting was carried out, as well as restoration of the temporary road and installation of trails for public access.



Bulkhead plan view as mapped prior to removal.

(Design by Coastal Geologic Services, Inc.)



Bulkhead cross section as measured prior to removal.

Current Conditions

Technique Condition – The project site has very low wave energy and is very slowly adjusting to the altered conditions. A small but conspicuous amount of rock and debris remained on the upper intertidal and along the bank toe. The depression left by the pool wall removal had still not filled to the elevation of the adjacent shores, suggesting that the amount of net shore-drift on the upper beach was limited. Additional rock had apparently migrated waterward from the old bank toe or the upper beach was slightly lower in 2012 than it had been in late 2009, resulting in persistence of the void in the saltmarsh through the fourth year after removal. The low bank was slowly beginning to naturalize. A portion of the rock and debris left during removal was being covered by sand, but not across the entire former pool site.

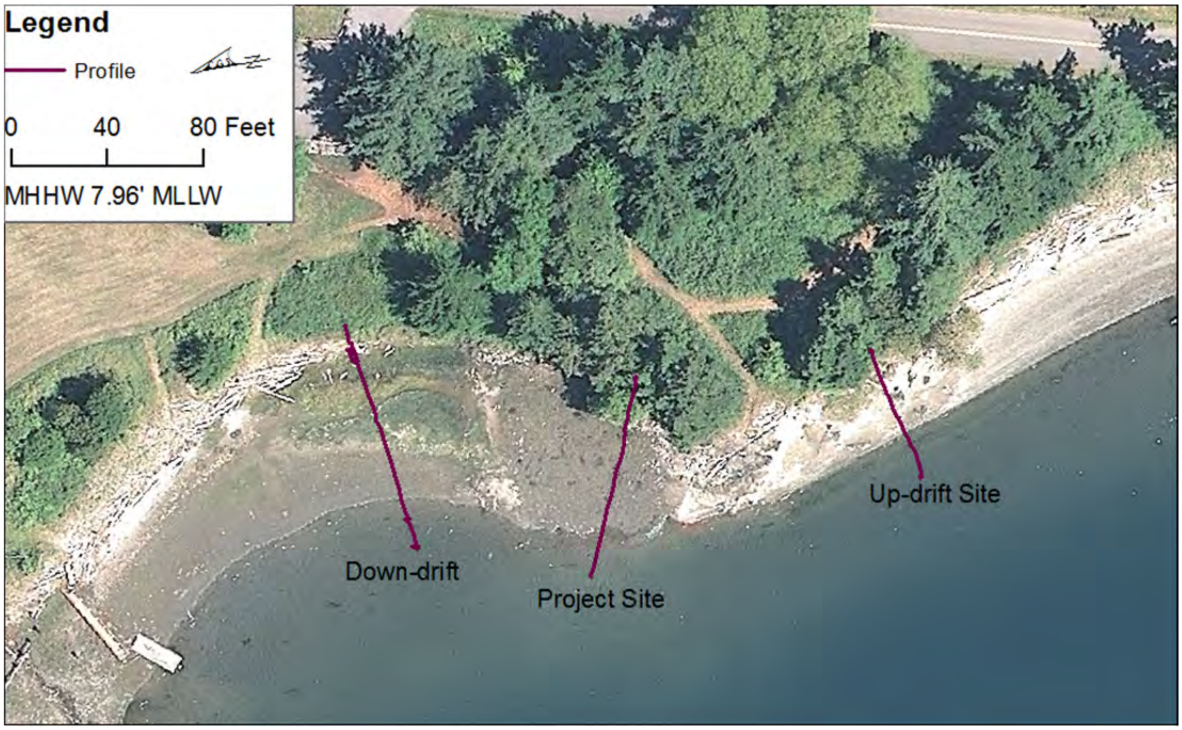
Upland Threats – No buildings are located landward of the removal site, and the road is 125 ft landward of the toe of a very low-slope bank and upland area. Trails have been installed through the upland forest, along with a small parking lot to the northeast. There was no evidence of erosion or any threat to the improvements.

Beach Characteristics – The beach in the former removal area contained a variety of sand sizes, including medium and fine sand, which is generally not typical of other sites surveyed. This appeared to be due to the very low beach slope and very low wave energy. The low slope and relatively fine-grained sediment in the removal area in 2012 resulted in the beach holding water for a long time after the tide receded. No saltmarsh had colonized the former pool area because the elevation was still a little too low.

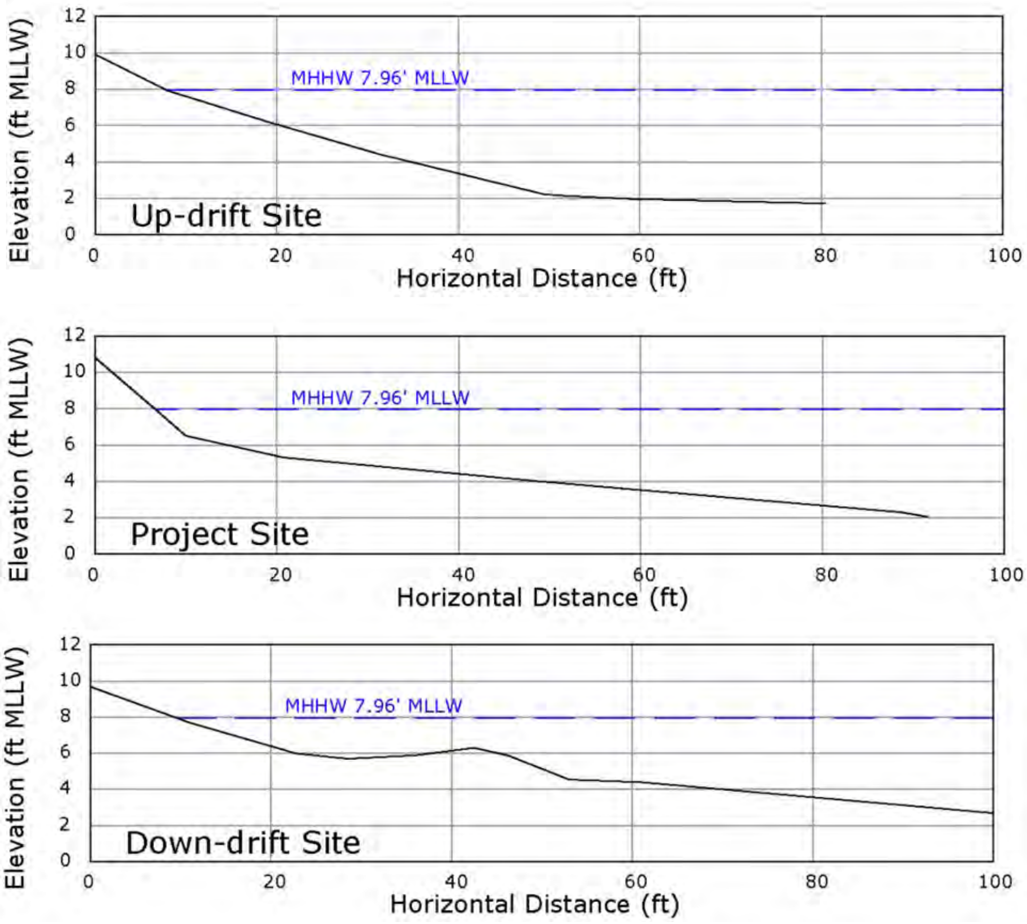
Adjacent Shores – The beach in the former pool area differed from the adjacent sites. The up-drift beach, which has a different aspect on the south side of a small rocky point, always contained slightly coarser sediment than the pool area or the down-drift beach. However, the pool site contained more variable sediment composition and angular boulder in the back shore as compared to adjacent beaches. The mid to upper intertidal in the removal site contained slightly finer sands and more angular boulder than the adjacent beaches.


Former pool area 2.5 years after removal in late 2009, looking up-drift.


Former pool area 4 years after removal in 2012, looking up-drift. Note boulders on upper beach and lack of saltmarsh vegetation.



Project site aerial view showing location of profiles.



Project profiles measured during the 2012 site visit.

Features mapped during the 2012 site visit.

Comparison of beach surface sediment at project and adjacent sites.

Location	Backshore	Difference	Upper Intertidal	Difference
Up-drift	SAND	finer	SAND, fine pebble	different
Project Site	FINE PEBBLE, sand, boulder	-	SAND (finer), boulder	-
Down-drift	SAND	finer	SAND	finer

Performance

The pool-removal project was very successful overall. It was accomplished with a very simple, land-based approach and removed the vast majority of concrete, rock, and other debris. Along-shore and cross-shore connectivity were restored, and the site should slowly adjust to a naturalized condition with additional recruitment of saltmarsh vegetation. Adjustment of the beach sediment and vegetation in this type of low-energy site near a bayhead may take on the order of 10 or more years. Relevant project decisions and their outcomes from the Deer Harbor pool removal include the following:

- To avoid lengthy and more costly federal permitting, no nourishment sediment was added. This has hindered recovery of the former pool area as net shore-drift sediment has been limited along the upper beach in this very protected setting.
- The only area not restored was along the south-central reach of the bank toe, where about half of the former pool bulkhead rock was not removed. The material was left in the field to try to avoid undermining native trees along the bank toe, but this area appeared to be the source of the boulders and debris that have gradually migrated to the upper intertidal.
- The elevation remained lower in the old pool area, and the amount of exotic boulder appeared slightly higher within the pool removal area than it was 2.5 years earlier.

Removal has not caused on- or off-site erosion and has helped build momentum for removing other structures on the island. Several projects are moving toward implementation in the next few years

Project performance scoring.

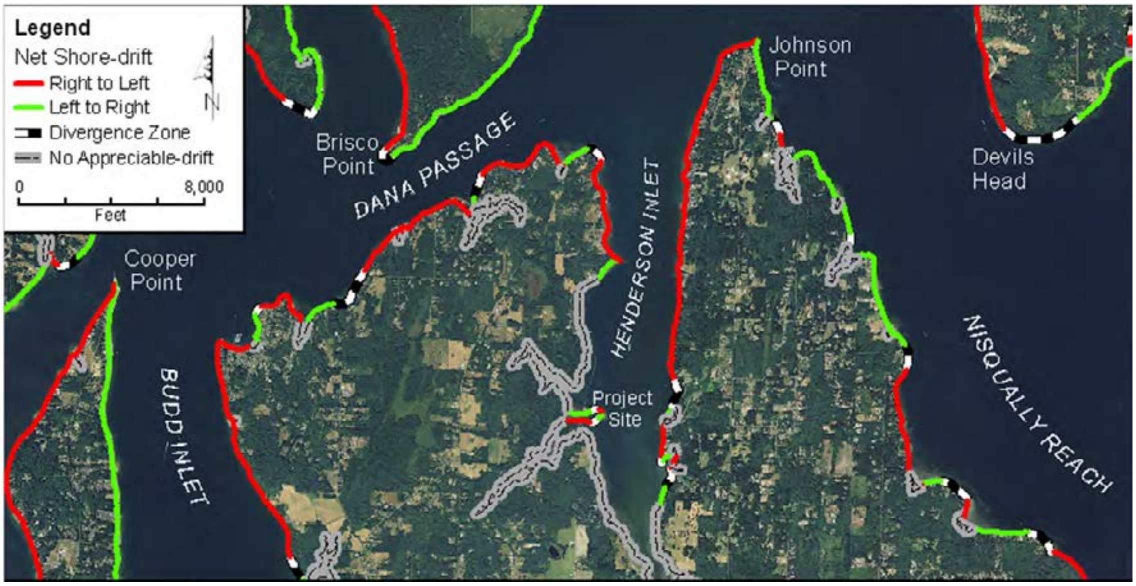
Category	Parameter	Rating	Score	Rationale
Benefits	Removed structures restoring natural processes*	Med	4	The large majority of structures were removed, although not all
	Sediment volume augmented	None	0	Only a small amount of nourishment sediment was included in the design
	Input/exchange of LWD, detritus	High	3	Cross-shore and alongshore structures removed
	Backshore vegetation enhanced	None	0	The project did not include backshore planting, nor is there room to establish a backshore vegetation community
	Marine riparian vegetation enhanced	Med	2	Marine riparian vegetation was preserved and enhanced, but a small area where rock remained could not be planted
	Low-cost and simple installation	High	3	Installation was very low cost and easy to complete with upland access
Impacts	Structures bury backshore & intertidal areas	Low	-1	The remaining portions of the rubble bulkhead prohibit vegetation from growing
	Structures impound littoral sediment	None	0	No impediment to littoral transport remains in place
	Coarser/steeper beach profiles created	Low	-1	Project beach has lower slope but coarser upper beach
	LWD/detritus recruitment reduced	None	0	No impact
	Adjacent end erosion	None	0	No end erosion
	Required maintenance interval	None	0	No maintenance has been required
Design-specific benefits	Restored cross-shore connectivity	High	3	Dramatic increase in connectivity in project area
	Reclaimed or created backshore/upper intertidal substrate	Med	2	Intertidal and backshore reclaimed from almost entire pool area, still adjusting
Design-specific impacts	Infrastructure threatened	None	0	No infrastructure threatened
	Off-site erosion increased substantially	None	0	No impact
Total			15	

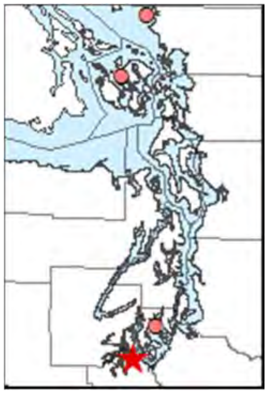
*Scores at double other values (e.g., high=6); all others, none=0, low=1, med=2, high=3

Totaling the above scores, benefits equal +17 points and impacts equal -2 points, for a final combined score of +15.

WEYER POINT – Bulkhead Removal (2005)

Waterbody: Henderson Inlet	Shoretype: Bluff-backed beach	Net Shore-drift Cell: TH-4-8	Direction: Convergent at Weyer Point
Project Elements: Bulkhead and upland structures (house and sheds) removal, native vegetation planting, large wood addition in uplands		Objective: Remove coastal erosion-control structure as component of site restoration for Natural Resources Conservation Area	
Fetch: 5.8 mi N Wave Energy: Low Aspect: East	Land Use: Residential/Industrial (log loading yard) MHHW: +14.2 ft MLLW Toe Elev: +12.3–15.4 ft MLLW	Structure: None (removed) Setback: n/a Risk Index: 8	Benefit Index: +14 Impact Index: 0 Total BI Index: +14





Project Site as red star with dots showing all other bulkhead removal projects Sound- wide.

Project Background

The site is located on the northeast- and southeast-facing portions of a point of land projecting eastward into Henderson Inlet. Its shoreline and uplands are part of a large land parcel acquired by the Washington Department of Natural Resources (DNR) for a Natural Resources Conservation Area (NRCA). It is managed for unique wildlife and habitat features, including the largest maternity bat roost in Washington State, a haul-out area for harbor seals, and nesting and breeding areas for waterfowl. Previously the site served as a log loading and transfer yard for Weyerhaeuser Company. The NRCA includes 90 acres of subtidal land leased by DNR to The Nature Conservancy to restore the Olympia oyster.

From 1928 to 1985, the area west of the treatment area was operated as a Weyerhaeuser log dump for eventual transfer and transport to lumber mills. From 1930 to 1980, dredging of sediment occurred about every 2 years along the west side of Chapman Bay Pier. Dredged material was placed in open water or along the railroad sidetrack (and possibly adjacent to the bulkhead removal area as fill on and behind the crib walls). In 1988, DNR purchased the uplands, tidelands, and all "improvements" south of the former South Bay Log Dump.

In 2005, DNR removed the house, boathouse, shed, and bulkheads of log, rock, and concrete, and planted native vegetation in the uplands. Along a short section of the southern reach (about 15 ft) where the concrete bulkhead was removed, the bluff was regraded to a gentler slope and planted with willow stakes. A 5-year monitoring plan, including surveying, photography, and sediment sampling, was designed for the shoreline areas of the site and initiated prior to bulkhead removal. Minimal surveying and sediment sampling were done immediately after bulkhead removal; photography continued at various times in the years following removal.

Removal of the concrete bulkhead in progress in 2005 at the western portion of the site.

Log bulkhead at the site in 2005 shortly before removal.

Design

In 2005, DNR removed nearly 250 ft of bulkhead from the shoreline using an excavator transported to the site via an upland dirt road. Materials removed included concrete, pit-run basalt rock, large logs, and other items composing the site infrastructure. Project drawings are sparse and the topographic data was never corrected to accurately represent conditions.

The concrete portion of the bulkhead, located at the southernmost end of the treatment area, was about 25 ft long and 15 ft high. After this was removed, the upper part of the slope in this area was regraded to about 45° and planted with willow stakes. The 60-ft-long pit-run basalt rock section of the bulkhead was underlain by weed cloth. Both rock and weed cloth were removed from the site. The log bulkhead, the longest section of bulkhead removed, was about 115 ft long. It protected the point and extended from the northeast end of the rock bulkhead, around the point, and west along the north side of the point. Behind (landward) of the log bulkhead was an obviously older log crib wall. The large bulkhead logs were removed but the rotting crib wall logs remain embedded in the bluff sediments (primarily fill). The crib walls may originally have been built to support dredged material placed there to extend the point of land north and east to create the home site.

No vegetation was planted on the bluff face. Nonnative cherry laurel (*Prunus laurocerasus*) growing at the crest of the bluff was cut just before or during the restoration effort.

Removal of the bulkhead was originally scheduled for year 3 of the planned restoration work, but was moved to the first year for better logistical coordination, ultimately saving project money. The restoration objectives were to make habitat improvements, remove a house that invited ongoing vandalism, and reduce liability risks at the site. A boathouse and shed were also removed from the site.

A document (Thom et al. 2007) prepared for the Puget Sound Nearshore Ecosystem Restoration Program noted the following about the Weyer Point project:

Pre-restoration monitoring included a multi-agency collaboration effort to collect data and analyze physical site characteristics (Gerstel 2005). Monitoring efforts included monitoring of vegetation, sediment analysis, elevation profiles, and invertebrate sampling (Michelle Zukerberg, pers. comm. July 2007). A monitoring plan was developed for the Woodard Bay-Weyer Point restoration site. Aside from on the ground photo documentation, the inability to adequately fund post-restoration monitoring has prevented most of the monitoring action items from being implemented (Michelle Zukerberg, pers. comm. July 2007).

The Woodard Bay-Weyer Point monitoring plan serves as a template for other projects in that it outlines project objectives as well as questions intended to be answered at multiple time scales. The monitoring protocols are supplemented with specific methods for implementing sampling efforts. Further, the monitoring plan was embedded with a timeline to streamline sampling efforts following restoration actions (Gerstel 2006).

Oblique view of project site prior to bulkhead and structure removal. Dashed black line shows the approximate original shoreline. Solid blue, brown, and purple lines delineate the concrete, rock, and log sections, respectively,of bulkhead planned for removal. Note overhanging concrete pad just left of the pit-run rock bulkhead and waterward of the house. This platform atop the concrete bulkhead was the site of the boathouse.

Weyer Point restoration site plan provided by DNR showing outline of the larger site, which included structure removal, weed control on 17 acres of riparian habitat, and native vegetation installation areas. Red arrow indicates site location.

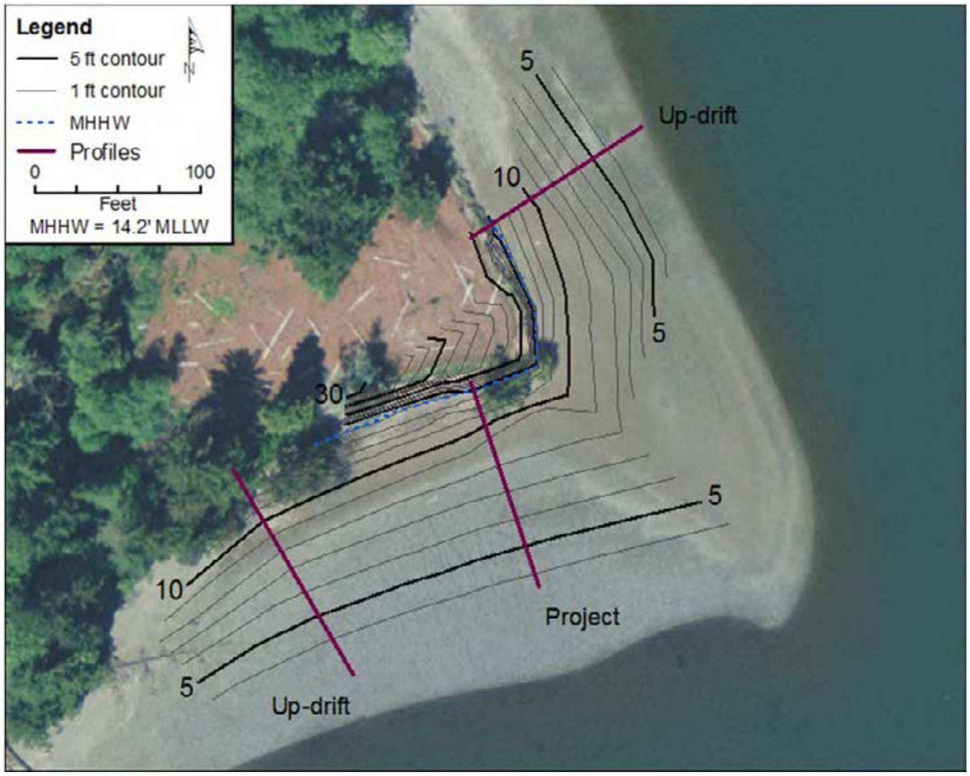
Current Conditions

Technique Condition – Erosion of the unprotected bank has continued, exposing fill and other unconsolidated sediments, both likely originating from nearby, either as dredged material or material excavated during road and railroad construction. The erosion also exposed remnants of the log crib wall behind the rock and log bulkheads. As the surveyed beach/bluff profiles show, the beach rose in elevation and the bluff face retreated between initial monitoring in 2006 and that done for this project in March 2012. In light of the observable erosion of the bluff face, this would be expected. What was unexpected was the increase in height of the bluff, suggesting an error in survey data or methods between the two monitoring events.

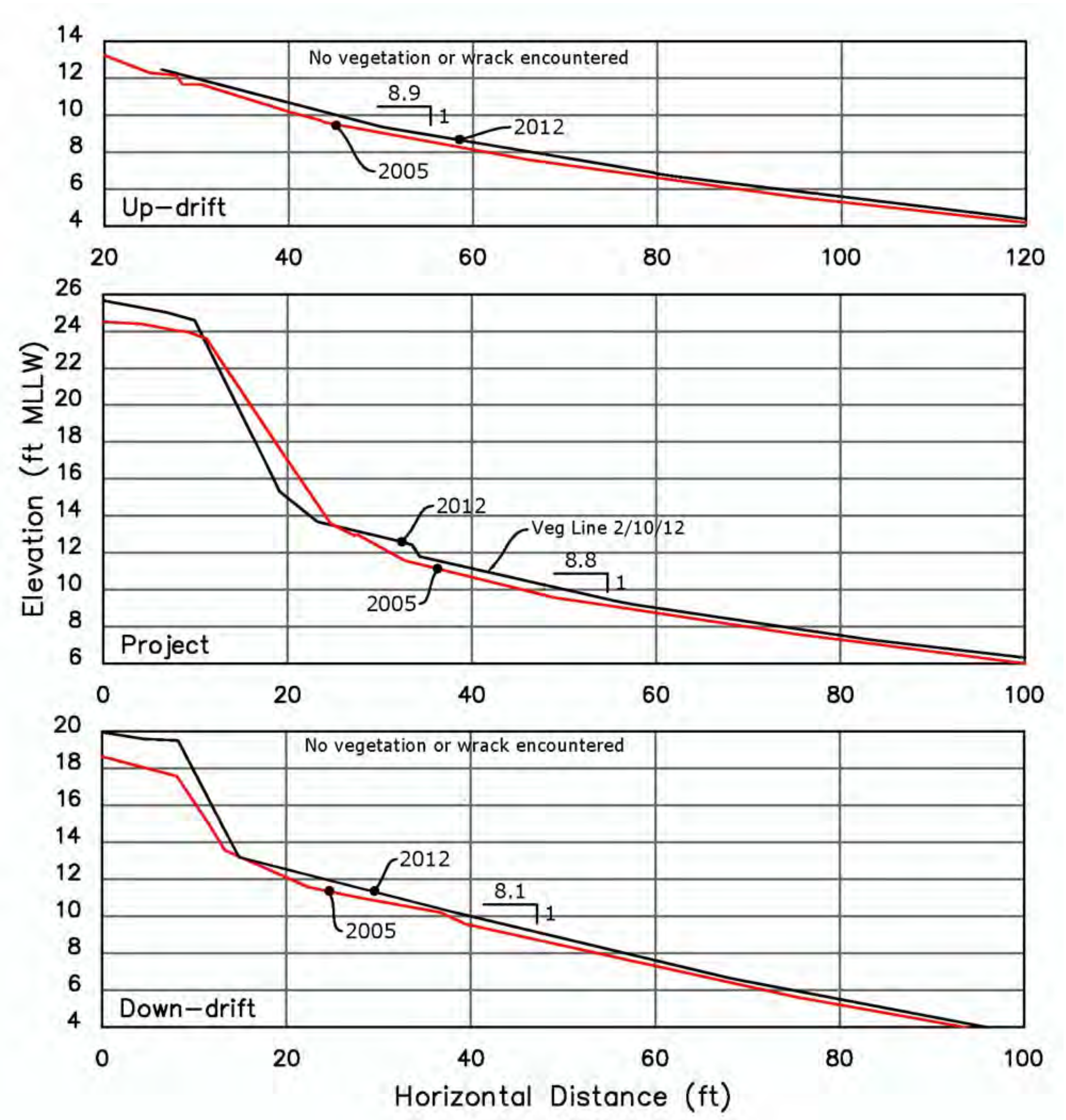
Upland Threats – Because the anthropogenic structures have all been removed, there are no threats to the upland area other than to restoration plantings near the edge of the bluff. Plantings consisted of alder, fir, and other typical native plants. Plantings that were part of restoration work may be compromised as the bluff continues to retreat, at least as far back as the suspected original shoreline. Those that remain rooted long enough will provide organic debris and possibly large wood to the beach as they fall.

Beach Characteristics – Adjacent to the eroding bluff/bank and northeast of the point, beach sediments were sandy and unconsolidated (very loose). A spit of sand extended northeastward at low tide, a consequence of convergent drift directions at the point. Patches of pickleweed were growing at the base of the south side of the point, where about 1 to 1.25 ft of sand over cobbles and gravel. Seaward of mid-low tide level was a sharp transition to fine tidal silt and mud. Minimal backshore existed along portions of the southeast-facing bluff, with none observed along the northeast-facing bluff.

Adjacent Shores – Up-drift, the modified shore consisted of an old railroad grade and access-road grade, both of which were now vegetated. Down-drift was a mature forested bluff about 6 to 8 ft high. Undercutting of the surface soils exposed dense coarse sands near the south end of the treatment area, likely a lodgement till.



Aerial view of project site showing landform, vegetation, and man-made features identified by GPS locations. Taken shortly after restoration work was completed, photo shows large wood scattered in the uplands where native vegetation was planted.



Project profiles measured immediately after bulkhead removal (2005) and during the 2012 site visit.

Aerial view of project site showing landform, vegetation, and man-made features identified by GPS. Taken shortly after restoration work was completed, photo shows large wood scattered in the uplands where native vegetation was planted.

Although the adjacent reaches on either side of the treatment area are technically up-drift of it, for the purposes of discussion and dominant drift influence, the up-drift reach was considered to be the northeast-facing portion of the bluff beyond the treatment area, and the down-drift reach the southeast-facing portion of the bluff. Both up- and down-drift reaches showed little change in sediment distribution and type. A qualitative increase in the areal extent and thickness of the sand observed in the treatment reach was clearly related to the retrogression of the bluff face. During the March 2012 site visit, the sand appeared to be burying some of the pickleweed cover.

The change from coarse sediments of cobble and pebble up- and down-drift of the treatment reach to finer sand and silt at the treatment reach were interpreted to be a result of shoreline modifications that created the extended Weyer Point. The photo in the design section shows the approximated original shoreline with a dashed black line.

The reach from which the concrete bulkhead (left half of photo) and the pit-run rock bulkhead (right half of photo) were removed. Note the willow growing from the left portion of the bank. Here, the bluff was regraded to a gentler angle and planted with willow stakes. The extent of pickleweed, visible growing in front of the right portion of the bank, appears to have been slightly reduced through burial by eroding sediment since bulkhead removal.

Two units of fill burying the log crib wall along the portion of the bluff where the pit-run rock bulkhead was removed. The lower fill unit appears to be dredged material composed of fine silt and tidal muds with shell fragments. The upper fill unit appears to be the sand/silt component of coarse outwash excavated next to the treatment site.

Reach where log bulkhead was removed. Exposure is towards the north and prevailing winds. Dark roots are remnants of a laural hedge that lined the top of the bluff and that is shown alive in pretreatment photos. This hedge was cut before or during the initial restoration effort.

Remnants from rock bulkhead as well as accreted sand from eroding bank, some of which might also be washed from coarser material west and up-drift of the treatment site. These sediments have buried the upper intertidal extent of the pickleweed.

Comparison of beach surface sediment at project and adjacent sites. n/a indicates the location was not present for sampling.

Location	Backshore	Difference	Upper Intertidal	Difference
Up-drift	MEDIUM PEBBLE, cobble, coarse pebble	-	MEDIUM PEBBLE, coarse pebble, cobble	coarser
Project site	n/a	-	SAND, fine pebble, medium pebble	Increased sand thickness
Down-drift	MEDIUM PEBBLE, sand, coarse pebble	-	COARSE PEBBLE, cobble, medium pebble	coarser

Performance

The bulkhead removal project has been successful to the extent that the majority of the structures were removed. Scoring potential benefits and negative impacts of the Weyer Point treatment considered treatment objectives and longer term site-management history. Bulkhead removal was a component of overall site restoration, which included upland structure removal and native vegetation planting. Removal of the bulkhead revealed a deteriorating log crib structure that extended into the bluff at least 10 ft. The crib structure was likely constructed well before the bulkheads to fill (possibly with local dredged material) and expand the point eastward and southward. The crib structure is not scored as part of the treatment, but is considered here as part of the bluff or fill sediments now being eroded. Although a backshore may have existed prior to filling, the existence of the fill precludes reestablishing a backshore until fill sediment is removed far enough landward through erosion. Scoring of the Weyer Point treatment focused more on the longer and more exposed east-facing portion of the bluff, but considered the full treatment length.

Project performance scoring.

Category	Parameter	Rating	Score	Rationale
Benefits	Removed structures restoring natural processes*	Med	4	Majority of structures removed; some remain along with some fill
	Sediment volume augmented	Med	2	Feeder bluff sediment was reconnected to the nearshore from moderately low-elevation bluffs
	Input/exchange of LWD, detritus	High	3	Structure removal allowed unobstructed exchange of LWD and detritus
	Backshore vegetation enhanced	None	0	No backshore vegetation was planted, nor was there room to reestablish backshore vegetation
	Marine riparian vegetation enhanced	Low	1	Planting was very limited on the bluff face, and erosion has precluded broad vegetation reestablishment
	Low-cost and simple installation	Low	1	Removal was not complicated but involved several stages and manual labor
Impacts	Structures bury backshore & intertidal areas	None	0	Bulkhead was removed but crib wall, which appears to be protecting a portion of remaining fill, was not
	Structures impound littoral sediment	None	0	No major impoundment of natural bluff sediment
	Coarser/steeper beach profiles created	None	0	Project beach profiles were slightly less steep than reference site
	LWD/detritus recruitment reduced	None	0	Little backshore room available
	Adjacent end erosion	None	0	No end erosion observed
	Required maintenance interval	None	0	No maintenance anticipated for over 30 years
Design-specific benefits	Restored cross-shore connectivity	Med	2	Armor removal from the moderate-elevation bank, with some LWD in the local system
	Reclaimed or created backshore/upper intertidal substrate	Low	1	Minor backshore area
Design-specific impacts	Infrastructure threatened	None	0	No infrastructure located on site
	Up- or down-drift erosion increased substantially	None	0	No adjacent erosion and not a direct issue for this site, which is at end of 2 drift cells
Total			+14	

*Scores at double other values (e.g., high=6); all others, none=0, low=1, med=2, high=3

Totaling the above scores, benefits equal +14 points and impacts equal 0 points, for a final combined score of +14.

BIRCH POINT – Bulkhead Removal (2000)

Waterbody: Strait of Georgia	Shoretype: Bluff-backed beach	Net Shore-drift Cell: WH-2-4	Direction: Northward to Semiahmoo Spit
Project Elements: Removal of shoreline armor of gabion rock baskets		Objective: Remove unpermitted bulkhead protruding into intertidal zone at feeder-bluff shore	
Fetch: 33.5 mi WSW Wave Energy: Very high Aspect: West	Land Use: Residential MHHW: +9.2 ft MLLW Toe Elev: +7.6 ft MLLW	Structure: Single-family house Setback: 40 ft Risk Index: 35	Benefit Index: 18 Impact Index: -3 Total BI Index: +15

Project site as red star with dots showing all other bulkhead removal projects Sound-wide.

Project Background

The site is at the base of an approximately 80-ft west-facing bluff in a very-high-wave-energy regime. The gabion bulkhead was constructed without permits at the base of this bluff prior to 1994. The bulkhead was removed in 2000, as ordered by Whatcom County and the Washington Department of Fish and Wildlife (WDFW), following several legal appeals, all of which were lost by the owner.

The protrusion of the bulkhead into the upper intertidal zone created an area of erosion to the north (down-drift), extending about 20 horizontal ft landward and creating a moderate-sized backshore area where none had existed before. The erosion propagated upslope for a considerable distance. The erosion and resulting backshore allowed for room to install an experimental project with large wood anchored immediately north of the bulkhead-removal assessment area (also assessed in this document).

The upland area of the site hosts a single-family residence, patio, shed, driveway, and tram to the beach. The site has a history of bluff instability and bluff-face recession since site development. Shallow debris-flow-type landslides occurred periodically prior to bulkhead installation. Bluff geology is characterized by a sequence of compact glacial diamict (glaciomarine drift) overlying less dense sand, silt, gravelly sand, and sandy gravel. The bluff face has a moderate amount of seepage emanating from different elevations, with the greatest amount discharging mid-bluff through gravel lenses. Attempts to collect seepage water with a limited number of horizontal drains (prior to installation of the gabion basket bulkhead) were largely unsuccessful. Earlier attempts to revegetate the steep bluff face with Mugo pines and other species were not successful, as landslides caused the loss of almost all of these plantings. A plan to install geofoam blocks beneath Geoweb® (interconnected polystyrene cells filled with soil, sand, or other material) atop the bluff face was rejected by Whatcom County in 1996.

Gabion basket bulkhead in 1999 looking east. Note poorly vegetated bluff face, aerial tram, and lower gabions failing to south (right).

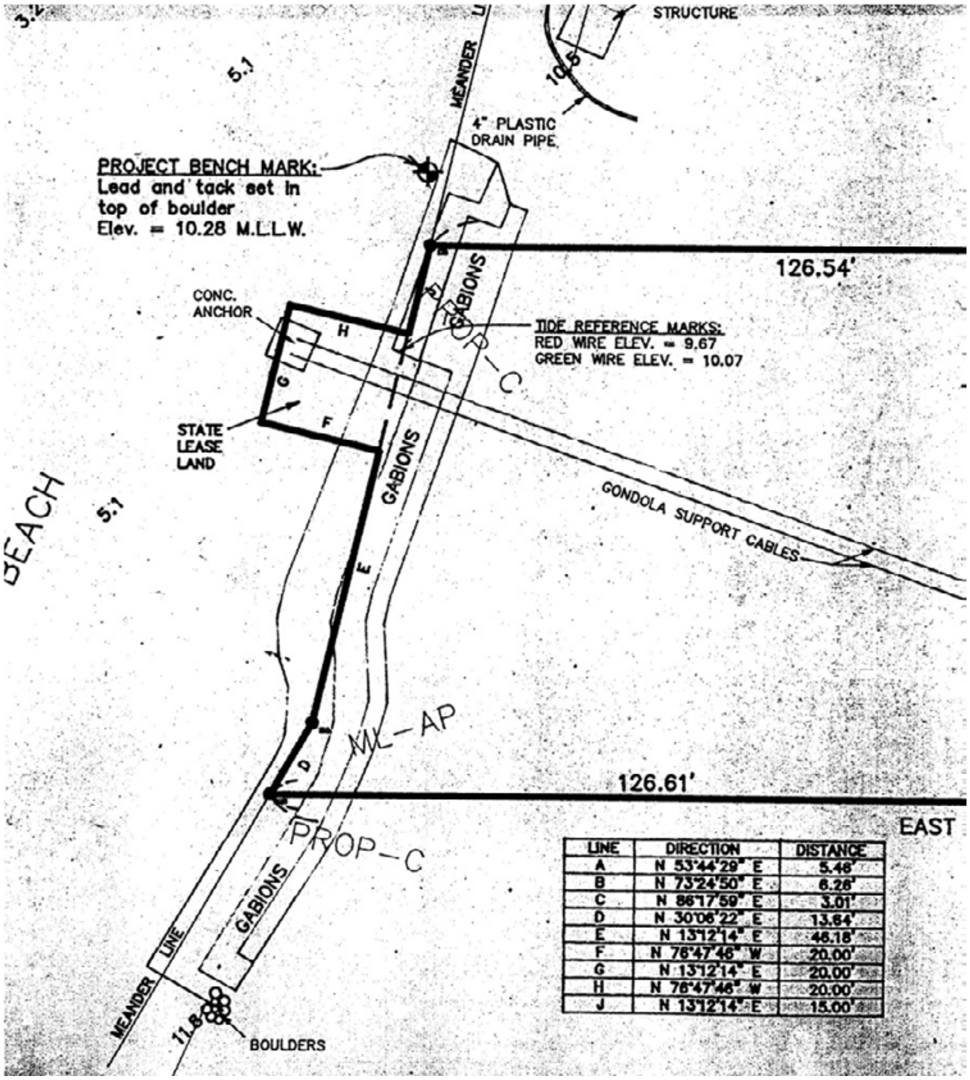
Note recently eroded bluff immediately north of the bulkhead due to end effects/wave refraction around the structure in 1999. Person above boulders for scale.

Design

The gabion (rock-filled wire baskets; approximately 6 lifts) bulkhead was constructed along 150 ft of the bank toe. The bulkhead extended approximately 96 ft across the full width of the subject property and along portions of adjacent properties to the south (36 ft) and the north (18 ft). It was installed without permits using cobbles collected from the subject and adjacent beaches. WDFW and Whatcom County required removal of the bulkhead after enforcement actions begun in 1999 culminated in the loss of several legal appeals by the owner. This site was part of a shoreline management unit that included Semiahmoo Spit, a 1.4-mi-long landform that protects all of Drayton Harbor from high-energy waves and has had critical erosion problems in the past.

The southern portion of the area from which the bulkhead was removed did not receive any treatment other than the removal, the subject of this assessment. Following serious end erosion (up to 20 ft landward) caused by the gabion wall, the northernmost portion of the removal area was treated experimentally with an installation of anchored large logs, the subject of a separate assessment for this project. The 25-ft-long overlap area of the bulkhead removal and the log project area were not considered in the assessment.

The removal of the gabion bulkhead was carried out by legal agreement and accomplished from land by cutting open and removing gabion baskets and leaving the cobble contents on the beach. The cobbles had originally been harvested from the beach, so they were simply redistributed back onto the beach on all 3 of the adjoining properties. Not all gabion baskets from the lower portion of wall were removed, and remnants of the wire mesh were still easily visible in the beach surface during the site visit for this project.



LINE	DIRECTION	DISTANCE
A	N 53°44'29" E	5.46'
B	N 73°24'50" E	6.26'
C	N 86°17'59" E	3.01'
D	N 30°06'22" E	13.64'
E	N 13°12'14" E	46.18'
F	N 76°47'46" W	20.00'
G	N 13°12'14" E	20.00'
H	N 76°47'46" W	20.00'
J	N 13°12'14" E	15.00'

Project design drawing.

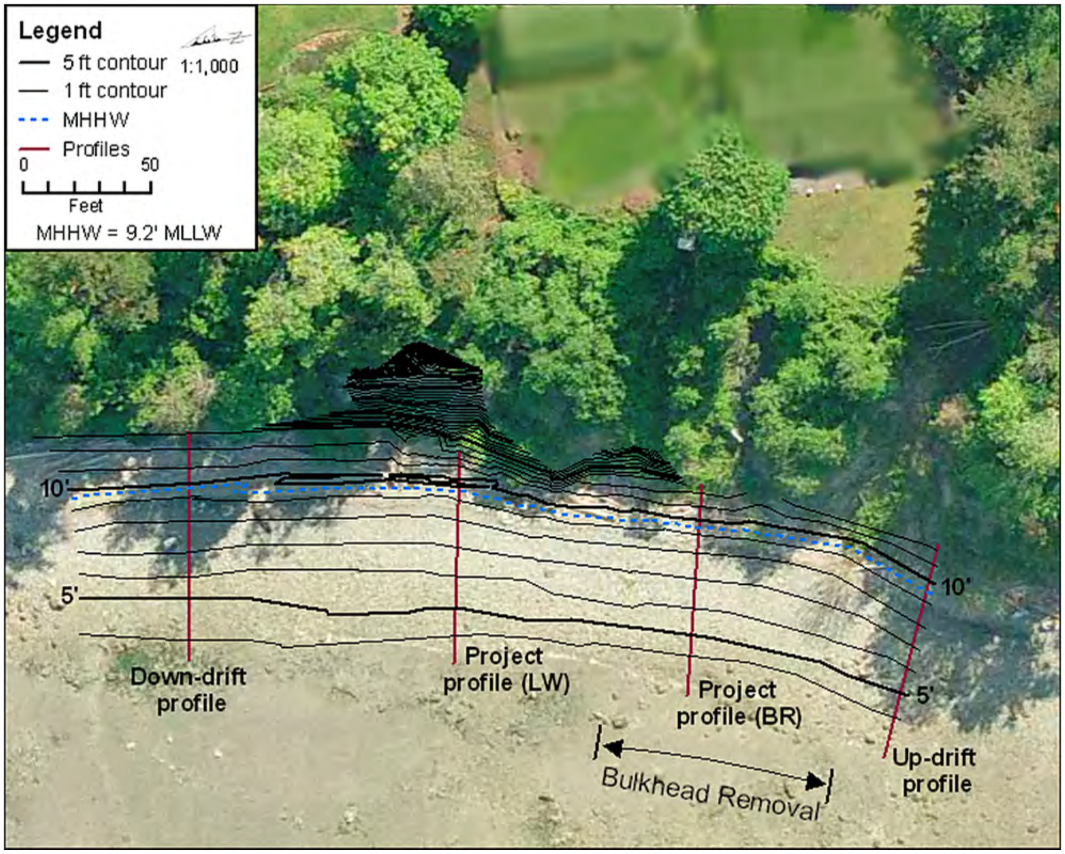
Current Conditions

Technique Conditions - Most of the gabion structure had been removed, but pieces of broken wire mesh from the lower tier of baskets were still visible in the upper intertidal beachface. Prior to removal, the gabion wall was failing after only 6–7 years.

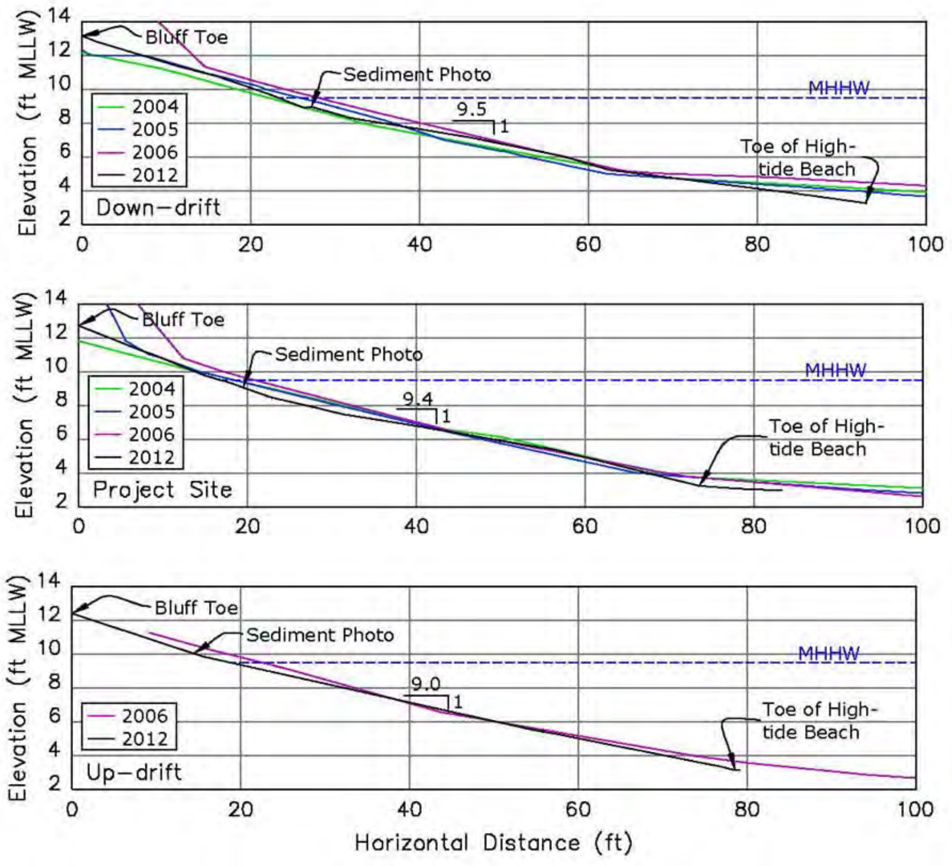
Upland Threats - Landsliding was continuing in places along the bluff through a process of undercutting and block-topple failures of the upper portions of the bluff. Large chunks of concrete rested on the slope and at the base of the slope toe in the area of the cable tram. To the south of the tram, groundwater seepage appeared to be incising into the sediments in the upper third of the bluff at a possible geologic contact, forming a channel that drained to the beach. The house at the top of the bluff has an appropriate setback distance under current climatic and erosion conditions, although the tram's top station may be at risk as the bluff crest retreats over time.

Beach Characteristics - The beach sediments were characterized as a mix of sand, gravel, cobble, and boulder, generally reflecting the larger fraction of sediment exposed in the bluff. The sand was likely derived from the lower portions of the bluff. Finer sediment, including silt from the upper unit and silt and clay from the diamicton, has presumably been winnowed out by wave action and moved down-drift (northward.)

Adjacent Shores - Along the adjacent shore south and north (up- and down-drift, respectively) of the removal area, numerous small and large toppling failures and debris flows persisted that are typical of the instability of the slopes along this reach. This included numerous landslides (approximately 6), which had occurred 1 to 2 years prior to the new fieldwork. Profiles of the upper intertidal beach slope in the bulkhead-removal area were very similar to those in the down-drift (large wood) site. The upper intertidal beach apparently has lowered since 2006 to a profile consistent with that measured during 2005 monitoring, but not to the extent of that shown in the 2004 monitoring data. The current beach profile at the treatment area suggests the removal by waves of landslide debris surveyed during monitoring in 2005 and more extensively in the following year.



Topographic map of conditions during the 2012 site visit.



Beach profiles from monitoring and the 2012 field visit.

Gabion bulkhead removal area in 2012. Note extensive recent landslides both on site and farther south (up-drift), as well as remaining concrete debris.

Gabion removal area in 2012 showing both immature vegetation and recent slope failures.

Comparison of beach surface sediment at project and adjacent sites. n/a indicates the location was not present for sampling.

Location	Backshore	Difference	Upper Intertidal	Difference
Up-drift	n/a	-	SAND, medium pebble, fine pebble	finer
Project site	n/a	-	MEDIUM PEBBLE, sand, cobble	-
Down-drift	MEDIUM PEBBLE, cobble	-	SAND, granule, fine pebble	finer

Performance

The bulkhead removal project has performed as would be expected within a very-high wave energy feeder bluff site with accelerated erosion and slope failures that resulted in substantial augmentation of sediment for the drift cell. Likewise, a moderate area of upper intertidal and backshore beach has been uncovered. This project is an example of

- A poorly designed bulkhead (placed low, angular projecting ends, subject to failure) that caused severe down-drift erosion
- Bulkhead removal to restore feeder bluff connectivity and sediment supply at a high-sediment-input bluff
- "Deferred erosion" after removal, with bluff toe erosion and slope failures in the removal area
- Shoreline codes holding up to multiple legal appeals and successful enforcement led by Whatcom County

The scoring of this project was based on the objective of removing a structure (gabion bulkhead) installed in violation of WDFW and Whatcom County regulations, as well as on the general intent of these regulations to maintain bluff sediment supply/connectivity. Evaluation of potential beneficial and negative impacts of the treatment also considered whether the removal of the structure was complete and whether natural processes were restored along the treatment area and adjacent portions of the bluff. Due to the very unstable nature of this bluff, bluff failures may or may not have occurred during the existence of the gabion structure. Potential benefits and negative impacts of structure removal were considered in light of height and instability of the bluff. Scoring assumed that with the expected continued retreat of the bluff crest, the landowner will likely want to mitigate bluff retreat in some way within the next 10 to 20 years.

Project performance scoring.

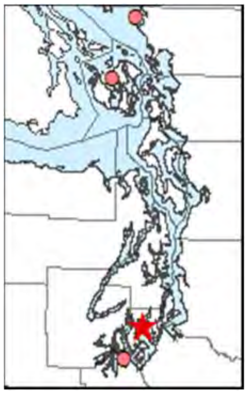
Category	Parameter	Rating	Score	Rationale
Benefits	Removed structures restoring natural processes*	High	6	All large structures removed, feeder bluff function restored
	Sediment volume augmented	Med	2	Both alongshore and cross shore sediment augmented through armor removal
	Input/exchange of LWD, detritus	Med	2	Removal has allowed for both alongshore and cross-shore exchange
	Backshore vegetation enhanced	None	0	No enhancement of backshore vegetation in removal area
	Marine riparian vegetation enhanced	None	0	No enhancement of marine riparian vegetation in removal area
	Low-cost and simple installation	High	3	Very straightforward removal completed by hand
Impacts	Structures bury backshore & intertidal areas	None	0	Improvement by removal, however portions of the gabion baskets were not removed on upper beach
	Structures impound littoral sediment	None	0	No impact for sediment impoundment
	Coarser/steeper beach profiles created	None	0	Beach profiles broader after removal and not steeper
	LWD/detritus recruitment reduced	None	0	Recruitment enhanced with removal
	Adjacent end erosion	None	0	No end erosion caused by removal
	Required maintenance interval	Med	-2	Because a house is present above with a tram near the bluff crest, erosion may necessitate some sort of action in 15 years
Design-specific benefits	Restored cross-shore connectivity	High	3	Moderately high bluff has been active
	Reclaimed or created backshore/upper intertidal substrate	Med	2	Moderate amount of both upper intertidal and backshore recovered
Design-specific impacts	Infrastructure threatened	Low	-1	Removal has caused erosion and slope failures to accelerate, potentially threatening tram
	Up- or down-drift erosion increased substantially	None	0	No negative impact
Total			+15	

*Scores at double other values (e.g., high=6); all others, none=0, low=1, med=2, high=3

Totaling the above scores, benefits equal +18 points and impacts equal -3 points, for a final combined score of +15.

KOPACHUCK STATE PARK – Bulkhead Removal (2006)

Waterbody: Carr Inlet	Shoretype: Bluff-backed beach	Net Shore-drift Cell: PI-11-31	Direction: Northeastward
Project Elements: Bulkhead removal with associated slope reshaping and vegetation planting		Objective: Remove creosoted wood bulkhead	
Fetch: 3.4 mi SW Wave Energy: Medium Aspect: West-northwest	Land Use: State park MHHW: +13.4 ft MLLW Toe Elev: +14.8 ft MLLW	Structure: None Setback: n/a Risk Index: 15	Benefit Index: 17 Impact Index: -3 Total BI Index: 14



Project Site as red star with dots showing all other bulkhead removal projects Sound- wide.

Project Background

This site, a relatively undeveloped northeast-trending reach, is dominated by a large deep-seated landslide within the typical central Puget Sound sequence of continental glacial deposits. Outwash sand, gravel, and cobble overlie a dense glaciolacustrine silt on or within which the sequence is sliding. Characteristic of such landforms, groundwater discharges as springs and seeps along geologic contacts, developing into small surface streams that discharge onto the beach. In one or two areas seeps saturate sediment at the toe of the slide, creating small fine-grained earth flows.

The removal of a wooden bulkhead on the site was prompted both by the goal of the Washington Department of Natural Resources (WADNR) to eliminate creosote-treated wood from the marine environment and by the state of disrepair of the bulkhead. The bulkhead was likely installed in response to wave-driven erosion at the toe of the low-bank slope. However, collapse of the bulkhead may not have been a consequence of the landward encroachment of wave action, but rather a result of land movement seaward via deep-seated landsliding. Although erosion of the slope toe is likely occurring to some extent, the forward lean and collapse of the creosoted-wood bulkhead mostly likely resulted from the landslide toe pushing it over to encroach into the upper intertidal zone.

The current shoreline is characterized by a series of gravel bars likely formed as sediment deposited by deep-seated landsliding is transported northward. Additional fine to coarse sediment is derived from eroding updrift bluffs located in the divergence zone south of the project area and beyond the limits of the landslide.

Wooden bulkhead mostly collapsed to expose fill and landslide deposits in 2006. Note waterward lean.

Bulkhead looking north in 2006.

Design

In fall 2006, WADNR and Washington State Parks partnered to remove this failing creosote-treated wooden bulkhead from the tidelands along 200 ft of the Kopachuck State Park shoreline. This was the southwestern of 2 reaches of shore that had shore protection installed in approximately 1989. The northeast reach of shore protection was not removed (see site plan). The 5 ft high bulkhead was built in 10-ft sections using 3 by 12 in lagging, which was also treated with creosote. Filter fabric was installed immediately landward of the lagging. The 30 piles were treated creosote, each 7–9 ft long. Piles were driven into the beach and also tied into the bank with 1.5 in steel anchors.

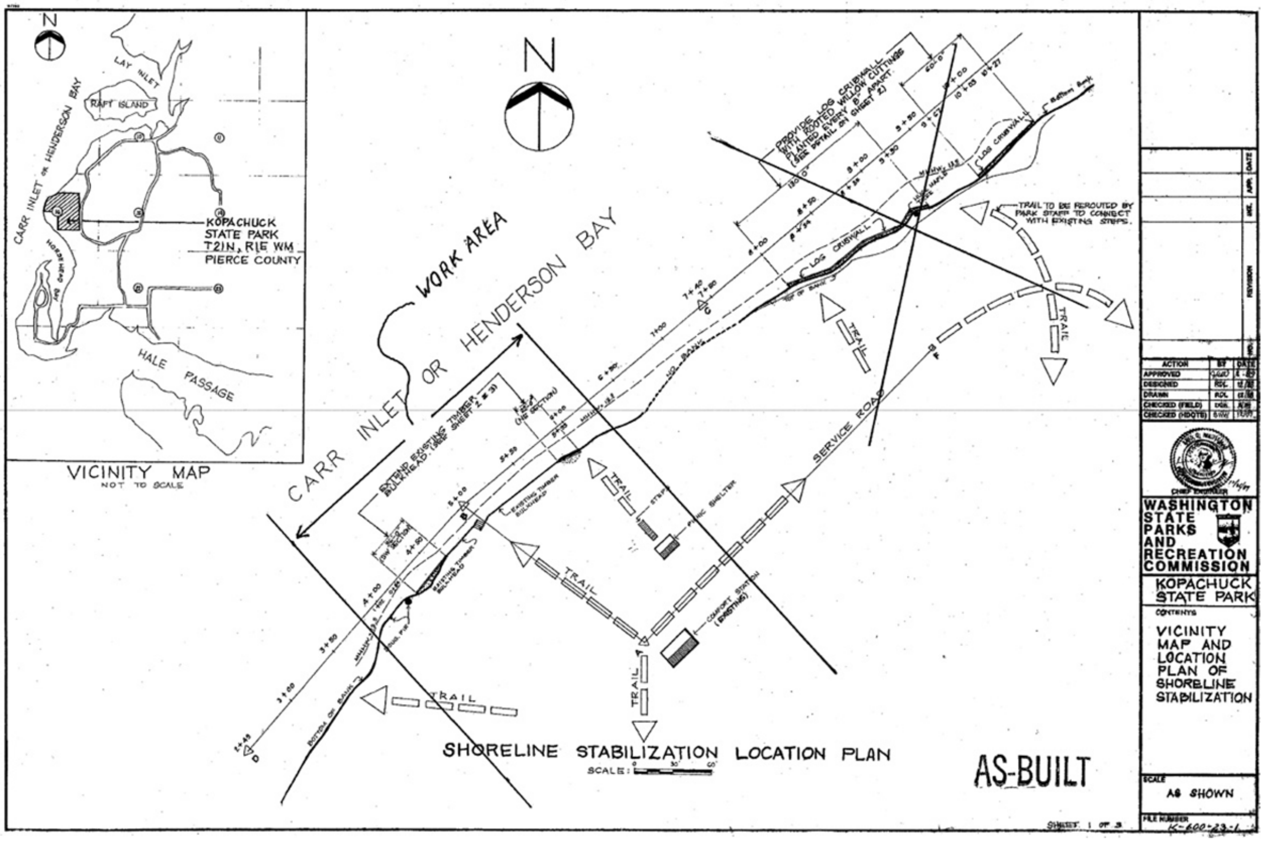
The goals of the project were to

- Remove creosoted wood from the marine environment
- Allow for the naturally occurring deep-seated slope instability to provide sediment to the beach system.

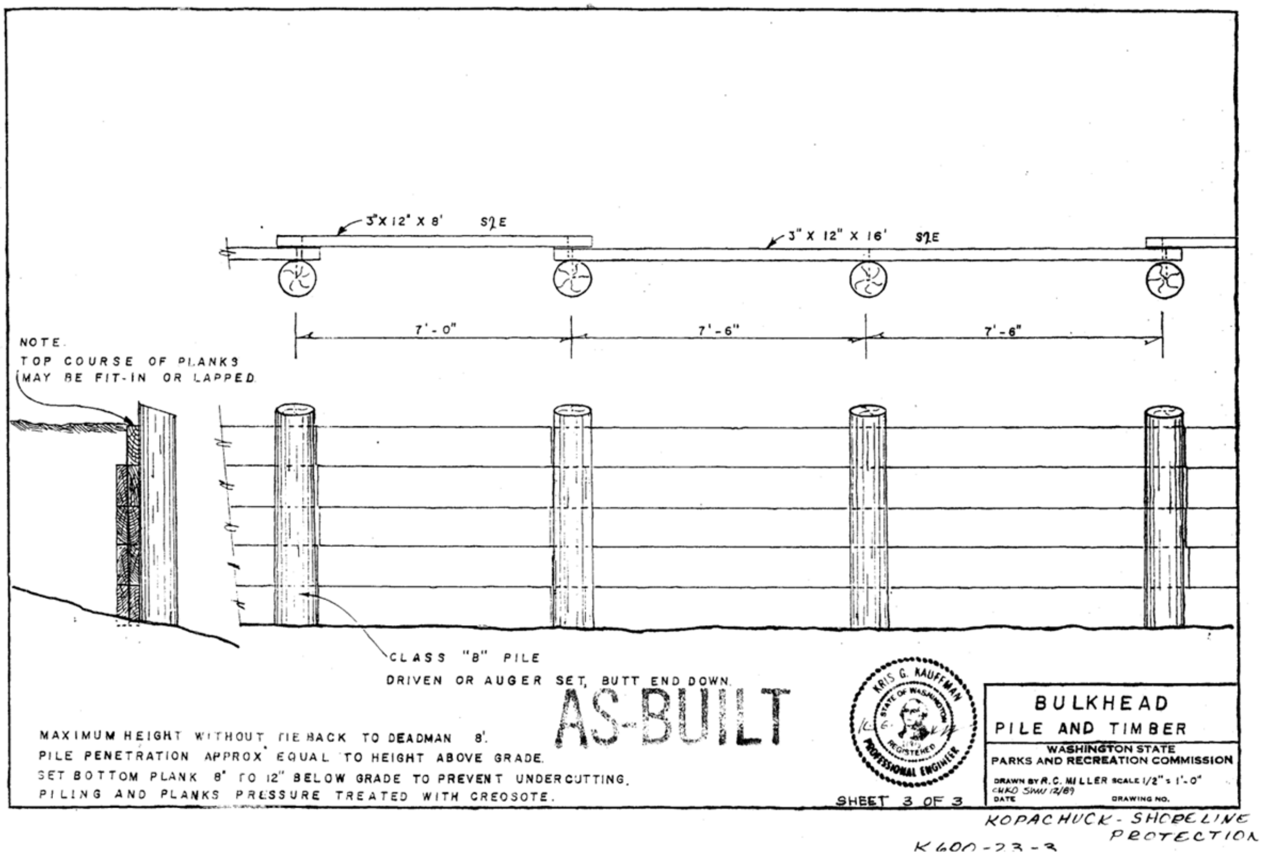
The bulkhead removal was a land-based project using an excavator. Tieback cables and anchors were also to be removed from the bank, although there are no “as-built” drawings for the removal to verify that this was done. For the most part, no vegetation was planted except for reseeding of grass damaged by equipment in the bulkhead removal. Only one area of shoreline bank, slightly north of the picnic area, appeared to have been planted with willow.

Photo looking north taken shortly after the bulkhead was removed looking northeast. Quarry spall was left on site. The steep bank was regraded and seeded with grass.

Picnic area in 2012 where bulkhead was removed, looking northeast. Regraded slope has since been eroded. Large wood is naturally recruiting, and sand and gravel are accumulating up-drift of the large wood. Some of the remaining natural log bulkhead is visible down-drift (north) of the treatment area.



Sheet 1 of the 1989 as-built drawing for creosoted wood bulkhead from Washington State Parks.



1989 as-built drawing for creosoted wood bulkhead from Washington State Parks.

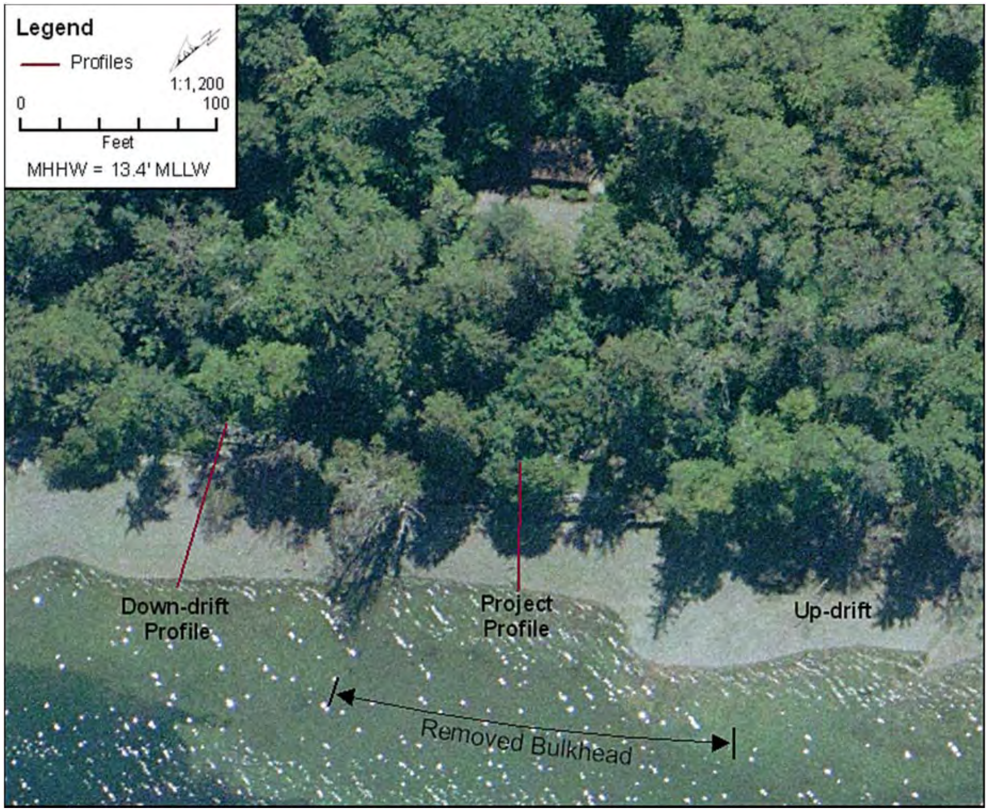
Current Conditions

Technique condition: There has been no development on this site except for limited park infrastructure such as access roads, parking lots, trails, foot bridges, and restrooms. Cracks in pavement and evidence of recurring repairs to foot trails and bridges pointed to continuing landslide movement, tree fall, and high creek flows. Active extensional cracks were located near and downslope of the restroom facility, trails, and picnic platform on the lower landslide bench. Surface streams and springs were abundant on the upland slopes. State tree experts reported diseased trees ("laminated root rot") throughout the upland forest, which forced closure of the park's campground. Removal of the bulkhead appeared to have allowed more natural cross-shore sediment transport and input of large wood from the upland forest. Erosion had reclaimed some of the old fill and slide sediment, and also re-exposed an even older concrete boat ramp. Some portions of a log crib wall remained along the northern portion of the beach access area, just south of the wooden steps. It appeared that erosion of the slope toe was continuing from both wave action and active landslide movement. The toe had liquefied in places where natural springs or corrugated pipes from upland facilities discharged within the bank at the shoreline. The picnic area was smaller, and access to the beach was generally via a 3 to 4 ft vertical bank. Stairs that remained at the north end of the lower slope bench were in need of repair.

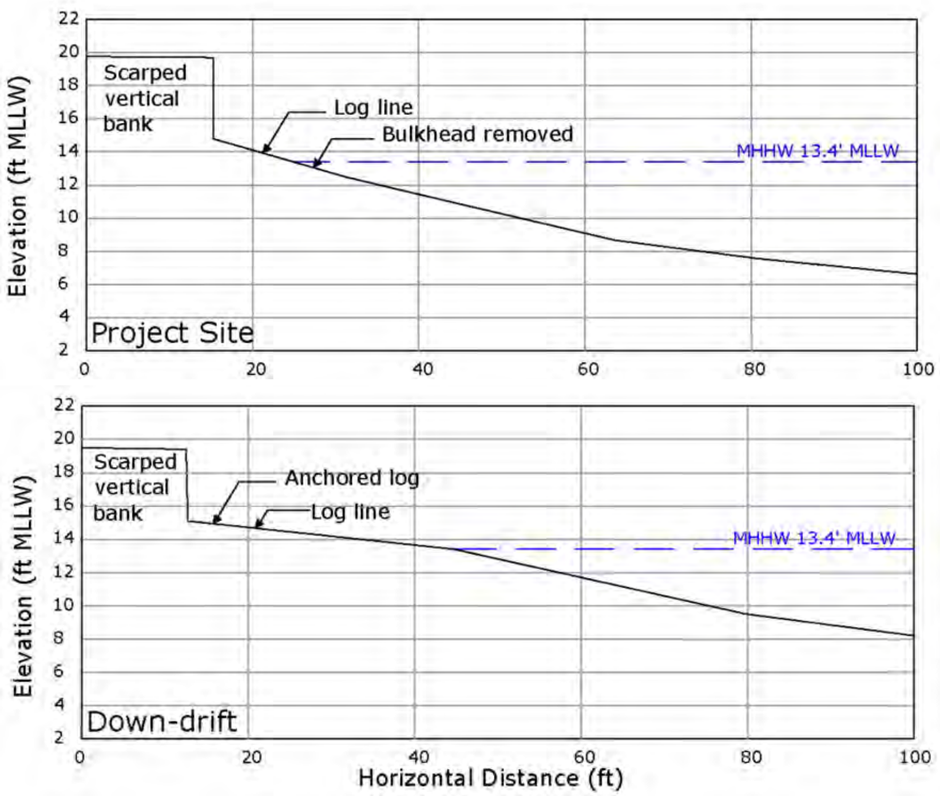
Upland threats: Threats to trails, primitive roads, the picnic area, and the restroom continue as a consequence of landslide movement. Tension cracks were obvious and expanding in the bench of the lower slope immediately landward of the beach.

Beach characteristics: The surface of the beach was characterized by coarse cobbles and small boulders at the south/updrift end of the project area. Surface grain size generally decreased northward, ending in the sand- and gravel-dominated curved accretionary spit (see photos). Uplift of the beach caused by the rotational movement of the landslide toe exposed dense silt and clay in the upper interidal zone. Farther seaward, this geologic unit was overlain, although likely not very thickly, by shore-transported sand, gravel, and cobbles.

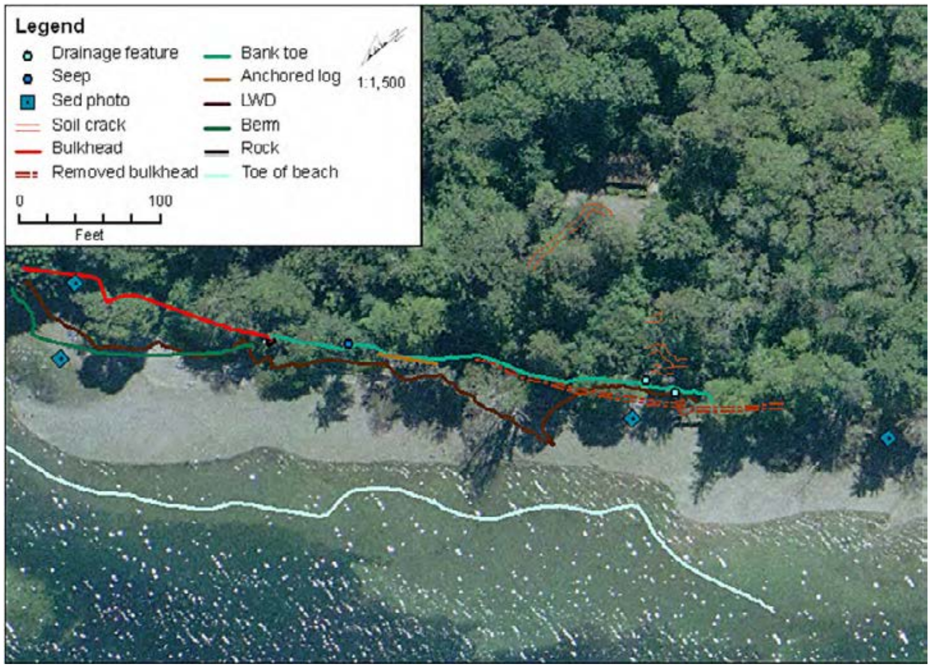
Adjacent shores: Shores both up- and down-drift of the treatment area showed evidence of mass wasting. The down-drift reach was a continuation of the deep-seated landsliding, with superimposed shallow slope failures emanating from the lower portions of the slope. The updrift reach, where bluff height increased to about 30 to 50 ft, was eroding by shallow debris flow and toppling failures, which exposed sediment ranging from silt and sand to cobbles and boulders.



Aerial view of project site showing location of beach profiles.



Beach profiles measured during the 2012 site visit.



Location of various features identified in the legend and surveyed by GPS. “Soil cracks” refer to tension cracks indicating recent movement of the deep-seated landslide. The toe of the landslide is indicated by the dark area below tide. The small accretionary spit discussed in the text is visible at the north end of the treatment reach.

Comparison of beach surface sediment at project and adjacent sites. n/a indicates the location was not present for sampling.

Location	Backshore	Difference	Upper intertidal	Difference
Up-drift	n/a	-	MEDIUM PEBBLE, fine pebble, coarse pebble	-
Project site	n/a	-	SILT (from slide), fine pebble, sand	Finer, due to deep seated slide
Down-drift	MEDIUM PEBBLE, fine pebble, sand	-	MEDIUM PEBBLE, coarse pebble, fine pebble	-

Performance

As the goals of the project were specifically to remove creosoted wood from the marine environment and allow the deep-seated slope instability to provide sediment to the beach, this was not a full restoration project. The bulkhead removal scored for Kopachuck is the removal of only that portion of the bulkhead that was constructed of creosoted logs. A lower log crib wall (bulkhead) that remained along a shorter shore reach to the northeast was not considered in the scoring for this site. Additional site treatment included resloping and revegetation of a small grassy picnic area landward of where the creosoted log bulkhead had been.

Deep-seated slide activity was evident during the initial and later field visits for this project. Tension cracks were numerous in the lower slope day use area, and erosion of the face of the lower bank was ongoing. Silt deposits from the bluff were observed on the beach landward of the former bulkhead area, which had likely been uplifted and deformed as part of an active rotational failure. This active slide area was supplying moderately large volumes of sediment to the beach system, and has the potential for greater reactivation, which would likely have happened with or without removal of the small bulkhead.

Project performance scoring.

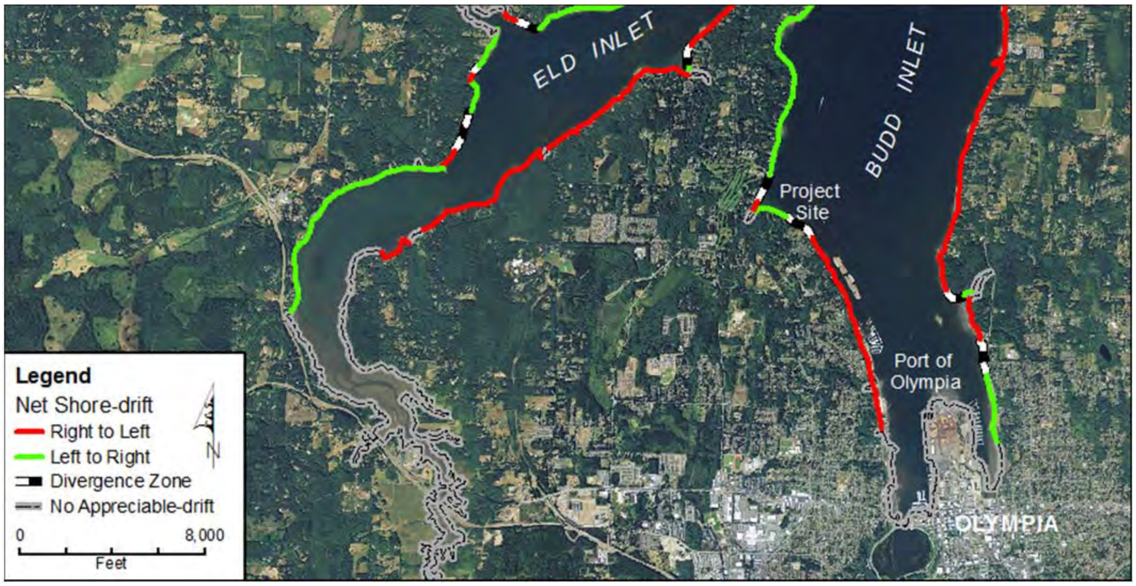
Category	Parameter	Rating	Score	Rationale
Benefits	Removed structures restoring natural processes *	Med	4	Majority of structures removed; moderate amount of rock and fill not removed
	Sediment volume augmented	Med	2	Bulkhead removal allowed active erosion, although not complete within shore reach
	Input/exchange of LWD, detritus	High	3	Cross-shore barrier removed
	Backshore vegetation enhanced	Low	1	Grasses planted at picnic area
	Marine riparian vegetation enhanced	Low	1	Possibly willow planted
	Low-cost and simple installation	Med	2	Project work was straightforward; cost information not received
Impacts	Structures bury backshore & intertidal areas	Med	-2	Old fill and some rock left over on upper beach
	Structures impound littoral sediment	Low	0	Littoral drift impediments, although small, have been largely removed
	Coarser/steeper beach profiles created	None	0	No change noted
	LWD/detritus recruitment reduced	None	0	No negative impact
	Adjacent end erosion	None	0	No negative impact
	Required maintenance interval	None	0	No maintenance of removal required other than larger issue of keeping access open in deep-seated slide area
Design-specific benefits	Enhanced potential spawning habitat for forage fish	Med	2	Sediment from high bluff more able to reach beach
	Sediment benefited down-drift beaches in process unit	Med	2	Creosoted wood vertical bulkhead was removed but down-drift crib wall was not removed at high bluff site
Design-specific impacts	Smothered eelgrass beds or other habitats	None	0	No infrastructure was directly threatened by removal
	Loss of substrate heterogeneity	Low	-1	Small area of negative impact due to quarry spall rock left on upper beach
Total			+14	

*Scores at double other values (e.g., high=6); all others, none=0, low=1, med=2, high=3

Totaling the above scores, benefits equal +17 points and impacts equal -3 point, for a final combined score of 14.

BUTLER COVE – Revetment (1999)

Waterbody: Budd Inlet	Shoretype: Bluff-backed beach	Net Shore-drift Cell: TH-7-6	Direction: Northwest
Project Elements: Rock revetment with resloped and revegetated uplands landward of the modification		Objective: Retard coastal erosion	
Fetch: 6.4 mi NNE Wave Energy: Medium Aspect: North	Land Use: Residential MHHW: +14.5 ft MLLW Toe Elev: +12.62 ft MLLW	Structure: House Setback: 0 Risk Index: 35	Benefit Index: 11 Impact Index: -12 Total BI Index: -1



Project site as red star with dots showing all other revetment projects Sound-wide.

Project Background

The site lies on a very high bluff on a medium-wave-energy shore with almost no structure setback. This project was one residential study site included in research conducted on alternative bank-protection methods in Puget Sound (Zelo et al. 2000). That study examined the bank reslope and revegetation portion of the project, but the project also included a new 270-ft rock wall at the toe of the slope, which is the subject of this case study. Near-vertical rock seawalls, locally termed “rockeries,” are common at single-family residences in the Puget Sound region. A rockery allows for armor stones to be supported by their own structure in that it has a steep front face with individually placed rocks and minimal void between them. Armor stones are typically larger than those used in sloping rock revetments. One advantage rockeries have over more traditional revetments is that rockeries typically cover less area than revetments.

Prior to the rockery and reslope installation, there was a 30-year-old failing wooden bulkhead at the toe of the structure, and the vertical bank slope was covered with English ivy. The actively eroding bluff consists of sand and silt with some bedded, laminar clays. The site also has some massive boulder in the low-tide terrace.

1992 oblique aerial photo of project site.

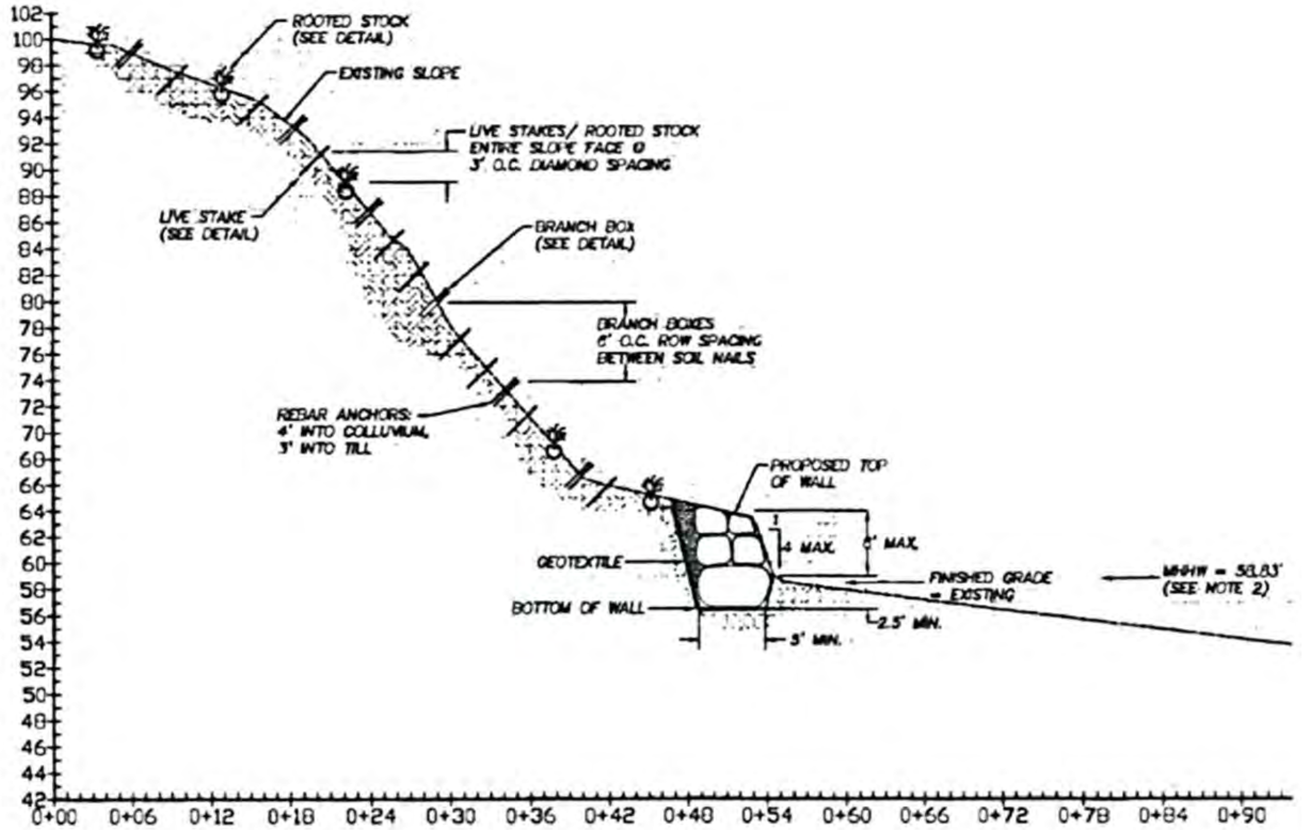
2006 oblique aerial photo of project site. Note the vegetation condition.

Design

Before construction began on the five-stage project in 1998, the bank was failing in blocks and some areas were undercut. The five stages of the project were preparation, soil nails, slope stabilization, toe protection (the subject of this case study), and drainage. During preparation, existing vegetation was removed and the bank resloped. Soil nails were then installed through the bank. Slope stabilization methods introduced marine riparian vegetation and reinforced the surface with trenches. The drainage system was improved to collect up to 90% of the precipitation falling on the residential parcel. The revegetation project is not assessed here, and assessment would not be possible in any event as the owners have removed most of the (expensively installed) vegetation in recent years.

The rockery wall was installed as bank toe protection in the spring of 1999. The full design drawing set could not be located by the Washington Department of Fish and Wildlife (WDFW). No as-built survey or monitoring was completed. The 3 cross sections included in the Zelo et al. (2000) study documented the design cross section (below; note the 3 cross sections contained the same rockery cross section). The design called for the following details:

- The front face slope was to have a slope of 1:4 (horizontal:vertical) at maximum.
- The base course of rocks was designed to have a 3 ft minimum dimension on the broader axis, with smaller rock used for the upper courses.
- The base of the lower course of armor stones was to be 5 ft in depth (cross shore width) at a minimum.
- The toe of the base rocks was to be set a minimum of 2.5 ft into the native beach substrate, with the exposed structure toe at or immediately above MHHW.
- The wall was designed to have a maximum of a 6 ft high exposed face.
- A separation geotextile was to be placed on the face of the exposed soil near the toe of the bluff. However, it was not clear if the geotextile was to be placed beneath the bottom of the structure as well.
- According to the design drawings, small rock was not to be included below the base rocks, however quarry spall or similar small rock appeared to have been placed landward of the armor stones.



Project design cross section (design by AguaTierra Environmental Consulting).

Current Conditions

Technique condition - The rockery remained in very good condition with a consistent front face and crest elevation. Rock placement appeared to have been careful enough to minimize large voids and maintain the design, however, significant amounts of quarry spall appeared to have been lost through the structure face and were observed throughout the beachface at the site. Some of these spalls could be from waves overtopping the wall and washing out from behind. The marine riparian vegetation along the bank slope designed for slope stabilization had been poorly maintained, with some planted species removed altogether. Most plants were highly degraded and trimmed short, presumably to enhance views. The rockery had no apparent seepage at the time of the site visit. The rocked access pathway seems to act as a small drift sill.

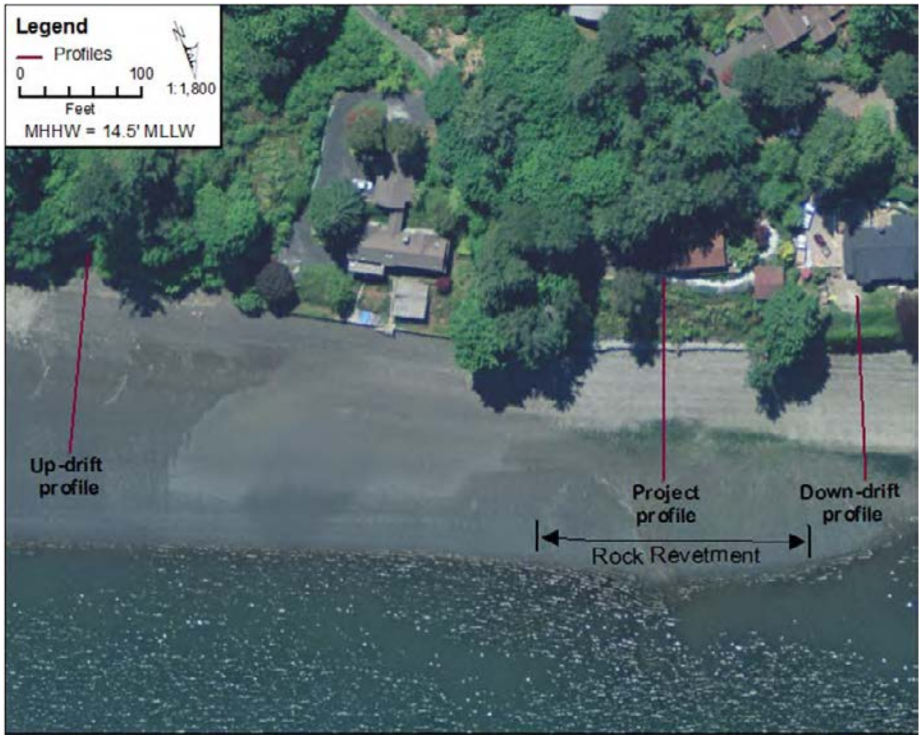
Upland threats - The driveway, the most waterward structure of the residential property, had been removed and realigned to reslope the bank from the original nearly vertical profile to the current grade. The garage had no setback, and the new driveway was at the top of the bluff. The house was set back approximately 25 feet.

Beach characteristics - A backshore was absent at the site. Quarry spalls from the rockery were scattered across the beachface.

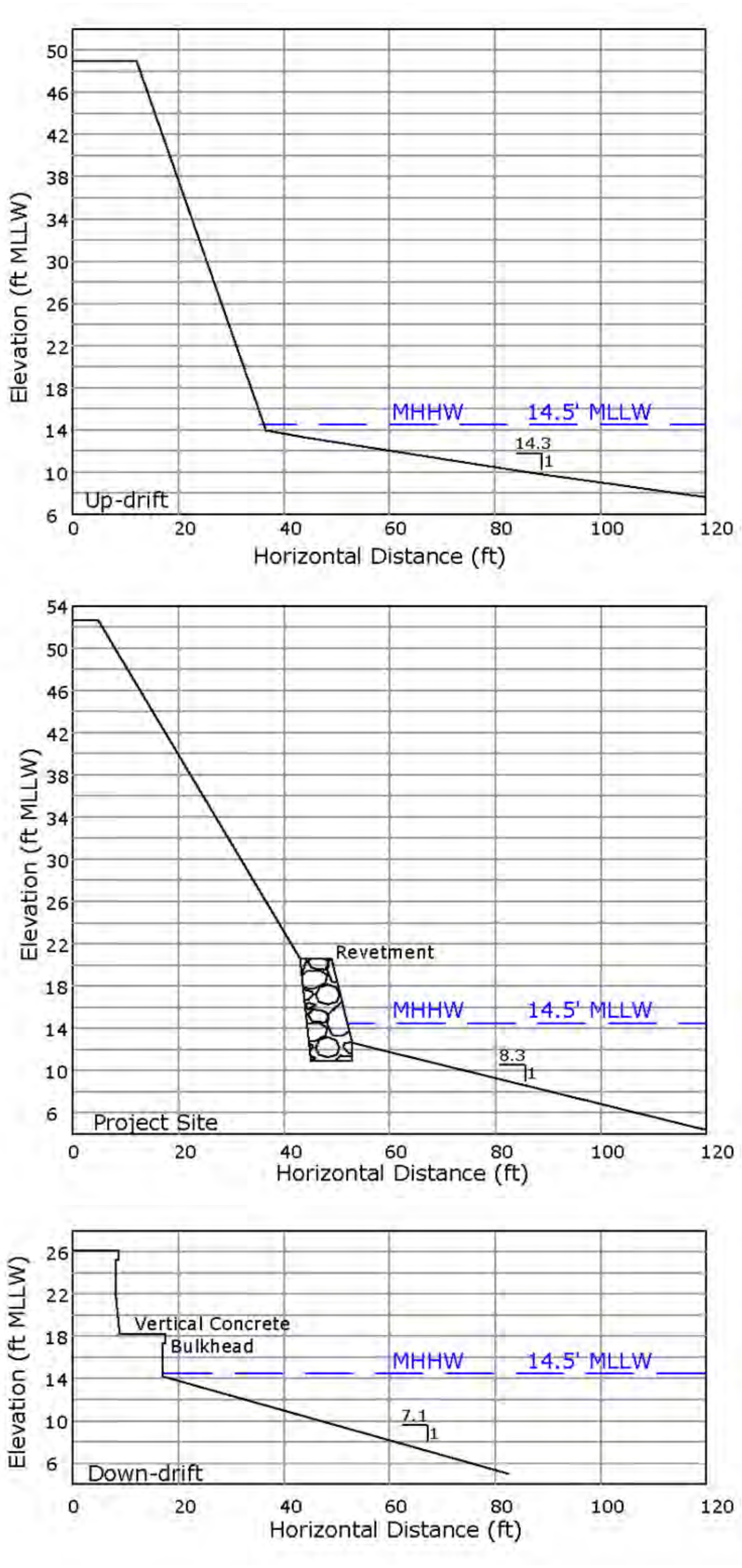
Adjacent shores - The up-drift project site next to the treatment site was an unmodified natural bluff-backed beach with minimal backshore. A vertical concrete bulkhead with a steep bank slope behind it stood at the down-drift project location. This bulkhead had an exposed toe elevation of approximately MHHW, which placed it in the upper intertidal zone.


Project site looking up-drift in 2012.

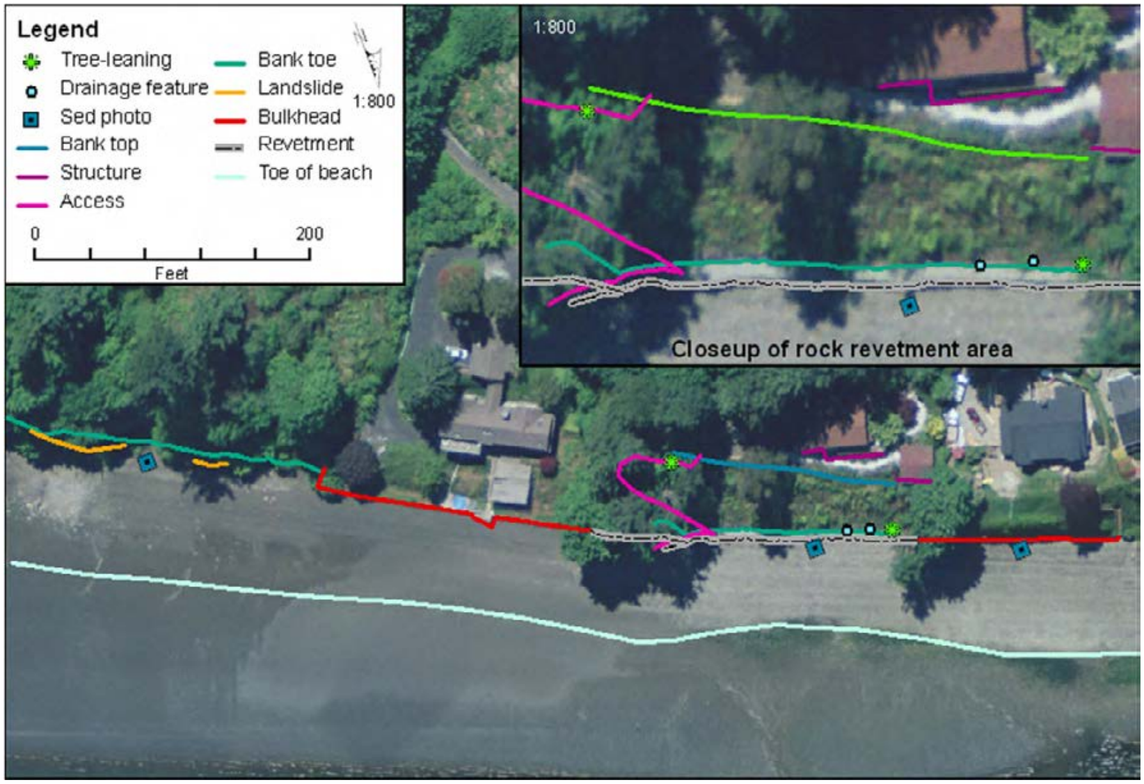

Project site looking down-drift in 2012.



Project site map with profile locations.



Beach profiles measured during the 2012 site visit.



General beach features mapped during the 2012 site visit.

Comparison of beach surface sediment at project and adjacent sites. n/a indicates the location was not present for sampling.

Location	Backshore	Difference	Upper intertidal	Difference
Up-drift	n/a	-	SAND	finer
Project site	n/a	-	MEDIUM PEBBLE, cobble, sand	-
Down-drift	n/a	-	COARSE PEBBLE, cobble, sand	coarser

Performance

The steep rockery or gravity wall has performed fairly well in this medium-wave-energy site since installation in 1999. The drainage design is performing well. There were no signs of seepage at the time of the field assessment. The rockery wall had the following negative impacts on the beach:

- Burial of upper beach
- Impounding sediment from a former feeder bluff
- Steeper beach slope than natural adjacent profile site (up-drift)
- Debris from bedding layer (quarry spall rock) covers a moderate portion of the beach

No large stones appeared to have toppled to the beach. The rock sizing in the design stage and/or the rock placement in the construction phase may have needed more attention. The stones have maintained the design crest and slope, but inner-layer quarry spalls were found distributed throughout the beachface. Because it is not completely aligned with the rockery, the access pathway acts as a small drift sill. Although the design called for marine riparian vegetation to be planted landward of the structure, the plantings have been poorly maintained and were highly degraded with some completely removed.

Project performance scoring.

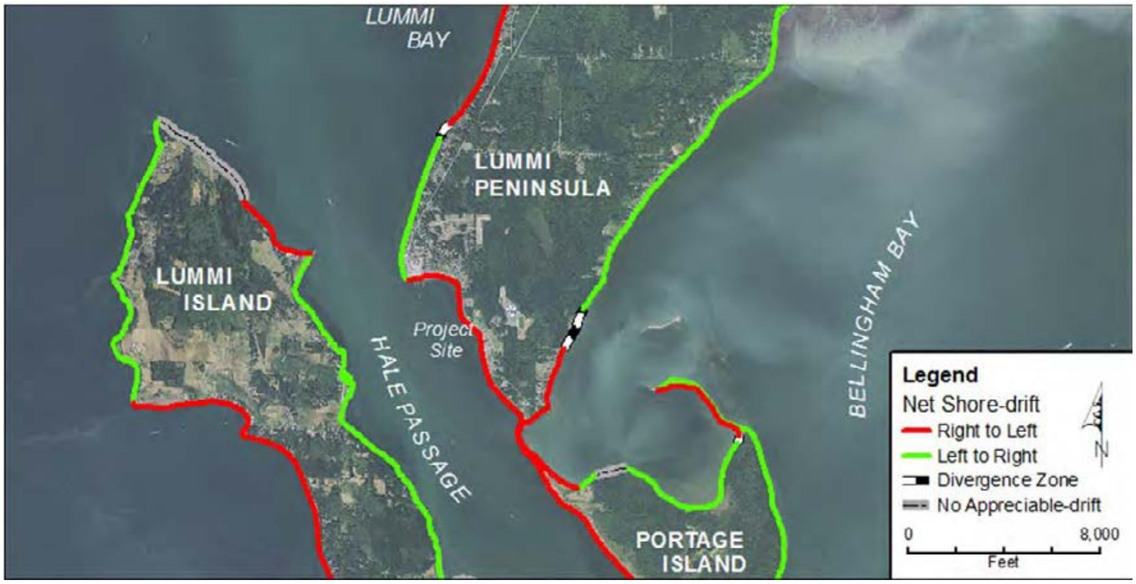
Category	Parameter	Rating	Score	Rationale
Benefits	Effectively mitigated landward erosion	High*	6	Landward erosion stopped since installation
	Sediment volume augmented	None	0	No structure removal or nourishment
	Input/exchange of LWD, detritus	None	0	Structure acts as cross-shore barrier
	Backshore vegetation enhanced	None	0	No planting occurred
	Marine riparian vegetation enhanced	Med	2	Up to 60 ft width planted but poorly maintained and partially removed
	Low-cost and simple installation	None	0	Assume more expensive than $200/LF
Impacts	Structures bury backshore & intertidal areas	Med	-2	Structure installation buried less than 7 ft (average) of backshore
	Structures impound littoral sediment	High	-3	Very high, as bank greater than 45 ft high (historical feeder bluff)
	Coarser/steeper beach profiles created	Med	-2	Project site has 8:1 slope while reference sites had 13.5:1 slopes
	LWD/detritus recruitment reduced	High	-3	No LWD band on site
	Adjacent end erosion	None	0	None evident on site
	Required maintenance interval	None	0	No maintenance has been needed to date
Design-specific benefits	Structural integrity & function maintained	High	3	Structure has not deteriorated
	Cross-shore location of exposed toe of structure	None	0	Exposed toe of structure is below MHHW
Design-specific impacts	Scour at structure	None	0	Scour not evident behind structure
	Debris on beach from structure	Med	-2	Limited quarry spall rock toppled; 20–75 SF/100LF
Total			-1	

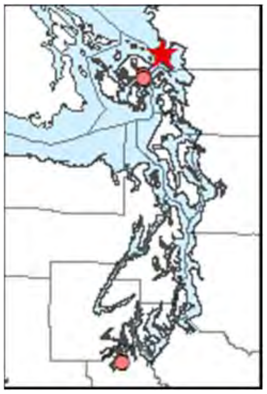
*Scores at double other values (e.g., high=6); all others, none=0, low=1, med=2, high=3

Totaling the above scores, benefits equal +11 points and impacts equal -12 points, for a final combined score of -1.

LUMMI VIEW DRIVE – Revetment (2002)

Waterbody: Hale Passage	Shoretype: Bluff-backed beach	Net Shore-drift Cell: WH-4-13	Direction: Northward
Project Elements: Revetment, slope buttressing		Objective: Slow coastal erosion to protect exposed sewer main	
Fetch: 2.4 mi SSE Wave Energy: Medium Aspect: Southwest	Land Use: Industrial MHHW: +8.83 ft MLLW Toe Elev: +8.36 ft MLLW	Structure: Sewer main and road Setback: 0 Risk Index: 40	Benefit Index: 3 Impact Index: -19 Total BI Index: -16





Project site as red star with dots showing all other revetment projects Sound-wide.

Project Background

This medium-wave-energy, low-bank site is exposed to storm waves from the south. The drift cell originates on southern Portage Island, and continues northward along the west shore of the Island and across to the west shore of Lummi Peninsula. The drift cell is little affected by shore modifications. Feeder bluffs on south Portage Island are unmodified, but the uncommon large intertidal bar known as “The Portage” south of Lummi Peninsula is an area of high tidal currents that appear to cause littoral sediment loss to Hale Passage and Portage Bay. The project site, all erosional feeder bluff, is exposed to both southerly and indirect northwesterly wind waves.

The project site experienced bank-toe erosion and shallow surficial landsliding in 2001 that exposed an approximately 20-ft-long reach of an active sewer main in the bluff face along the west road shoulder. The road and buried utilities were located immediately adjacent to the top of the bank in this reach. The Lummi Nation Public Works Department wanted site modifications to safeguard the exposed sewer main as well as this reach of road. The short revetment at this project was pursued through emergency permitting and was constructed soon after initial designs were developed.

Planning by the US Army Corps of Engineers (USACE) for shore protection was slowly progressing at that time for a much more comprehensive erosion control project (known as the Lummi Shore Road project for the adjacent, longer road on the west shore of Bellingham Bay). However, this reach was outside of that study area. The USACE built more than a mile of large revetment along Lummi Shore Road in 1998–1999.

April 1994 oblique aerial photo of project site before revetment installation.

Photo taken in January 2003 of the north end of the project revetment. Degradation—already apparent—began within 2 years of installation.

Design

Design drawings were not available for this project.

It appears that a straightforward rock revetment was constructed at the site with a layer of armor stones generally 2.5 to 4 ft in diameter placed on top of much smaller quarry spall rock. The depth of embedment into the beach at the time of construction is not known. Some rock buttressing of the upper bank face was constructed along with the revetment, most likely by dumping quarry spall and other material over the bank crest from the roadway.

Current Conditions

Technique condition - The revetment had a varying crest height and waterward slope throughout the structure. There was scour throughout the toe of the structure and the exposed toe was below MHHW for most of its length. Significant degradation of the revetment from rock toppling was observed during the 2012 site visit. The degradation had started 1 to 2 years after installation, as seen in the 2003 site photograph in the Project Background section above. The bluff toe had experienced end-effect erosion on both ends with scarps into dense soils; these appeared greater in landward extent than those in surrounding bluff areas that were gradually receding though ongoing background erosion.

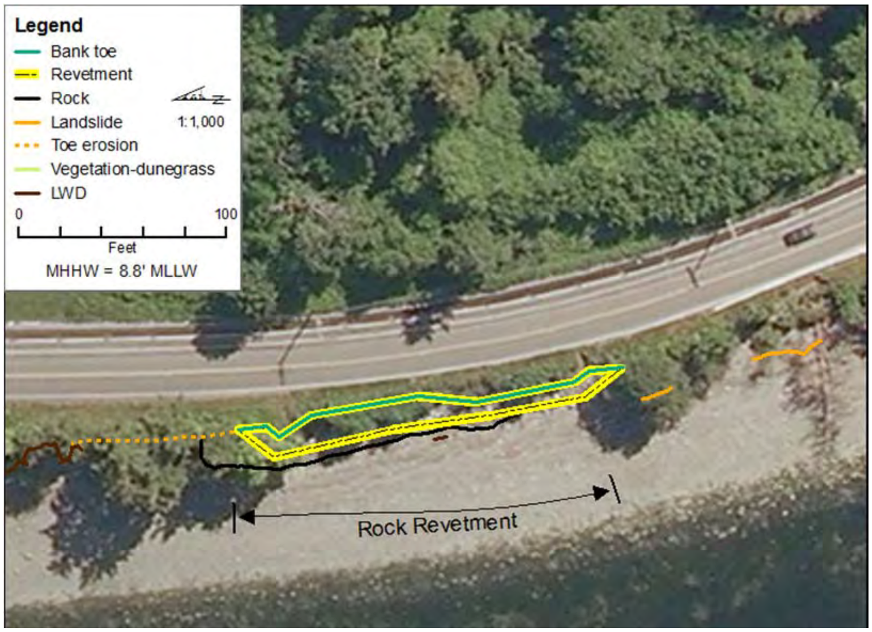
Upland threats - The sewer main was not exposed during the site visit and no design drawings were available; therefore, its exact location was not determined. End erosion of over 2 ft on both ends of the revetment was threatening the adjacent road sections as seen in the lower right photo. The section of the road between the two eroding ends did not seem to be critically threatened by erosion.

Beach characteristics - Toppled rock from the structure lay on the upper beach, with smaller rock through the beach profile. Comparison of surveyed beach profiles from 2003 and 2012 revealed that the upper beach face had lowered on the order of 1.5 ft waterward of the rock revetment. Similar erosion had occurred on the down-drift side of the revetment. Erosion since 2003 was generally on the order of 1 to 1.5 ft above +8 ft MLLW. Mid-intertidal beach lowering also had occurred both at and down-drift of the project site, suggesting that area-wide erosion may be occurring. The beach had pebble with sand and coarse pebble substrate.

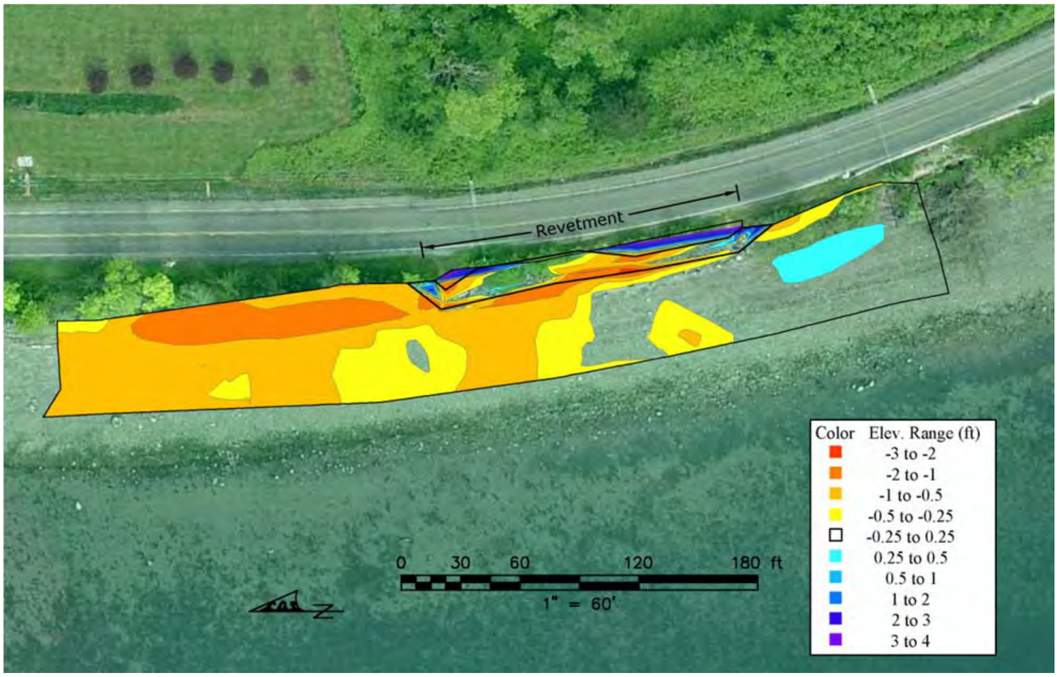
Adjacent shores - The up-drift beach profile showed virtually no change since 2003, as shown in surface-change analysis and profile comparisons, indicating that the revetment may indeed have caused erosion waterward and immediately down-drift of it. The dominant substrate of the up-drift location's upper intertidal beach was medium pebble with coarse pebble and fine pebble; the down-drift location's upper intertidal substrate had medium pebble with sand, and coarse pebble.

Project site revetment in 2012 near the south, up-drift end with a shovel in the photo for scale. Note slope-buttressing small rock above revetment.

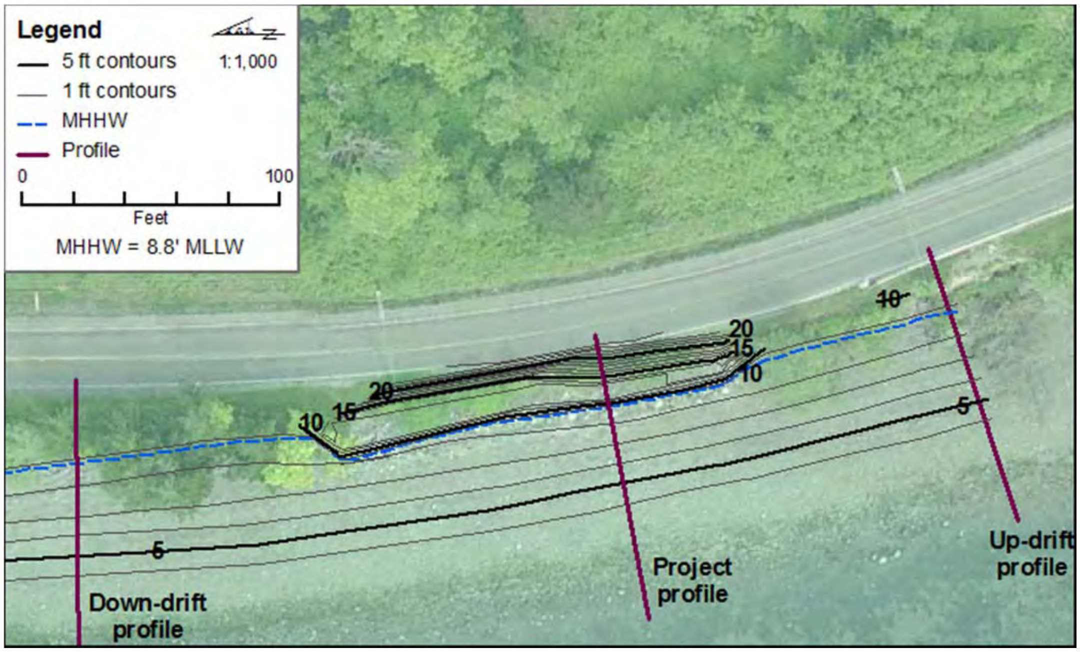
Project site revetment north end in 2012 looking up-drift of the structure end. Note toppled armor rock and quarry spall, which has moved out of the structure.



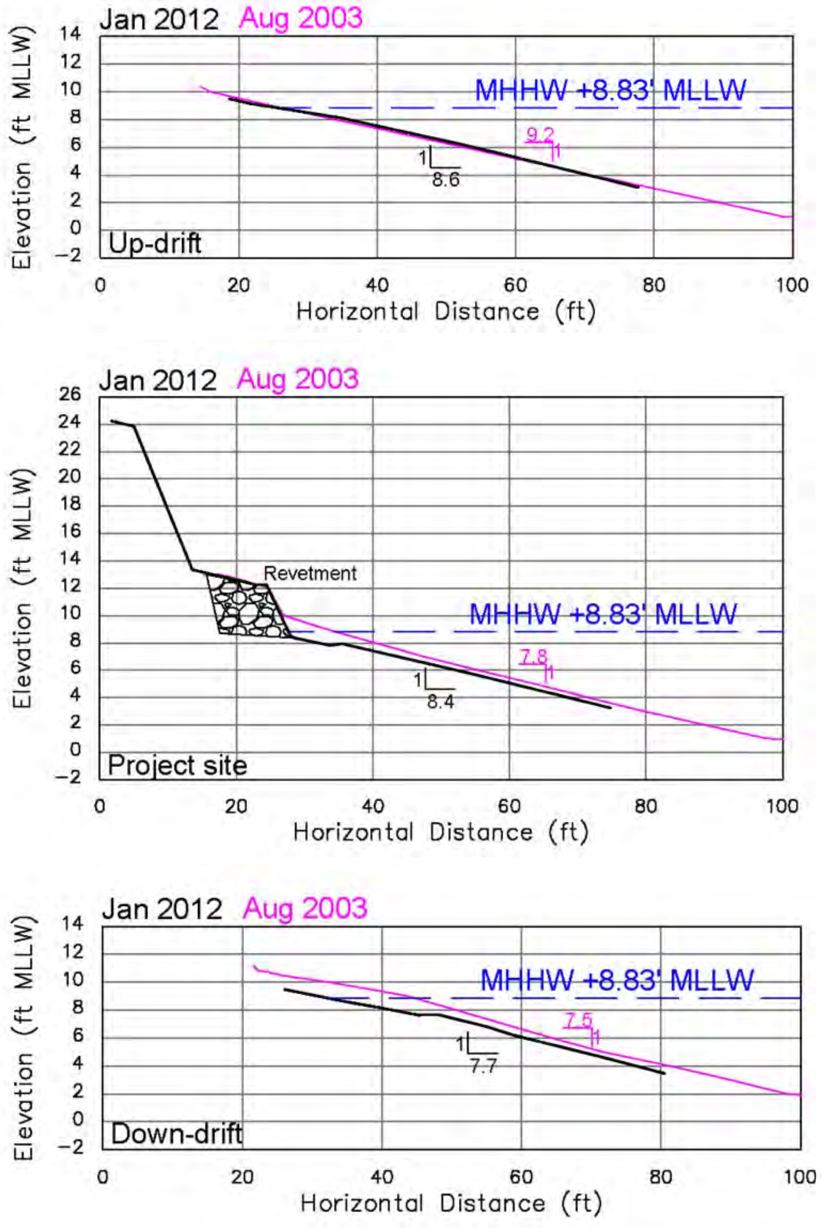
The rock revetment extends along the area with eroded road shoulder. Note toppled and eroded rock debris on upper beach and down-drift end of revetment. Image date May 2009, with 2012 field mapping.



Surface change analysis from August 2003 to January of 2012 indicated that the north end and toe of the revetment had lowered. Also note beach erosion at structure toe and in a linear reach extending north (down-drift) of the revetment.



Topographic map of Lummi View Drive RV with profile locations.



Beach profiles from monitoring in 2003 and the 2012 site visit.

Comparison of beach surface sediment at project and adjacent sites. n/a indicates the location was not present for sampling.

Location	Backshore	Difference	Upper intertidal	Difference
Up-drift	n/a	-	MEDIUM PEBBLE, coarse pebble, fine pebble	coarser
Project site	n/a	-	MEDIUM PEBBLE, sand, coarse pebble	-
Down-drift	n/a	-	MEDIUM PEBBLE, sand, coarse pebble	similar

Performance

The revetment allowed the sewer main to remain unexposed and slowed erosion of the road through the middle of the modified reach but the revetment did not hold up well and it caused a number of impacts to the nearshore. Reasons for poor performance include the following:

- The project was constructed under emergency conditions with a rushed design and what appeared to be poor installation.
- Most of the revetment toe is currently below MHHW, which causes high impacts.
- The structure caused accelerated erosion around both ends (“end-effects”). This end erosion is destabilizing the bank that supports the road and sewer line.
- Due to its low-elevation placement, there is no log zone waterward of the structure, and logs have recruited landward of the structure crest. Because these logs have no connectivity to the beach they are not backshore habitat.
- Due to the rock buttressing of the slope above the revetment, no marine riparian vegetation became established, in contrast to the partial tree cover in adjacent areas.

Due to the problems with design and construction, much of the bedding layer quarry spalls of the revetment were displaced throughout the beachface waterward of the structure. In addition, a scour trough (a linear depression near MHHW) was observed on the down-drift beach starting from near the northwest corner of the revetment (see surface change map and site photos). This project has the lowest cumulative score of all design techniques and project sites studied for this report and is the only one to score in all impact categories.

Project performance scoring.

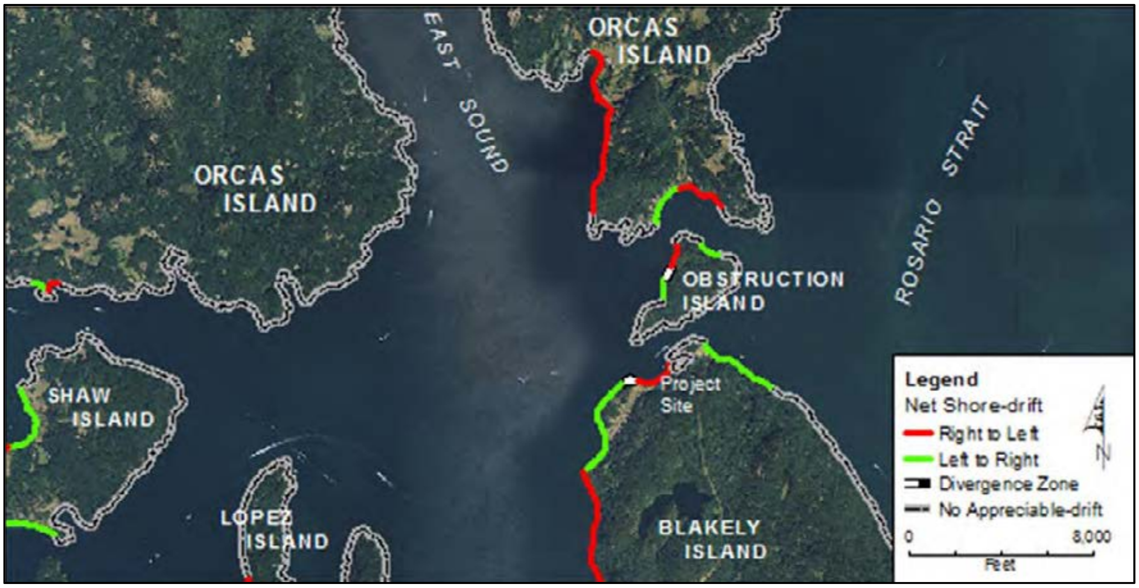
Category	Parameter	Rating	Score	Rationale
Benefits	Effectively mitigated landward erosion	Med*	2	Landward erosion stopped since installation but end effect erosion exists
	Sediment volume augmented	None	0	No nourishment structure removal occurred
	Input/exchange of LWD, detritus	None	0	Revetment acts as cross-shore barrier
	Backshore vegetation enhanced	None	0	No planting occurred
	Marine riparian vegetation enhanced	None	0	No planting occurred
	Low-cost and simple installation	None	0	Assume more expensive than $200/LF
Impacts	Structures bury backshore & intertidal areas	High	-3	Structure installation buried an average of 11.9 ft of backshore width
	Structures impound littoral sediment	Med	-2	Bank height is less than 30 ft
	Coarser/steeper beach profiles created	Med	-2	Project site has 8.5:1 slope while reference sites had 9.2:1 and 9.3:1 slopes
	LWD/detritus recruitment reduced	High	-3	No log zone waterward of the structure
	End erosion adjacent	High	-3	Both ends had over 2 ft of erosion
	Required maintenance interval	Low	-1	Estimated between 15 and 30 years
Design-specific benefits	Structural integrity & function maintained	Low	1	Structural integrity maintained with significant crest toppling
	Cross-shore location of exposed toe of structure	None	0	Exposed toe structure is below MHHW for some of the length
Design-specific impacts	Scour at structure	Med	-2	0.5 ft of scour at Profile A
	Debris on beach from structure	High	-3	Rock and quarry spall on beach from structure, greater than 75 SF/100LF
Total			-16	

*Scores at double other values (e.g., high=6); all others, none=0, low=1, med=2, high=3

Totaling the above scores, benefits equal +3 points and impacts equal -19 points, for a final combined score of -16.

NW BLAKELY ISLAND – Revetment (1980)

Waterbody: Peavine Pass	Shoretype: Barrier beach	Net Shore-drift Cell: BL-10	Direction: Northeastward
Project Elements: Rock revetment with minor fill		Objective: Stabilize shore and minor amount of fill	
Fetch: 4.8 mi West Wave energy: Moderate Aspect: NW	Land Use: Residential MHHW: + 8.0 ft MLLW Toe Elev: +9.8 ft MLLW	Structure: Park infrastructure Setback: 61 ft Risk Index: 9	Benefit Index: 8 Impact Index: -10 Total BI Index: -2



Project site as red star with dots showing all other revetment projects Sound-wide.

Project Background

The project site on Blakely Island, in the eastern San Juan Islands, lies at the down-drift end of a relatively short drift cell. Wave energy from the west and northwest is moderate although the site is not exposed to any southerly wind-generated waves. Net shore-drift is northeastward (right to left). The drift cell has a very short reach of feeder bluff composed of a large percentage of sand and gravel with several shorter reaches of historical feeder bluff that have been modified. The project site is at the end of the net shore-drift cell.

The 112 ft-long rock revetment was built just prior to 1980 on a barrier beach shore. A pier is adjacent to the northeastern end of the revetment. The easternmost portion of the revetment was not assessed as it was far lower on the beach profile and is influenced by the adjacent rock modification for the pier. The portion of the revetment assessed is 31 ft waterward of a picnic shelter with lawn in between. The picnic shelter and lawn are parts of the larger marina developed in the early 1970s. The backshore was apparently raised by 2 to 3 ft at the time of site development as seen in the project site cross section. It appears that the central and eastern portions of the revetment were also pushed waterward of the original shore by adding fill.

Design details were not available. A marina employee mentioned minor maintenance in the form of moving toppled rocks back upslope to the wall several times, including during the last 15 years. He also stated that recently some juniper bushes were removed and there has been excessive erosion in those areas. This assessment focuses on the central and southwestern portions of the revetment and not the low-elevation portion next to the pier and its associated modifications.

Project location in June 1977 before project installation.

Project location in 2002. Note the toppled rock and intertidal beach debris.

Design

No design drawings or details were available.

The rock revetment was 112 ft long. The front-face slope was generally 2:1 (horizontal:vertical), although it was likely steeper at the time of construction. Rock diameter varied widely, ranging from 1.5 to 6 ft, and rocks were very angular.

The revetment installation, although typical for the era (and still seen occasionally), was not well engineered or constructed. The armor stones were likely not placed with great precision and therefore have not maintained at least three points of contact between each rock as recommended with revetment projects currently. Individual rock size varied greatly throughout the project with most rocks being oversized for the application. The crest elevation may not have been consistent and rocks may not have been buried adequately. No geotextile fabric was used in design or construction. It is likely this installation was not intended to last for a long time without maintenance, but its performance is instructive in terms of avoiding some of the methods that caused the structure to deform in places and require maintenance.

Current Conditions

Technique condition- Armor rock has toppled onto the beach along many portions of the revetment. The western portion, which was constructed higher on the beach and has a higher crest elevation, was in the best condition with the fewest rocks toppled on the beach. The central and eastern portions contained several small gaps and several low-elevation crest areas, with erosion scarps cut into the adjacent fill. Toppled rock was present over portions of the upper beach. The toppled rocks have been moved back upslope on one occasion in the past 15 years. Some juniper bushes have been removed in the last 5 years and there has been erosion in those areas.

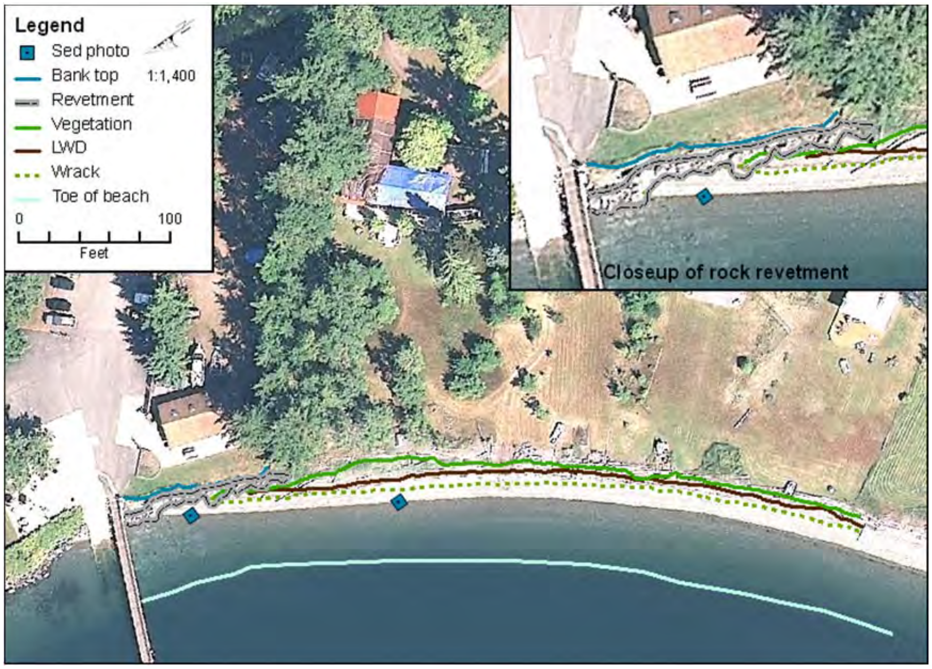
Upland threats- A picnic shelter was located 31 ft landward of the revetment. The picnic shelter was adequately setback from wave attack. No other improvements lay close to the assessment portion of the revetment. Minor loss of the filled, outer lawn area has occurred due to wave attack at portions of the revetment with lowered crest elevation.

Beach characteristics- Substrate was a mix of pebble with minor amounts of sand. The mostly small pebble sediment provided continuous potential spawning substrate for forage fish in the upper intertidal up to where the upper beach disappears near the heavily protected pier. Backshore vegetation and large woody debris (LWD) areas were absent waterward of the revetment except at its higher elevation west end.

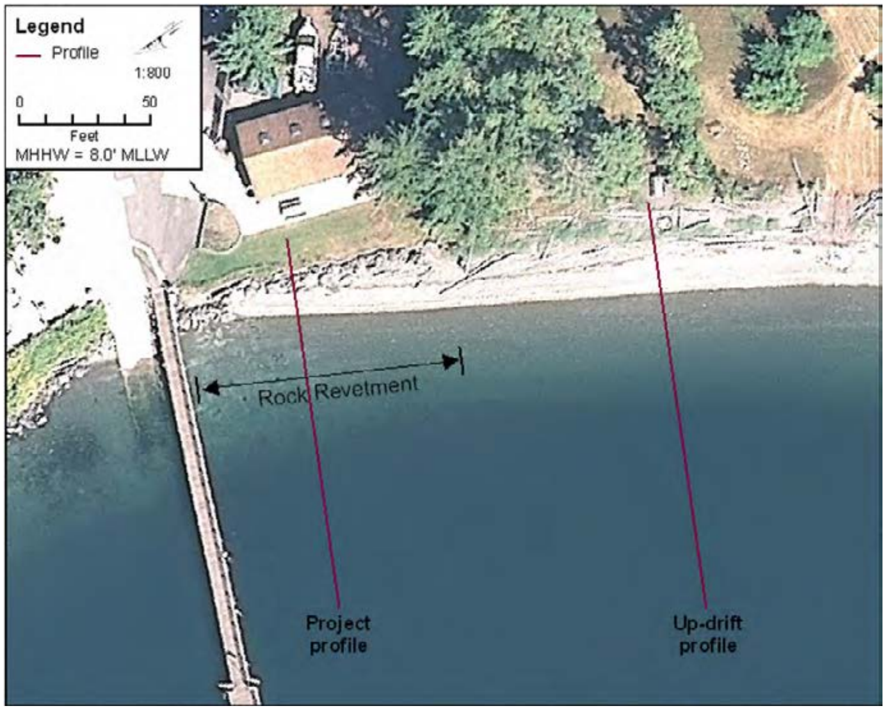
Adjacent shores- No erosion was evident at the western no-bank beach area, either now or, as observed periodically, in the past 15 years. The modified area surrounding the pier and the filled revetment shore to the east has become degraded over the years and has minimal habitat value.

Project site and profile location looking up-drift in 2012. Note toppled rock in foreground and erosion of backshore fill with fewer toppled rocks on beach within the further section of revetment.

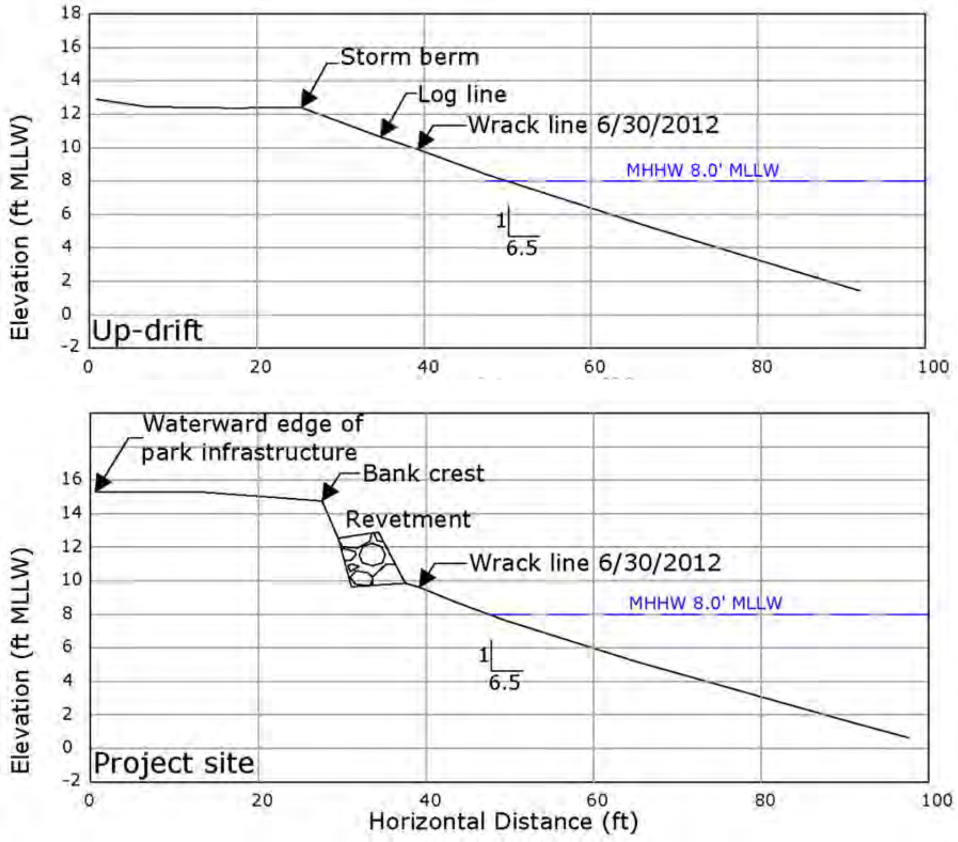
Project site and profile location looking down-drift in 2012. Note rock toppling and lower elevation of eastern portion of revetment.



Map of field data obtained with GPS with profile locations.



Project site map with profile locations.



Beach profiles from the 2012 site visit. Note that there wasn’t a down-drift beach.

Comparison of beach surface sediment at project and adjacent sites. n/a indicates the location was not present for sampling.

Location	Backshore	Difference	Upper intertidal	Difference
Up-drift	n/a	-	COARSE PEBBLE, medium pebble	coarser
Project site	n/a	-	MEDIUM PEBBLE, coarse pebble	-
Down-drift	n/a	-	n/a	-

Performance

The rock revetment has performed adequately with some maintenance since installation in or soon before 1980. It appears that the lawn, which was planted on fill over the old barrier beach backshore, will continue to scarp due to wave run-up over the irregular crest of the structure, and the projected rise in sea level will likely enhance run-up and overwash. The beach lacked a backshore or marine riparian vegetation throughout both the western and central reaches, demonstrating impacts to nearshore habitats.

Because the western end of the revetment was constructed at a higher elevation and with a lower volume of fill landward than the central portion, there were fewer impacts on the beach and lower maintenance needed for the western end than for the central portion. The differences in performance and impacts between the 2 areas included the following:

- The revetment did not allow room for drift logs in the lower elevation central reach and did have room for a very narrow drift-log zone waterward of the structure's higher elevation (western) portion.
- The wrack was present waterward of the western portion of the revetment and was absent in the central reach.
- Revetment rocks have toppled to the beach much more frequently in the lower elevation central portion.
- The erosion landward of the revetment was greater in the central lower elevation reach.

The placement of the central portion of revetment rock further waterward than the western portion—leading to poor performance of the central portion—was likely done to protect a greater volume and aerial extent of fill. The poor performance was likely exacerbated by the lack of sound soils below the beach to bear the load of the revetment rocks. The underling soils appeared to consist of loose beach gravel, which often contributes to revetment instability on barrier beaches. In addition, the likely imprecise placement of armor stones created a varying crest height, which was subjected to toppling and occasional overtopping. The large rocks on the west end fell into the beach face shortly after construction and were moved back into the structure. As seen in the oblique aerial photo, in 2002 the rocks on the west end had again toppled waterward of the main structure alignment.

Project performance scoring.

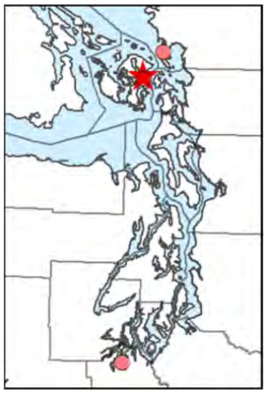
Category	Parameter	Rating	Score	Rationale
Benefits	Effectively mitigated landward erosion	Med*	4	Landward erosion mostly abated since installation, however some overwash and scarping has occurred
	Sediment volume augmented	None	0	No nourishment or structure removal occurred
	Input/exchange of LWD, detritus	Low	1	Allows alongshore exchange
	Backshore vegetation enhanced	None	0	No planting occurred
	Marine riparian vegetation enhanced	None	0	No planting or establishment occurred
	Low-cost and simple installation	None	0	Assume more expensive than $200/LF
Impacts	Structures bury backshore & intertidal areas	Med	-2	Structure installation buried 6.5 ft (average) of backshore
	Structures impound littoral sediment	Low	-1	Bank height is approximately 2.5 ft
	Coarser/steeper beach profiles created	None	0	Project site and reference site have same slopes
	LWD/detritus recruitment reduced	High	-3	1.5-ft band of LWD onsite; 34-ft band of LWD on reference site
	End erosion adjacent	Low	-1	Erosion at one end is between 0.25 and 2 ft
	Required maintenance interval	Low	-1	Rocks were moved upslope once since construction 30+ years ago
Design-specific benefits	Structural integrity & function maintained	Low	1	Structural integrity maintained but with significant crest toppling
	Cross-shore location of exposed toe of structure	Med	2	Exposed toe of structure is above midpoint between MHHW and OHWM
Design-specific impacts	Scour at structure	None	0	None evident on site or in profile
	Debris on beach from structure	Med	-2	20–75 SF/100LF of toppled rock on beach
Total			-2	

*Scores at double other values (e.g., high=6); all others, none=0, low=1, med=2, high=3

Totaling the above scores, benefits equal +8 points and impacts equal -10 points, for a final combined score of -2.

OBSTRUCTION PASS – Revetment (2007)

Waterbody: Obstruction Pass	Shoretype: Pocket beach	Net Shore-drift Cell: OR-4	Direction: Northeastward, left to right
Project Elements: Revetment		Objective: Retard coastal erosion	
Fetch: 4.3 mi SE Wave Energy: Medium Aspect: Southeast	Land Use: Residential MHHW: +7.98 ft MLLW Toe Elev: +8.8 ft MLLW	Structure: House deck Setback: 48 ft Risk Index: 20	Benefit Index: 10 Impact Index: -12 Total BI Index: -2



Project site as red star with dots showing all other revetment projects Sound-wide.

Project Background

This site lies in a south-facing cove on the north shore of Obstruction Pass, on southeast Orcas Island. The site faces the southeast. It is a barrier beach with 4.3 miles of maximum measured fetch to the southeast across Rosario Strait. Two adjacent residential properties were experiencing landward retreat of lawn and scarping around the base of a small residential pier. The property owners installed a continuous, 150 ft long, low-elevation rock revetment in 2007.

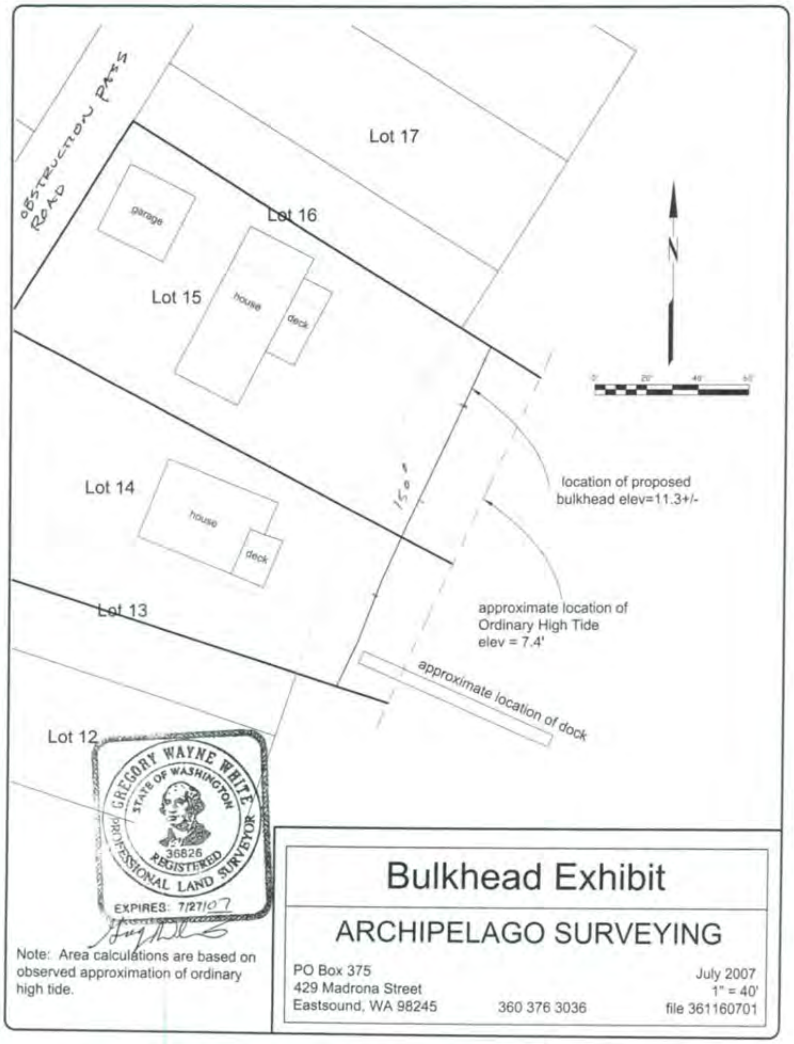
Erosion along shore looking SW, preproject.

Erosion at dock looking SW, preproject.

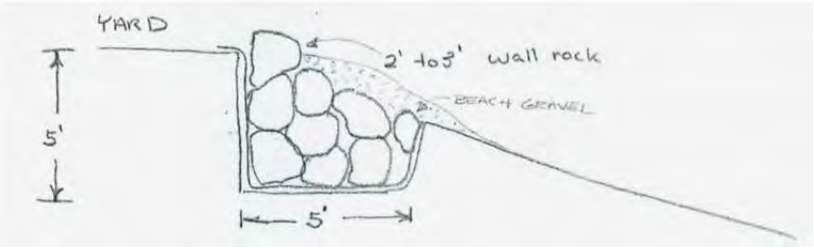
Design

Erosion control was desired to abate shoreline recession, property loss, and damage to a pier for two adjoining properties. A low-profile rock revetment design was applied, according to project permits, “to maintain the current low elevation of the beach,” although considerable fill was placed in the backshore historically and the natural backshore elevation was likely much lower than current conditions.

The design entailed a largely buried rock revetment composed of 2- to 3-ft-diameter rock, in a 5-ft-wide by 5-ft-deep trench. The trench was layered with geotextile fabric and excavated landward of the position of MHHW. Drawings showed the planned revetment installation area at approximately +11.3 ft MLLW elevation, although it appeared that the revetment was installed further waterward. The site plan with the permit application also showed that the revetment was to be installed landward of “ordinary high tide, +7.4 ft MLLW.” This elevation corresponds roughly to MHW for this site, as MHHW is approximately +7.98 ft MLLW. This is an example of often-confused tidal elevations, and in this case the elevation used on the plans suggests that the revetment was to be located further landward than was the case. Rock was placed nearly flush with the land surface and angled approximately 45 degrees to the toe of the slope. The rock was then topped with gravel excavated from the beach so that only 1.5 ft of imported rock was visible. The east and west ends of the revetment decrease in elevation at the property lines to prevent end effects.



Project design drawing.



Project design cross section.

Current Conditions

Technique condition - The revetment had a varying crest height and waterward slope throughout, most likely due to imprecise rock placement during installation. Geotextile fabric was exposed intermittently throughout the length of the structure, which has been overwashed an average of 4 ft landward, up to a maximum of 12 ft. Imported gravel placed on top of the revetment had eroded, exposing the entire top layer of armor stones. The exposed toe of the structure was barely above MLLW at the time of the field assessment. A small width of large woody debris (LWD) lay waterward of the structure.

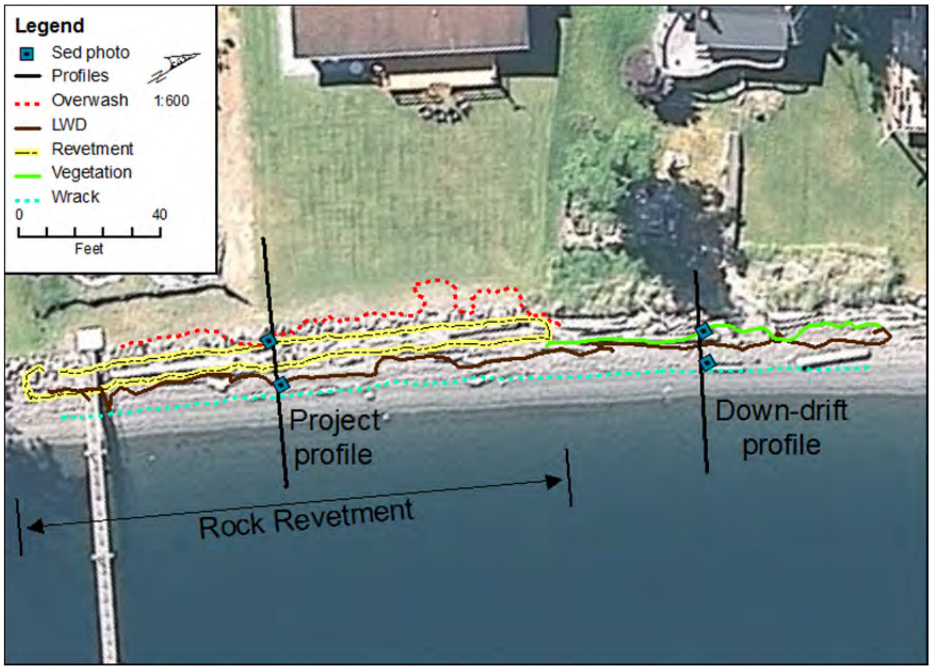
Upland threats - Although the structure has experienced overwash landward, no LWD lay landward of the structure at the time of the field assessment. It was not determined if a septic drainfield lies between the deck and the structure.

Beach characteristics - The beach had a steep slope with medium and coarse pebble substrate. The project profile had an upper intertidal slope of 4.4:1 (the steepest of all sites surveyed for this report) and the adjacent, down-drift site had a slope of 5.2:1. The project beach may have been steeper due to the presence of the structure. The apparent lack of sand in this beach has allowed for an extremely well-drained beach and the steep slopes observed.

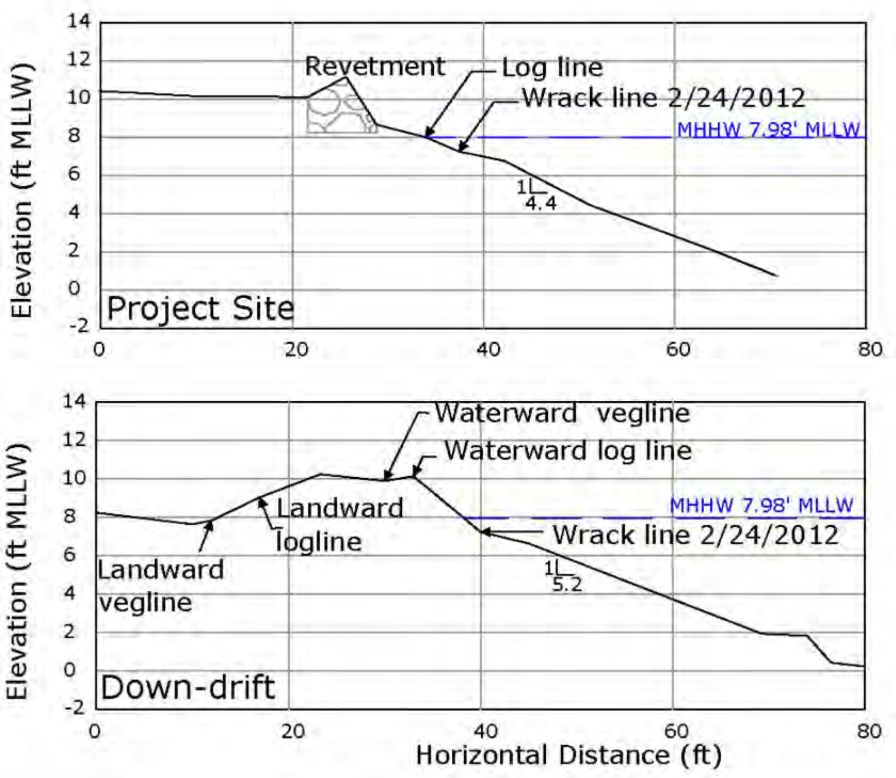
Adjacent shores - The down-drift property had a large band of vegetated backshore and larger logs, which were generally absent at the subject property. On the uppermost beach, the down-drift property had elevations and waterward extents of log and wrack lines similar to those at the project site.

Project site looking down-drift in 2012. Note landward overwash of the revetment, exposed rock and geotextile fabric, and small log zone waterward of structure.

Down-drift profile looking down-drift in 2102. Note the backshore vegetation.



Map of field data obtained with GPS with profile locations.



Beach profiles from the 2012 site visit.

Comparison of beach surface sediment at project and adjacent sites. n/a indicates the location was not present for sampling.

Location	Backshore	Difference	Upper intertidal	Difference
Up-drift	n/a	-	n/a	-
Project site	MEDIUM PEBBLE, coarse pebble	-	MEDIUM PEBBLE	-
Down-drift	MEDIUM PEBBLE, coarse pebble	same	MEDIUM PEBBLE	same

Performance

The rock revetment has performed well in largely preventing erosion of the lawn area landward of the wall since installation in 2007. The large stones may not have been placed as precisely as the design called for, resulting in a varying crest height and structure slope. The imprecise placement of stones also allowed for rock toppling to the beach due to an inadequate number of points of contact between stones. Performance for the next 20 years is unknown, given that the revetment is already being overwashed with projected sea-level rise. The performance in smaller areas over the next 5 to 10 years is uncertain due to the exposed geotextile fabric. Intermittent overwash may gradually worsen and allow for landward erosion of the shore. Wave attack will likely continue to scour at the structure's toe and may enhance the probability of the large revetment stones toppling onto the beachface.

The map with overlaid GPS data showed that the log, vegetation, and wrack lines maintained consistent alignment with the shoreline when transiting from waterward of the revetment or natural shoreline. However, the revetment has caused some negative impacts for nearshore habitats:

- The revetment currently allows for a narrow drift-log zone waterward of the structure but has no backshore or marine riparian vegetation throughout its length.
- The revetment has created a steeper beach than the adjacent natural shoreline as shown in the cross sections.
- The gravel that was placed per design on top of the large revetment stones has been eroded away.
- Overwash was more prevalent at the revetment. Therefore, it appears that the natural shoreline with associated large wood and a mixture of vegetation is providing a similar degree of coastal erosion protection as the revetment in this medium energy setting.

Project performance scoring.

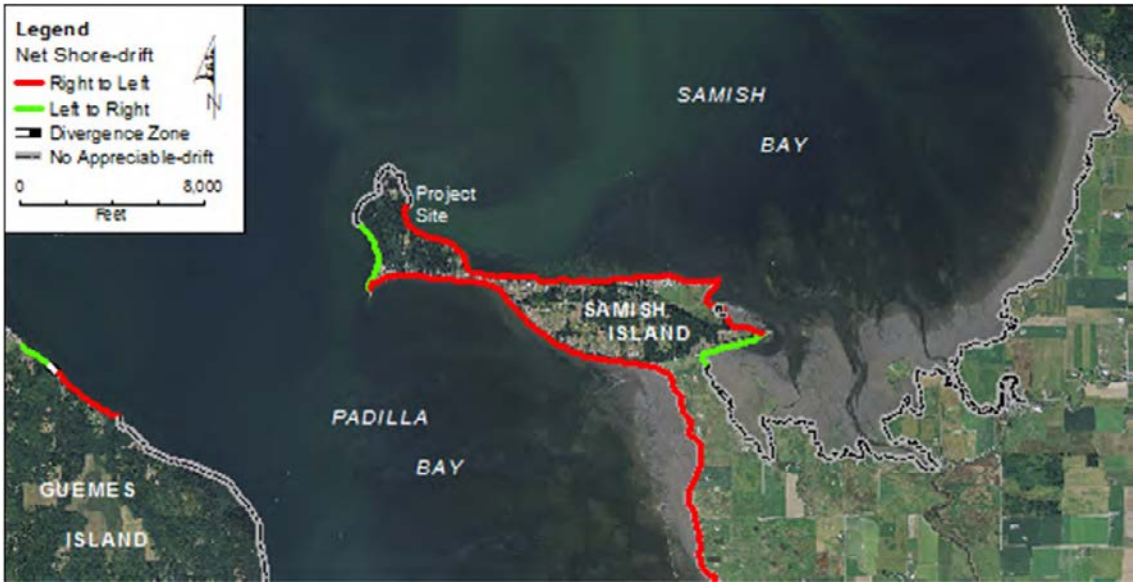
Category	Parameter	Rating	Score	Rationale
Benefits	Effectively mitigated landward erosion	High*	6	Landward erosion stopped since installation
	Sediment volume augmented	None	0	No nourishment or structure removal
	Input/exchange of LWD, detritus	Low	1	Allows cross-shore LWD exchange
	Backshore vegetation enhanced	None	0	No planting occurred
	Marine riparian vegetation enhanced	None	0	No planting occurred
	Low-cost and simple installation	None	0	Assume more expensive than $200/LF
Impacts	Structures bury backshore & intertidal areas	Med	-2	Structure buried an average of 5.8 ft of backshore
	Structures impound littoral sediment	Low	-1	Bank height less than 5 ft
	Coarser/steeper beach profiles created	Med	-2	Project site beach had 4.4:1 slope, reference site had 5.2:1 slope
	LWD/detritus recruitment reduced	High	-3	16-ft width at reference site and 5-ft width on site
	End erosion adjacent	Low	-1	One end had less than 2 ft of end erosion
	Required maintenance interval	Low	-1	Estimated between 15 and 30 years
Design-specific benefits	Structural integrity & function maintained	Med	2	Structure crest not uniform but has mitigated erosion
	Cross-shore location of exposed toe of structure	Low	1	Exposed toe of structure is barely above MHHW but below midpoint between MHHW and OHWM
Design-specific impacts	Scour at structure	Med	-2	Less than 0.25 to 2 ft of scour, with geotextile fabric exposed
	Debris on beach from structure	None	0	Natural beach sediment present
Total			-2	

*Scores at double other values (e.g., high=6); all others none=0, low=1, med=2, high=3

Totaling the above scores, benefits equal +10 points and impacts equal -12 points, for a final combined score of -2.

NORTH SAMISH ISLAND – Vertical Bulkhead (1997)

Waterbody: Samish Bay	Shoretype: Bluff-backed beach	Net Shore-drift Cell: SK-C-6	Direction: Eastward along north Samish Island
Project Elements: Untreated wooden soldier pile wall and short concrete section		Objective: Slow marine-induced erosion of bluff toe	
Fetch: 5.0 mi NE Wave energy: Medium Aspect: Northeast	Land Use: Residential MHHW: +8.4 ft MLLW Toe Elev: +7.7 ft MLLW	Structure: Single-family home Setback: 50 ft Risk Index: 25	Benefit Index: 11 Impact Index: -16 Total BI Index: -5



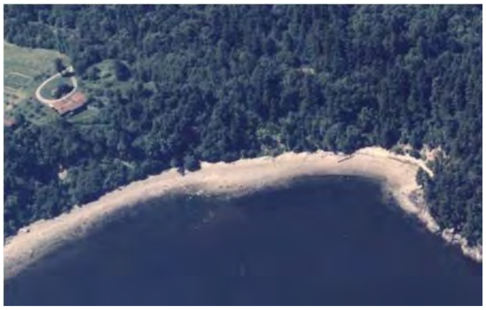
Project site as red star with dots showing all other vertical bulkhead projects Sound-wide.

Project Background

The site is on the northwest portion of Samish Island within drift cell SK-C-6, which has eastward net shore-drift to the barrier beach and an altered barrier lagoon. The lagoon, known as Freestad Lake, is the subject of a restoration project. The high bluffs of western Samish Island are the only feeder bluffs providing sediment for the drift cell, of which only several reaches remain unmodified. The central portion of the drift cell has been almost completely modified for many decades, with subsequent down-drift erosion as documented in Canning and Shipman (1995) and Johannessen and Chase (2003).

The soldier pile wall was installed along an approximately 600-ft-long reach of high bluff, all within the same ownership, reportedly to halt wave attack and toe erosion. The high bluff (130 to 140 ft high) is composed of Vashon till overlying pebbly sand and sand of Vashon advance outwash deposits. The eastern and central portions of the bulkhead reach had experienced several large landslides in the 20 years preceding installation. The west-central portion of the bulkhead shore appeared to have been a transitional area in terms of bluff instability, and the western portion to have been moderately stable and forested with near-mature Douglas firs. Substantial sediment input was coming from the more western bluffs through surficial landslides in sandy sediment overlain by till.

The house, built in 1958, was set back at least 50 ft from the bluff crest above the eastern portion of the bulkhead. No buildings or other substantial improvements lay above the central portion of the bulkhead except for a trail down the bank, apparently a remnant of an early 1900s log-dump road. A small boathouse and aerial tram base lay above the eastern end of the bulkhead. A small concrete bulkhead had been uprighted immediately east of the subject bulkhead and extended for approximately 60 ft. No bulkheads were present west of the soldier pile wall, where the shore curved around to face the east before transitioning into a rocky headland.

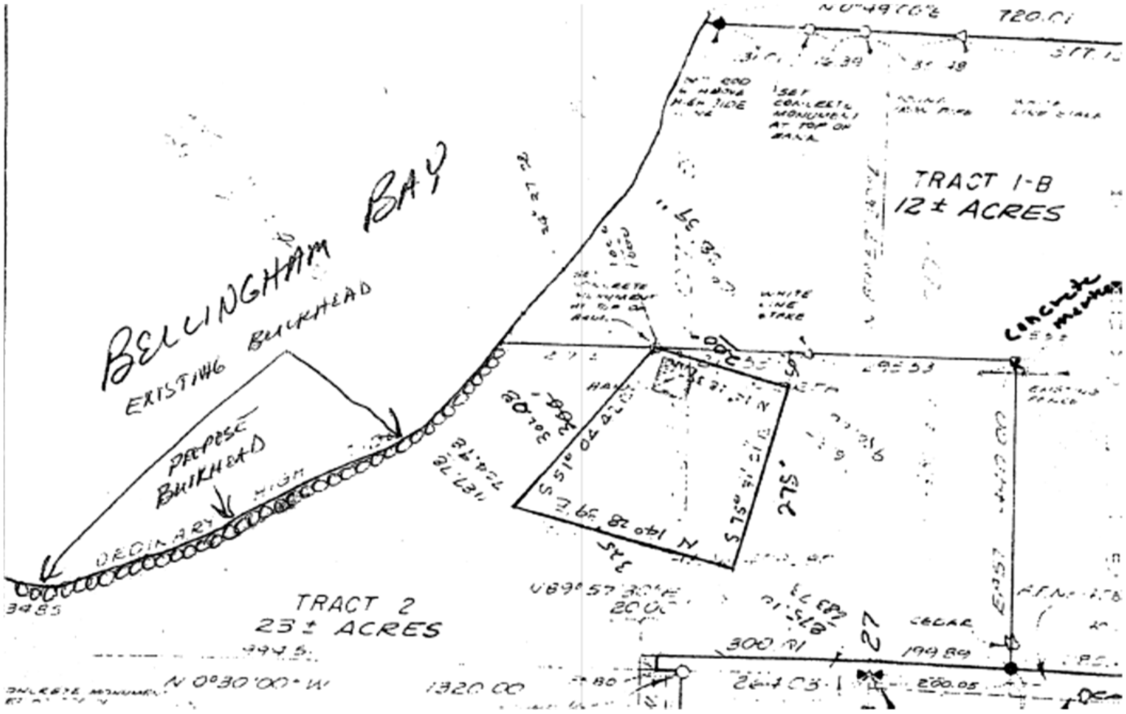


Oblique aerial view of the site from 1977. Landslides visible northwest of the site (to right). (The only photos showing preproject conditions are aerial views.)

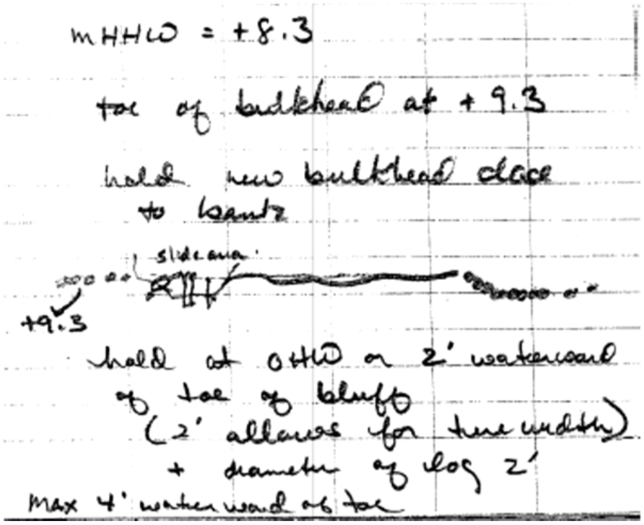
Oblique 1994 aerial view with an older bulkhead present. Large landslide visible in east-central bulkhead area, with smaller failure to right.

Design

- Few design documents were available. The bulkhead was reportedly installed in three stages, working from east to west, in successive summers of 1997 to 1999. Aerial photos from 1994 showed some form of bulkhead was already present in the eastern portion of the area.
- The approximately 600 ft of bulkhead consisted of tightly placed soldier piles with an average diameter of 1.7 ft (range of 1.4 to 2.4 ft). Permit notes stated that the wall was allowed to extend up to 2 ft waterward of the bank toe with a maximum encroachment width over the beach of 4 ft.
- Soldier piles were “boom stick” logs from Canada purchased out of Anacortes, Washington. The logs were reportedly sound when installed, but likely had some damage from worms and years of exposure to marine waters.
- Piles extended approximately 4.2 to 6 ft above beach grade during the assessment. According to the owner, the depth of footing was approximately 4 to 6 ft below beach grade.
- The soldier pile wall had a continuous wooden whaler (a long board bolted in front of the piles) composed of 18-ft lengths of 4- by 12-in horizontal timbers on the upper, front face of the wall. Joints between the whalers were overlapped on the front face by additional 10-ft lengths of timbers.
- The down-drift section was an older, badly damaged vertical concrete bulkhead, approximately 60 ft long and 1.2 ft thick, which was not specifically assessed.



Project design drawing.



mHHW = +8.3

toe of bulkhead at +9.3

hold new bulkhead close
to bank

slide area

+9.3

hold at OHW or 2' waterward
of toe of bluff
(2' allows for tree width)
+ diameter of log 2'
Max 4' waterward of toe

Additional archived design details.

Current Conditions

Technique Condition – Degradation of the piles immediately above beach level and on the tops of piles was minor to moderate. Many portions of the bulkhead had damage to the piles from rot. The most deterioration was in the sediment line where landslides had caused some piles to lean waterward, but gaps were still minimal and limited to several inches. Whalers all appeared to be sound. Flanking erosion had not gotten behind either wall end, but small amounts of wood appeared to have been added to the ends over the years.

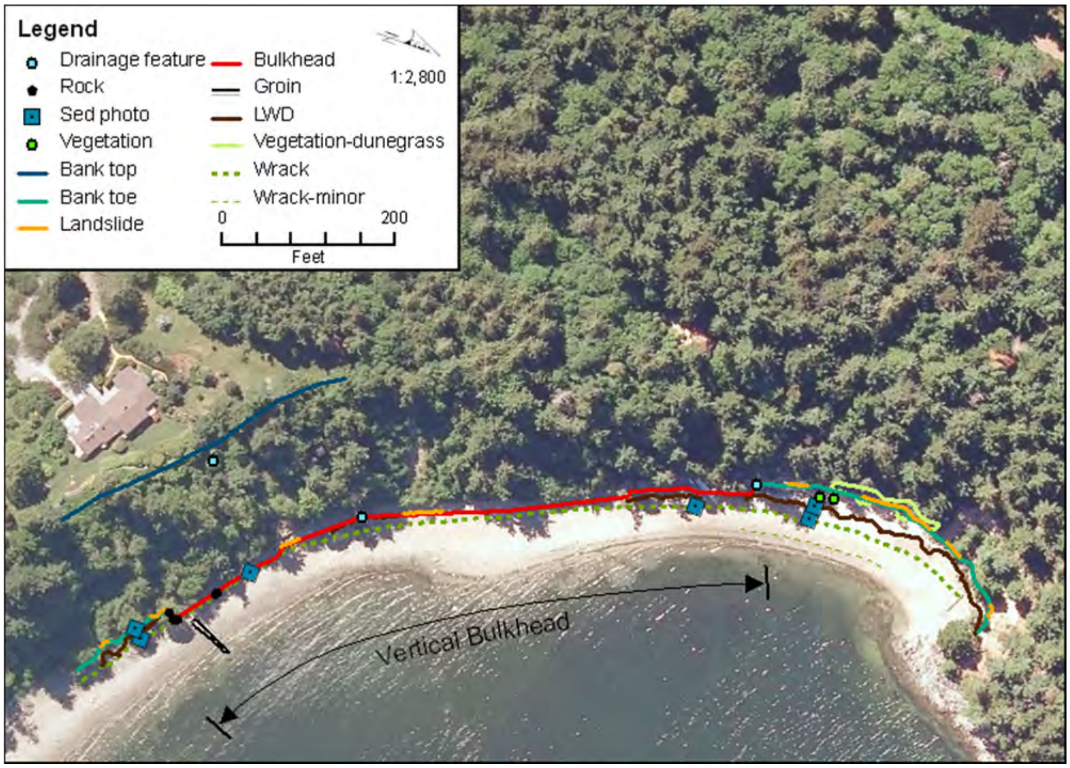
Upland Threats – The soldier pile wall seemed to have been functioning well to stop wave attack at the toe of the bluff since installation in 1997–1999. The house and other improvements did not appear threatened by erosion or slope instability. An aerial tram and a ramp that ran down the bank to land on the level area behind the bulkhead were well protected.

Beach Characteristics – A mix of medium pebble with moderate amounts of sand covered the western and central portions of the beach waterward of the bulkhead. The backshore log zone was very wide west of the project, very narrow at the west end of the bulkhead, and absent along the large majority of the bulkhead as the structure projected over the backshore. The upper intertidal zone contained a continuous band of good potential spawning substrate for forage fish. This band narrowed sharply along the eastern portion of the bulkhead and adjacent areas to the east, where waves driven by the northwest wind changed the dominant substrate to cobble.

Adjacent Shores – End erosion was observed extending up to 5 ft landward along approximately 35 ft of shore adjacent to the western end of the bulkhead. This erosion appeared to exceed background erosion, as it was more pronounced in the area adjacent to the wall. Similar erosion extended for approximately 10 ft alongshore at the east end of the concrete wall immediately adjacent to the subject bulkhead.

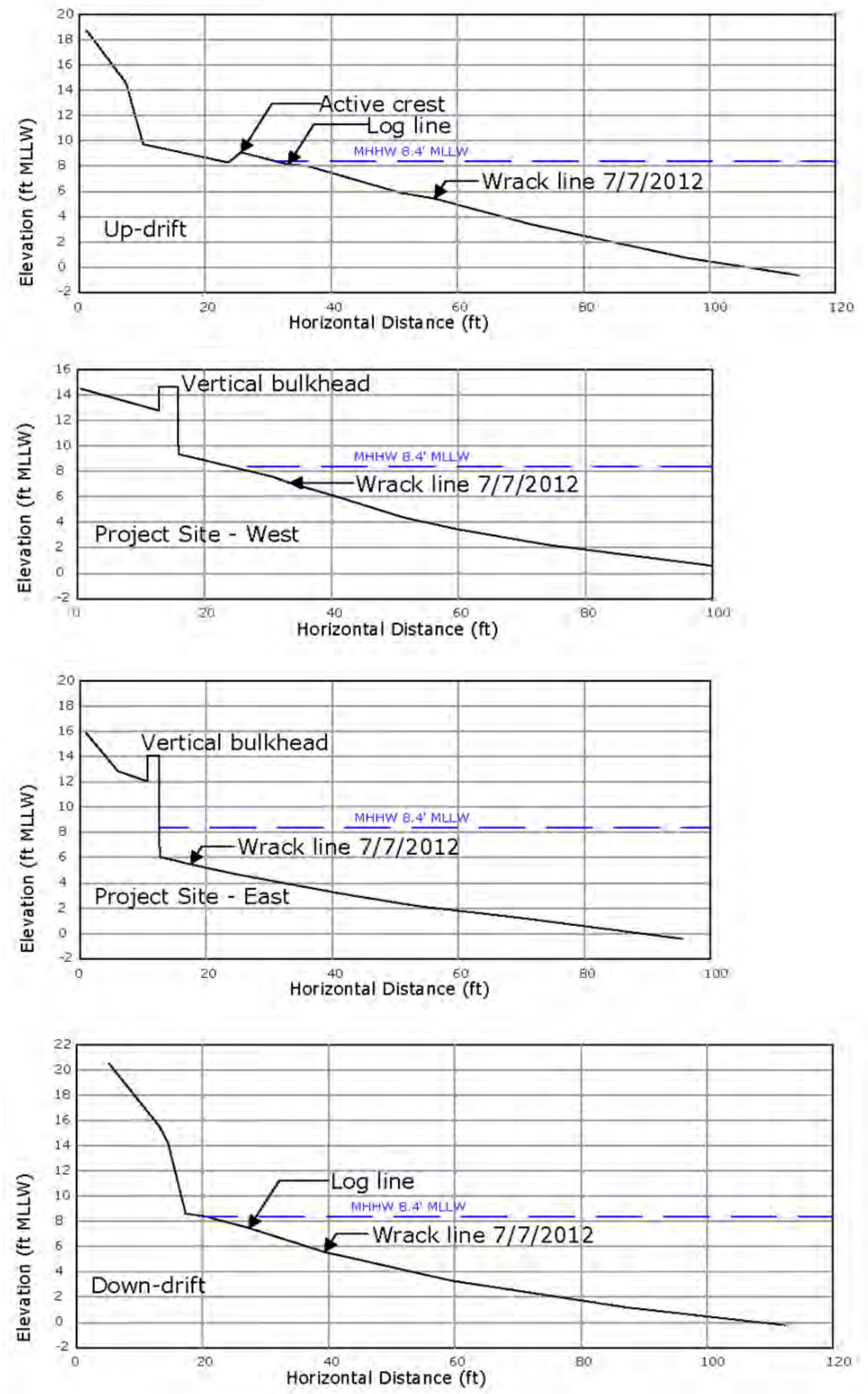
Eastern portion of vertical soldier pile bulkhead looking down-drift in 2012.

Up-drift beach and vertical soldier pile bulkhead looking down-drift in 2012.



Current beach and bluff characteristics as observed and collected in July 2012.

Project site map with profile locations.



Beach profiles measured during the 2012 site visit.

Comparison of beach surface sediment at project and adjacent sites. n/a indicates the location was not present for sampling.

Location	Backshore	Difference	Upper intertidal	Difference
Up-drift	SAND	n/a	MEDIUM PEBBLE, sand	similar
Project site	n/a	-	MEDIUM PEBBLE, sand	-
Down-drift	SAND, fine pebble	n/a	COARSE PEBBLE, medium pebble, sand	coarser

Performance

The soldier pile wall has generally performed well since installation in 1997–1999. Maintenance appeared to have been limited to the addition of several small piles and miscellaneous pieces of driftwood placed at both ends of the wall. One long section of wall was leaning waterward and could potentially fall in coming years, and some rot and wood degradation has occurred at beach level and at the top of piles, limiting the functional life of the structure. The site bluff had been mapped as "unstable" in the 1979 Coastal Zone Atlas of Washington, although no recent slides had been mapped. Older air photos, site reconnaissance, and the owner highlighted the occurrence of landslides at the site, particularly its eastern portion. The frequency of landslides at the bluff appeared to have been reduced, although several have occurred since installation of the wall, up until 2008–2009. To the extent that the bulkhead protects the bluff and the structures behind it from erosion, it likely represents the loss of 600 ft of feeder bluff and feeder bluff exceptional (very high sediment input bluff), leading to down-drift impacts.

Other findings and observations included the following:

- The bulkhead has buried a moderate amount of backshore, as the wall placement encroached beyond the maximum allowed by permit notes (4 ft horizontal), especially in the western reaches.
- The difference in the location of the ends of the structure relative to adjacent unmodified bluffs (which shows greater horizontal offset) may be partially due to passive or background erosion but bluff toe erosion appears greater at the ends of the structure, such that it appears at least exacerbated by the wall. High-energy waves from the long northwest fetch will likely lead to erosion beyond the eastern end of the structures.
- The typical band of large woody debris (LWD) was mostly absent where the bulkhead was present.
- Adjacent sediment was similar, although down-drift sediment was coarser, likely due to the higher wave energy and a different lower-beach elevation.

Overall, this relatively low-cost installation has been effective to date, showed some signs that structural integrity could decline, and has caused moderate on- and off-site impacts.

Project performance scoring.

Category	Parameter	Rating	Score	Rationale
Benefits	Effectively mitigated landward erosion	High*	6	Landward erosion stopped since installation
	Sediment volume augmented	None	0	No structure removal or nourishment
	Input/exchange of LWD, detritus	Low	1	Allows alongshore exchange
	Backshore vegetation enhanced	None	0	No planting occurred
	Marine riparian vegetation enhanced	None	0	No planting occurred
	Low-cost and simple installation	Med	2	$60,000 for project, $135/LF (1998)
Impacts	Structures bury backshore/intertidal	High	-3	Structure installation buried 4 to 8 ft of backshore
	Structures impound littoral sediment	High	-3	Very high as bank greater than 80 ft high (historical feeder bluff) with good beach-quality sediment
	Coarser/steeper beach profiles created	High	-3	Project site has 7.1:1 slope; reference site has 8.5:1 slope
	LWD/detritus recruitment reduced	High	-3	Very little LWD onsite, no band along most of wall; 16 ft wide up-drift; 10 ft wide down-drift
	End erosion adjacent	High	-3	Both ends had over 2 ft of erosion
	Required maintenance interval	None	0	Owner has not needed to do maintenance in over 22 years since installation (although piles now show a moderate amount of deterioration)
Design-specific benefits	Structural integrity & function maintained	Med	2	Structure was leaning waterward in one long section, and had some wood rot at beach level and top of piles
	Cross-shore location of exposed toe of structure	None	0	Exposed toe of structure is below MHHW for some of length
Design-specific impacts	Scour at structure	None	0	No scour evident
	Debris on beach from structure	Low	-1	Rock on beach apparently from structure, less than 20SF/100LF
Total			-5	

*Scores at double other values (e.g., high=6); all others, none=0, low=1, med=2, high=3

Totaling the above scores, benefits equal +11 points and impacts equal -16 points, for a final combined score of -5.

SKYLINE MARINA – Vertical Bulkhead (1985)

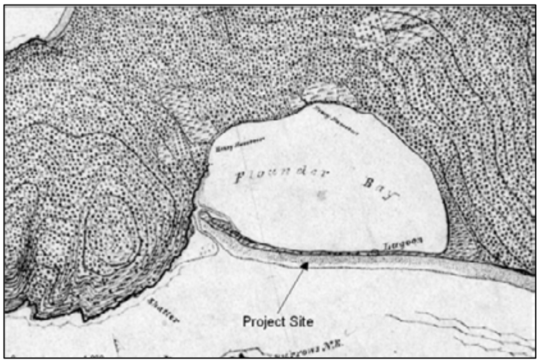
Waterbody: Burrows Bay	Shoretype: Artificial (historically barrier beach)	Net Shore-drift Cell: SK-D-3	Direction: Northeastward to bedrock at Fidalgo Head
Project Elements: Concrete vertical bulkhead		Objective: Shore protection for filled and developed barrier beach	
Fetch: 15 mi SSW Wave Energy: High Aspect: South	Land Use: Residential MHHW: +7.9 ft MLLW Toe Elev: +9.1 ft MLLW	Structure: Condominium Setback: 28 ft Risk Index: 35	Benefit Index: 12 Impact Index: -13 Total BI Index: -1

Project site as red star with dots showing all other vertical bulkhead projects Sound-wide

Project Background

This site at the northern shore of Burrows Bay is on a high-wave-energy narrow spit, most of which has been modified with hard structures. Historically it was a barrier beach extending east to west across the mouth of Flounder Bay. A tide channel at the west end of the spit prior to development served as the terminus of drift cell SK-D-3. This is a classic example of an alteration of natural coastal processes by artificially placing an inlet channel on the up-drift side of the barrier spit. The jetty and dredged channel east of the site now intercept the large majority of littoral sediment.

The spit was likely only 3 to 4 ft above the elevation of MHHW in its natural condition, with fringing salt marsh on the bay side. The spit would have been overwashed by extreme high tides. Historical development included a large cannery in this general vicinity. Prior to development of the condominiums, a substantial volume of fill was placed at the site, apparently primarily on the landward side of the spit, for development of housing, parking, and access roads. Because minimal building setbacks (25 to 35 ft) were in effect until very recently in the City of Anacortes, the condominiums were built very close to this high-energy beach. This apparently led to the perceived need for a minimal-footprint, vertical structure for shore protection.



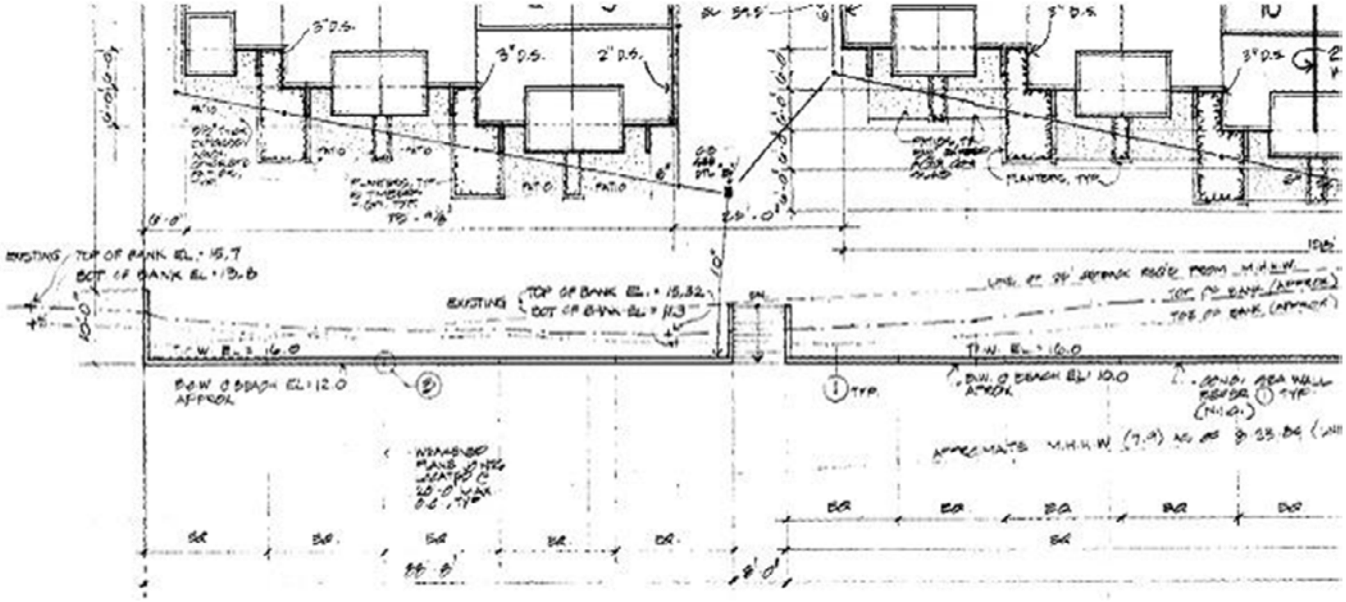
Topographic sheet (T-sheet) 1885 shows historical Flounder Bay with barrier beach and barrier estuary. Note the tide channel was on the west.

Oblique aerial photo from 1977 before the condominium complex and vertical bulkhead installation, and before the marina jetty was installed up-drift of the project site (Washington State Department of Ecology photo).

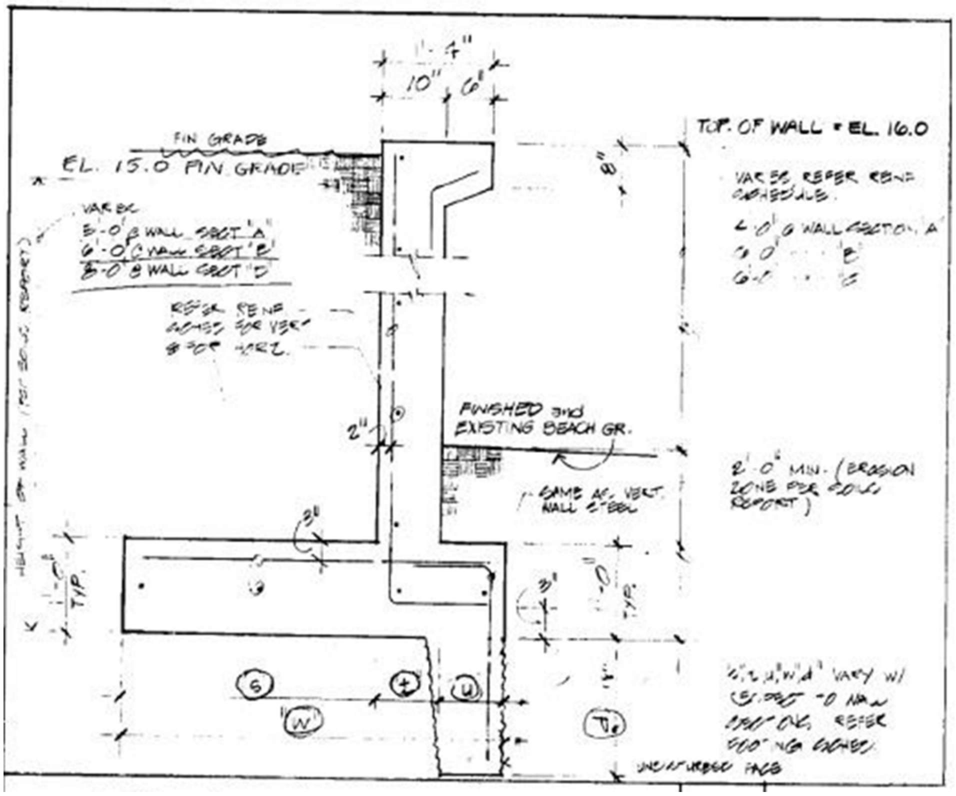
Design

Design elements included the following:

- A nearly continuous vertical concrete bulkhead in three sections, beginning 1,270 ft down-drift of the marina jetty.
- A total bulkhead length of 335 ft. The up-drift section was 65 ft long and set 10 ft landward of the other two sections, the middle section 175 ft long, and the down-drift section 85 ft long; with 10-ft-wide access stairs between middle- and down-drift sections (shown in plan view).
- A 1.5 ft wide band of quarry spalls used landward along three sections of the bulkhead top for drainage.
- Construction of the wall to an elevation of +16 ft MLLW, resulting in a 7 ft high vertical wall at project site. Concrete thickness was 16 in, with a 6 in formed concrete recurve at the top of the front face of the wall.
- 2 ft of elevation in design for “erosion zone.”



Project design drawing (design by Matthews and Henry Architects).



Bulkhead design cross section (design by Matthews and Henry Architects).

Current Conditions

Technique condition – The concrete bulkhead was relatively intact, with minor exposure of footings 150 ft south of the project site profile. The upper beach habitat has been impacted by the location and elevation of the concrete bulkhead, which leaves little or no room for a backshore area.

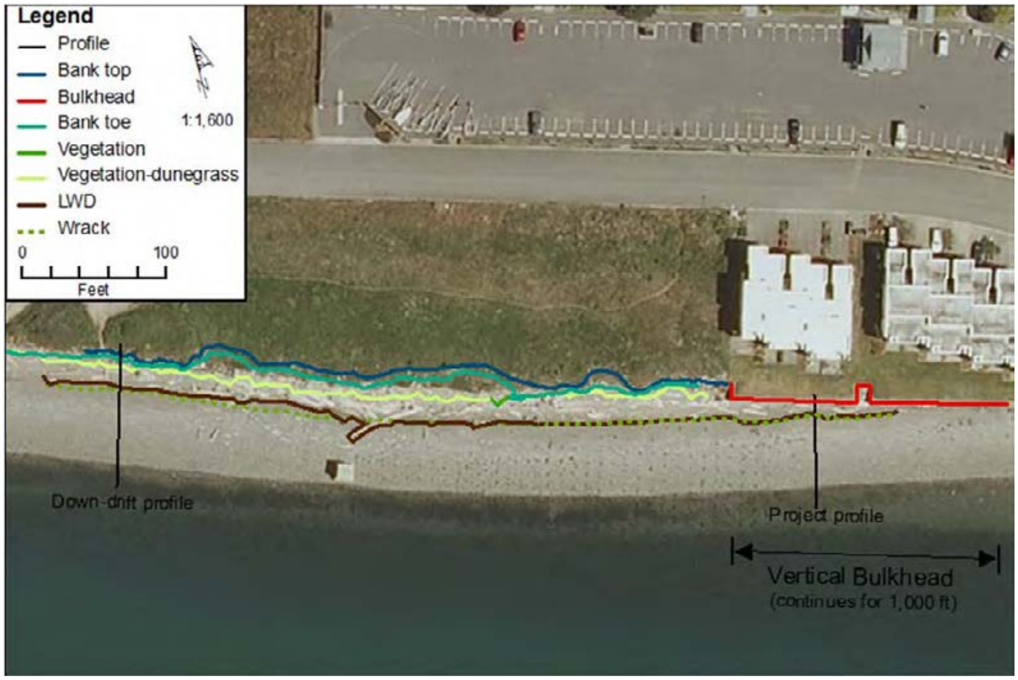
Upland threats –The westernmost condominiums that were the focus of the field survey have a minimal setback of approximately 28 ft. The buildings were constructed on built-up fill over a historical barrier beach (see photo and T-sheet overlay below). At present, the bulkhead has provided sufficient shore protection for both the buildings and the front yards adjacent to the buildings.

Beach characteristics – The beach was coarse and dominated by cobble and large pebble. Sand was found below the surface cobble and pebble in the mid-intertidal and backshore areas.

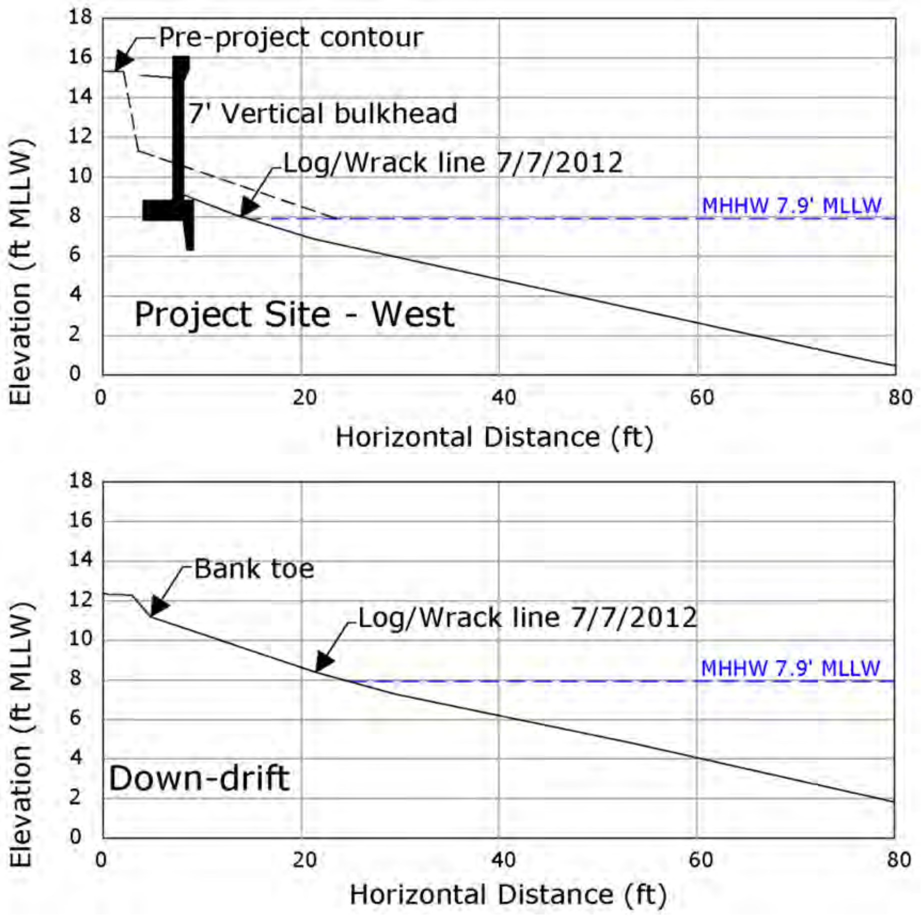
Adjacent shores – The up-drift shore, which was not surveyed, has been severely impacted by fill and structures over the upper beach. The up-drift shore no longer receives sediment through littoral drift (though it did prior to marine construction) because the marine inlet and associated jetty have truncated sediment transport down-drift. Uplands in the undeveloped area down-drift of the project site likely comprise fill material built up for a cannery operation. Remnants of this cannery included large concrete debris, slag deposits, and approximately 100 piling stubs. Large woody debris (LWD) recruitment was abundant, and various types of native vegetation, including dunegrass, have colonized the backshore. Toe erosion was also apparent in the uplands, which were approximately 2.5 to 3 ft above the backshore elevation.

Site profile in 2012, looking up-drift and showing marina jetty in background and sparsely scattered riprap.

Down-drift reference site profile looking towards project site in 2012. 1 m^2 quadrant for reference.



Map of project site with GPS data and profile locations.



Beach profiles measured during the 2012 site visit.

Comparison of beach surface sediment at project and adjacent sites. n/a indicates the location was not present for sampling.

Location	Backshore	Difference	Upper intertidal	Difference
Up-drift	n/a	-	n/a	-
Project site	n/a	-	COBBLE, coarse pebble	-
Down-drift	COARSE PEBBLE	-	COBBLE, coarse pebble	same

Performance

The bulkhead did not show significant signs of deterioration. Cracking, if any, was very minor. Up to 0.5 ft of the top of the bulkhead footing was exposed along approximately 15 linear ft up-drift of where the project profile was taken. That would leave about 2.5 to 3 ft of the footing below the current beach grade. Design drawings showed the top of the footing at least 2 ft below beach grade at the time of design, so the upper beach appeared to have lost at least 2 ft of elevation in this area since installation. Overall, the vertical bulkhead has maintained its structural integrity even though the upper beach appeared to have dropped a moderate amount.

Other conclusions included the following:

- Although the beach has likely dropped due to the improper siting of the inlet channel up-drift of the spit and loss of littoral drift sediment, the presence of the vertical face wall may have contributed to local beach scour.
- There was no sign of recent overwash or damage to the filled uplands, which showed that the wall was sufficiently high for protection.
- Minor protection of the bulkhead toe in the form of large boulders had been added at an unknown time. These boulders, found throughout the beach profile, were assumed to have toppled and moved waterward due to high wave energy.
- The deep footing and adequate crest elevation seem to have been important factors for maintaining the integrity of this wall in this high-energy and sediment-starved setting.

Project performance scoring.

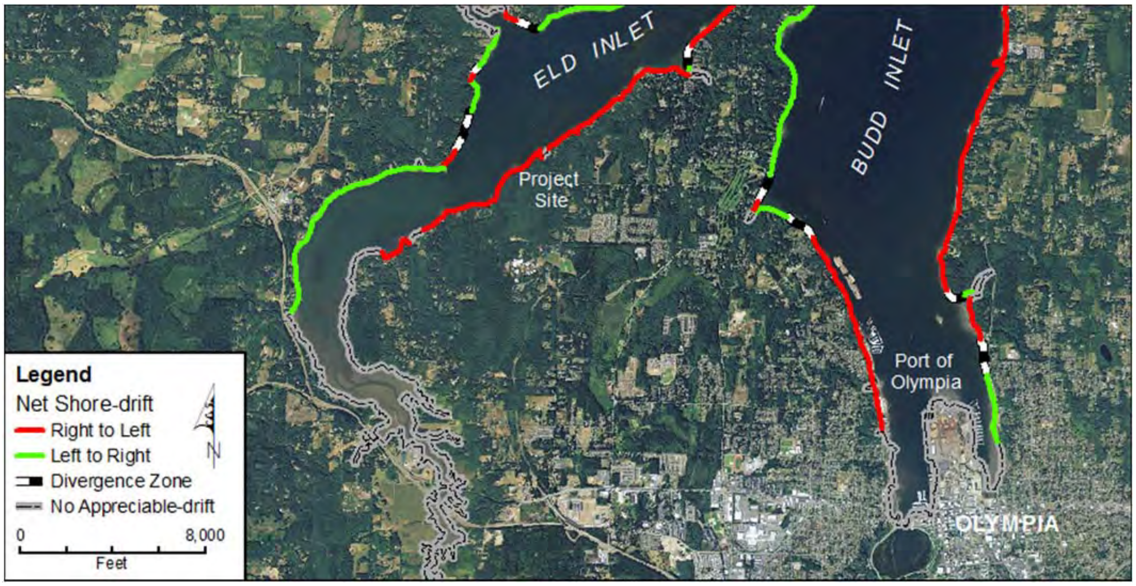
Category	Parameter	Rating	Score	Rationale
Benefits	Effectively mitigated landward erosion	High*	6	Landward erosion stopped since installation
	Sediment volume augmented	None	0	No structure removal or nourishment
	Input/exchange of LWD, detritus	Low	1	Allows alongshore exchange
	Backshore vegetation enhanced	None	0	No planting occurred
	Marine riparian vegetation enhanced	None	0	No planting occurred
	Low-cost and simple installation	None	0	Project was greater than $200/LF
Impacts	Structures bury backshore & intertidal areas	High	-3	Structure installation buried more than 7 ft (average) of backshore
	Structures impound littoral sediment	Low	-1	Bank height is less than 5 ft
	Coarser/steeper beach profiles created	None	0	Project site and reference site have same slopes
	LWD/detritus recruitment reduced	High	-3	6 ft LWD band width onsite, 17 ft LWD band width at reference site
	Adjacent end erosion	High	-3	West-end erosion is greater than 4 ft
	Required maintenance interval	None	0	Has not needed maintenance since installation
Design-specific benefits	Structural integrity & function maintained	High	3	Structure has not deteriorated
	Cross-shore location of exposed toe of structure	Med	2	Exposed toe of structure is above midpoint
Design-specific impacts	Scour at structure	Med	-2	Footing of structure exposed slightly but not for the entire project
	Debris on beach from structure	Low	-1	Minor toe protection needed since original installation
Total			-1	

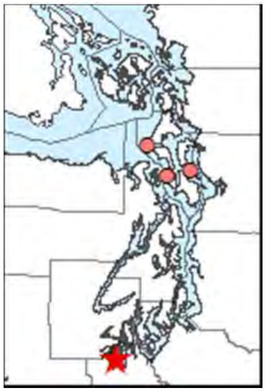
*Scores at double other values (e.g., high=6); all others, none=0, low=1, med=2, high=3

Totaling the above scores, benefits equal +12 points and impacts equal -13 points, for a final combined score of -1.

SNYDER POINT – Vertical Bulkhead (1990)

Waterbody: Eld Inlet	Shoretype: Bluff-backed beach	Net Shore-drift Cell: TH-11-1	Direction: Northeast
Project Elements: Vertical concrete wall		Objective: Slow coastal erosion and protect a large Douglas fir tree.	
Fetch: 2.7 mi NE Wave Energy: Low Aspect: Northwest	Land Use: Undeveloped institutional MHHW: +14.23 ft MLLW Toe Elev: +15.52 ft MLLW	Structure: None Setback: n/a Risk Index: 6	Benefit Index: 10 Impact Index: -8 Total BI Index: 2





Project site as red star with dots showing all other vertical bulkhead projects Sound-wide.

Project Background

The Snyder Point study area encompassed the terminus of drift cell TH-11-1, which originates at White Point. Sediment is transported northeastward alongshore. The cell terminates at the recurved spit just east of the subject bulkhead. A number of eroding bluffs (feeder bluffs, or sediment sources) exist up-drift of the bulkhead area. Shallow landslides and toe erosion up-drift (southwest) of the study area naturally nourish and sustain the down-drift beaches and enhance the resilience of the site beach and depositional landform just east of the bulkhead. Although considerable bulkheading (sediment impoundment) occurs up-drift of the study area, numerous eroding bluffs, including those close to the study-area shore, supply nearshore sediment in the drift cell. As a result, it is unlikely that the beach within the study area is experiencing erosion due to degradation of sediment supply in this low-wave-energy environment.

The uplands in the study area generally decline in elevation moving northeast and transition from medium-height bluff to low-bank to no-bank shores. Field observations of the exposed strata of the bluff indicated that the bluff landward of the concrete bulkhead at Snyder Point comprises undivided, Pre-Vashon sand and gravel deposits. These deposits contain virtually 100% beach-quality sediment and are generally less resistant to erosion than till. The northern bluff deposits at the tip of Snyder Point are more consolidated and resistant to erosion, with a slightly higher angle of repose, than those of the southwest bluff.

In the 1970s a short reach of low-elevation vertical bulkhead curved around the tip of the spit below a large Douglas fir tree.

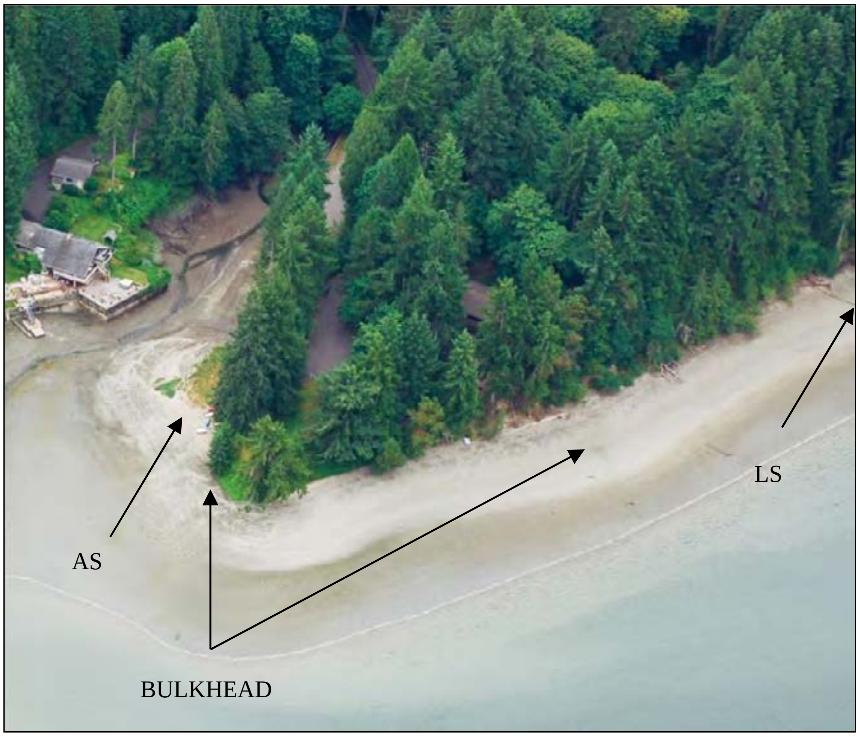
Earlier bulkhead looking northeast in the 1970s.

Earlier, shorter bulkhead looking southeast in the 1970s.

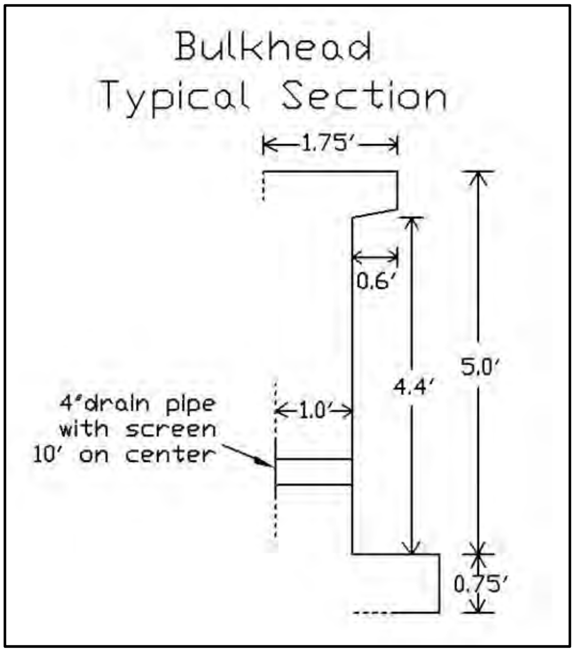
Design

This vertical bulkhead was constructed sometime in the early 1990s along a moderate-low-bank site on the east shore of Eld Inlet in southern Puget Sound. Maximum measured fetch at the site is less than 2 miles, resulting in a very low erosion potential. A building was located approximately 50 ft landward of the bluff crest along an area unprotected by the bulkhead. Prior to the installation of the current bulkhead, a smaller wall of concrete rubble and mortar with some large boulders had been constructed at the tip of Snyder Point (pictured above), reportedly to protect a large Douglas fir tree that was being undermined by slow bank erosion.

The present vertical bulkhead was a formed and poured concrete wall. A design could not be located, but a wall cross-section was drawn from measurements by CGS. The bulkhead, which contained some backfill, extended below MHHW.



Vertical bulkhead area, showing down-drift accretion shoreform (AS), bulkhead extent (BULKHEAD) and small landslide areas (LS) on a Washington Department of Ecology oblique aerial photograph from 2006.



Vertical bulkhead cross section as measured in the field. (No designs were available).

Current Conditions

Technique condition - The bulkhead measured 216 ft long, including the return walls at each end. Concrete stairways that served as the main access to the beach were found at both ends of the wall. The top of the bulkhead was +18.5 ft MLLW and this remained fairly constant throughout its length. Approximately 60 ft of bulkhead had a toe elevation below MHHW. The lowest bulkhead toe elevation, +13.9 ft MLLW, was found at the very tip of Snyder Point, immediately waterward of a large Douglas fir tree. The bulkhead measured 5.75 ft high from the bottom of the footing to the top. The bulkhead footing consisted of unformed poured concrete, while the wall and cap were composed of 10- to 30-ft formed sections. Drain holes were at 10-ft intervals in the forms using 4-in plastic pipe with wire mesh behind. Investigation through the drain holes revealed the bulkhead thickness at 1.0 ft. It appeared that there was fill behind the wall, specifically at the north point where the large Douglas fir tree was protected. Based on the distance that the bulkhead appeared to be from the location of the natural bank, it seemed likely that the original concrete rubble and mortar bulkhead built in the 1980s still remained behind the concrete structure. Excavations were made to the base of the wall footing, and it appeared that the wall was constructed directly on the firm surface below the beach level.

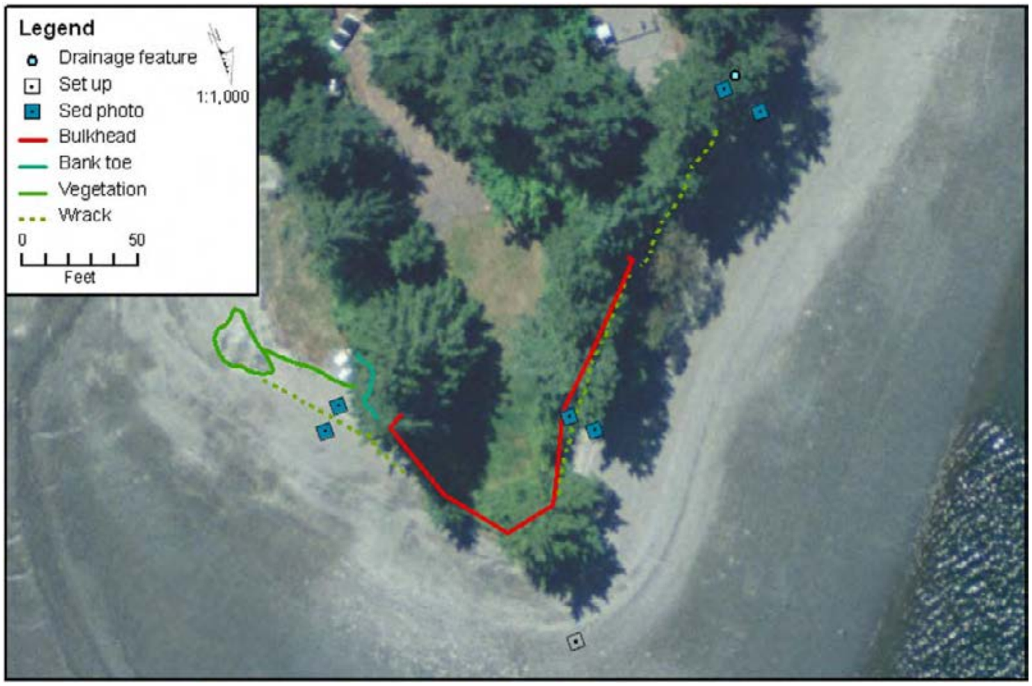
Upland threats - There were no threats to the upland. There was a large Douglas fir tree on the corner and no infrastructure except a minor trail protected by the bulkhead.

Beach characteristics - The beach fronting the bulkhead was probed, and firm underlying deposits were identified at 0 to greater than 2 ft below beach level. There was no wrack line waterward of the wall for 70 linear ft of the bulkhead. The substrate waterward of the bulkhead was medium pebble and sand.

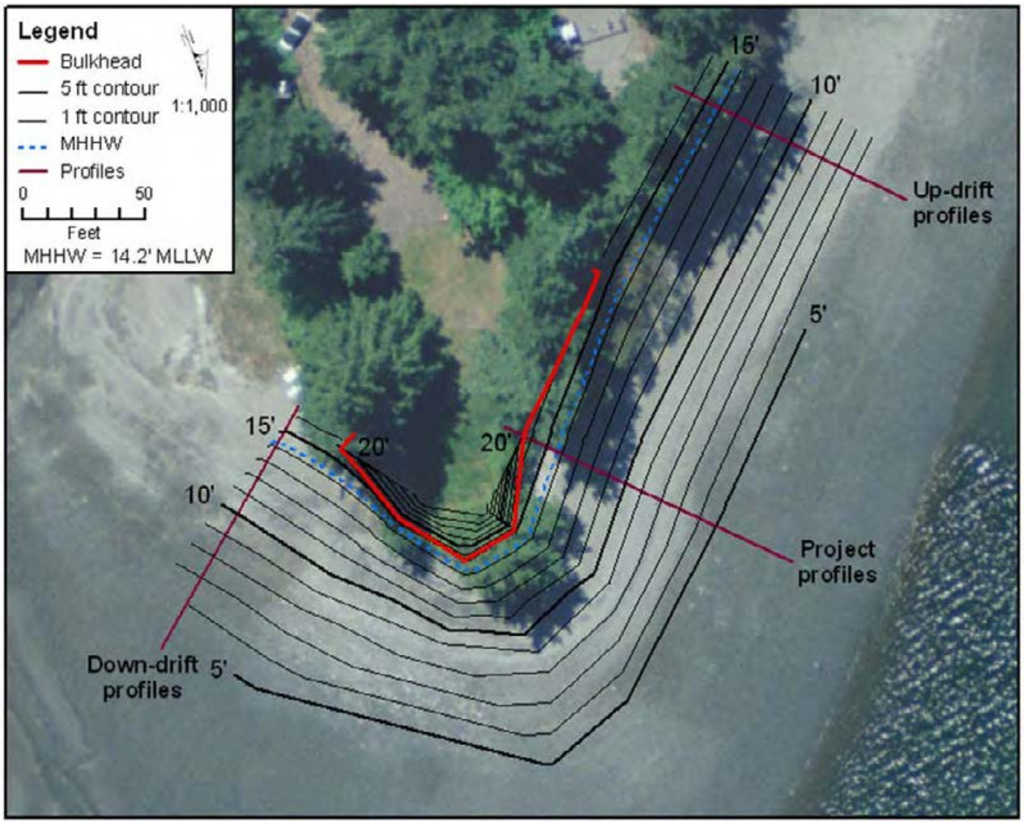
Adjacent shores -The down-drift beach profile showed a slope change, steepening from 9.9:1 to 7.9:1 between 2009 and 2012. The up-drift location had coarse pebble, medium pebble, and sand for upper intertidal beach substrate, while the down-drift location had the same upper intertidal substrate as the project site: medium pebble and sand.

Bulkhead looking northeast in 2009.

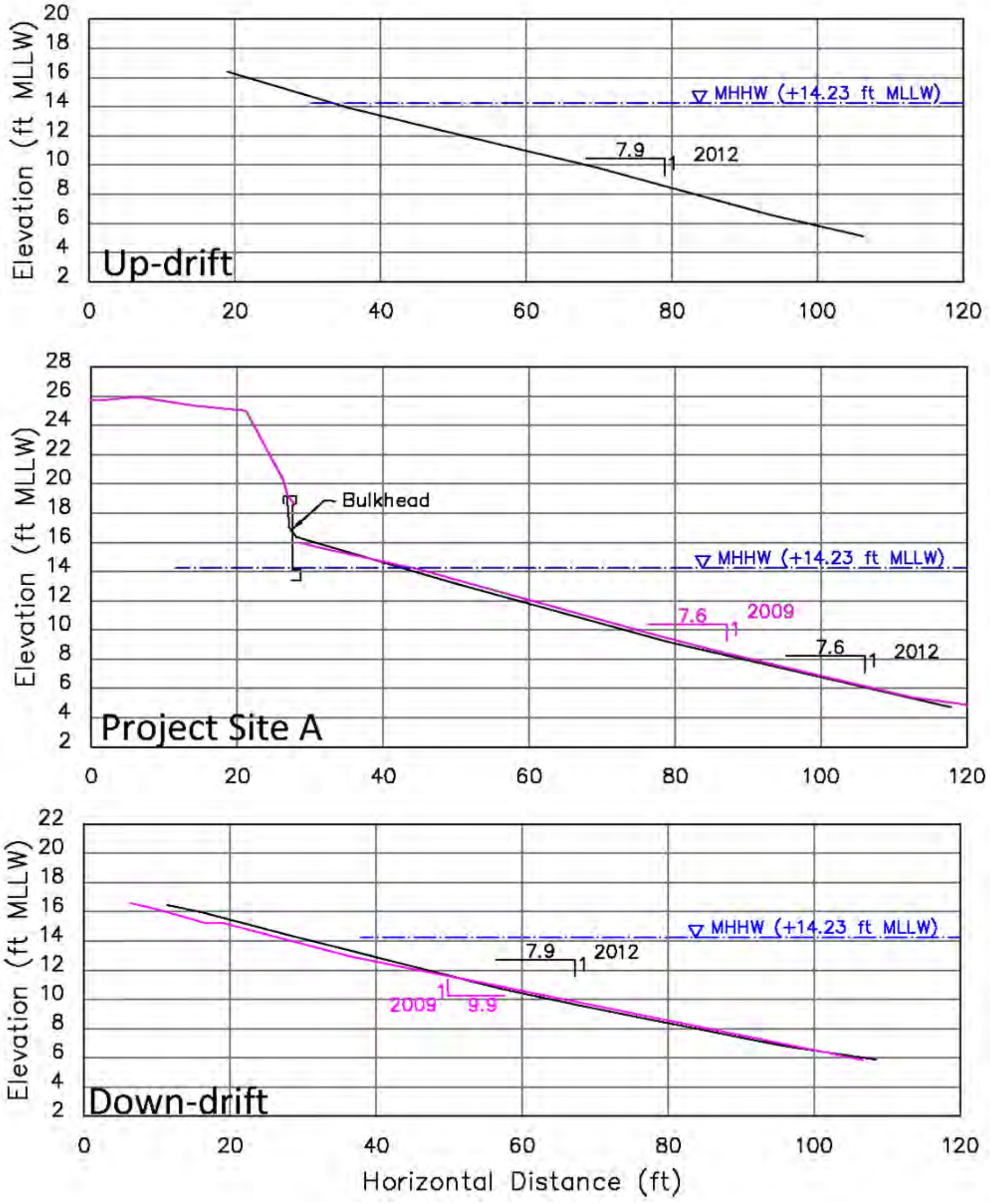
Bulkhead looking southeast from the point of Snyder Point in 2012.



Map of field data obtained with GPS.



Topographic map of Snyder Point with profile locations.



Beach profiles measured during site visits in 2009 and 2012.

Comparison of beach surface sediment at project and adjacent sites.

Location	Backshore	Difference	Upper intertidal	Difference
Up-drift	COARSE PEBBLE, medium pebble	coarser	COARSE PEBBLE, medium pebble, sand	coarser
Project site	SAND, medium pebble	-	MEDIUM PEBBLE, sand	-
Down-drift	SAND, fine pebble	coarser	MEDIUM PEBBLE, sand	similar

Performance

The bulkhead did not show significant signs of deterioration. Cracking, if any, was very minor. English ivy has grown over the structure and small trees in the upland have extended their boughs over it, shading the upper beach. End-effect erosion has caused minor upper beach scour below the down-drift access stairs, but has not compromised the structure. The bulkhead remained in place to protect a large Douglas-fir since no infrastructure except a minor trail was present landward of the bulkhead.

Project performance scoring.

Category	Parameter	Rating	Score	Rationale
Benefits	Effectively mitigated landward erosion	High*	6	Landward erosion stopped since installation
	Sediment volume augmented	None	0	No structure removal or nourishment
	Input/exchange of LWD, detritus	None	0	Revetment acts as cross-shore barrier
	Backshore vegetation enhanced	None	0	No planting occurred
	Marine riparian vegetation enhanced	None	0	No planting occurred but structure allowed a few upland trees to extend their boughs over it
	Low-cost and simple installation	None	0	Assume more expensive than $200/LF
Impacts	Structures bury backshore & intertidal areas	Low	-2	Structure installation estimated to have buried an average of 3 to 4 ft of backshore
	Structures impound littoral sediment	Med	-2	Bank height is greater than 5 ft but less than 30 ft
	Coarser/steeper beach profiles created	Med	-2	Project site beach had 7.2:1 slope, while reference site had 7.9:1 slope
	LWD/detritus recruitment reduced	None	0	No logline on-site or on reference site
	End erosion adjacent	Med	-2	Both ends had minor (less than 2 ft) erosion
	Required maintenance interval	None	0	No known maintenance in over 30 years since installation
Design-specific benefits	Structural integrity & function maintained	High	3	Structure has not deteriorated
	Cross-shore location of exposed structure toe	Low	1	Exposed toe of structure is just above MHHW
Design-specific impacts	Scour at structure	None	0	No scour evident
	Debris on beach from structure	None	0	Beach sediment only present
Total			2	

*Scores at double other values (e.g., high=6); all others, none=0, low=1, med=2, high=3.

Totaling the above scores, benefits equal +10 points and impacts equal -8 points, for a final combined score of +2.

SWAN LAKE – Vertical Bulkhead (1998)

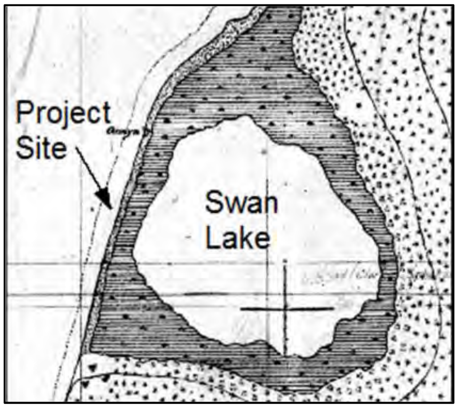
Waterbody: Admiralty Inlet	Shoretype: Barrier beach	Net Shore-drift Cell: WHID-25	Direction: Northward to Deception Pass
Project Elements: Soldier pile vertical bulkhead		Objective: Protect site for single-family residence from wave erosion	
Fetch: 70 mi W Wave Energy: High Aspect: West	Land Use: Residential MHHW: +7.5 ft MLLW Toe Elev: +8.9 ft MLLW	Structure: None Setback: n/a Risk Index: 10	Benefit Index: 6 Impact Index: -8 Total BI Index: -2

Project site as red star with dots showing all other vertical bulkhead projects Sound-wide.

Project Background

The berm at Swan Lake is a large modified barrier spit. Originally it was a narrow, low-elevation landform created by northward net shore-drift and frequent overwash. The berm has impounded the large lagoonal marsh complex called Swan Lake. Historical mapping from 1871 showed the berm at the project site as only about 55 ft across from mean high water (MHW) at the beach to MHW at the lagoon; wider areas of salt marsh were present on the landward side of the berm.

The site is exposed to a high-wave-energy climate, with swell and substantial wind waves from the Strait of Juan de Fuca. A series of bulkhead failures has occurred in the southern Swan Lake berm area, including the failure within one season of a large concrete wall south of the existing houses. Other houses have had bulkhead replacements and repairs over recent decades; these included addition of riprap at the toe of vertical walls for scour protection by almost all owners of vertical wall structures.



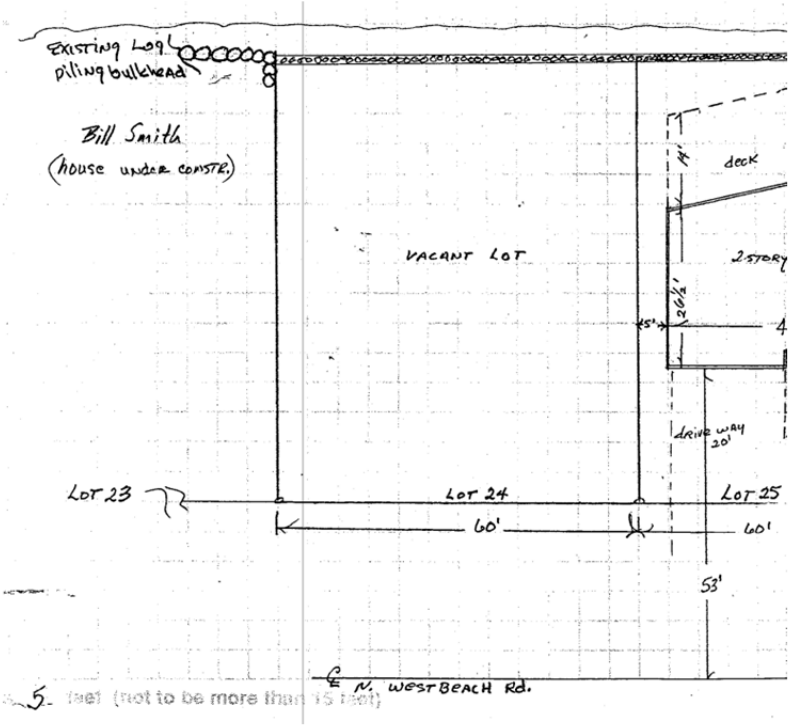
Site on narrow barrier beach fronting a coastal lagoon (Swan Lake).

Swan Lake project site in about the early 1970s, looking down-drift. Vertical concrete bulkhead and backfill at up-drift end of study area failed soon after construction.

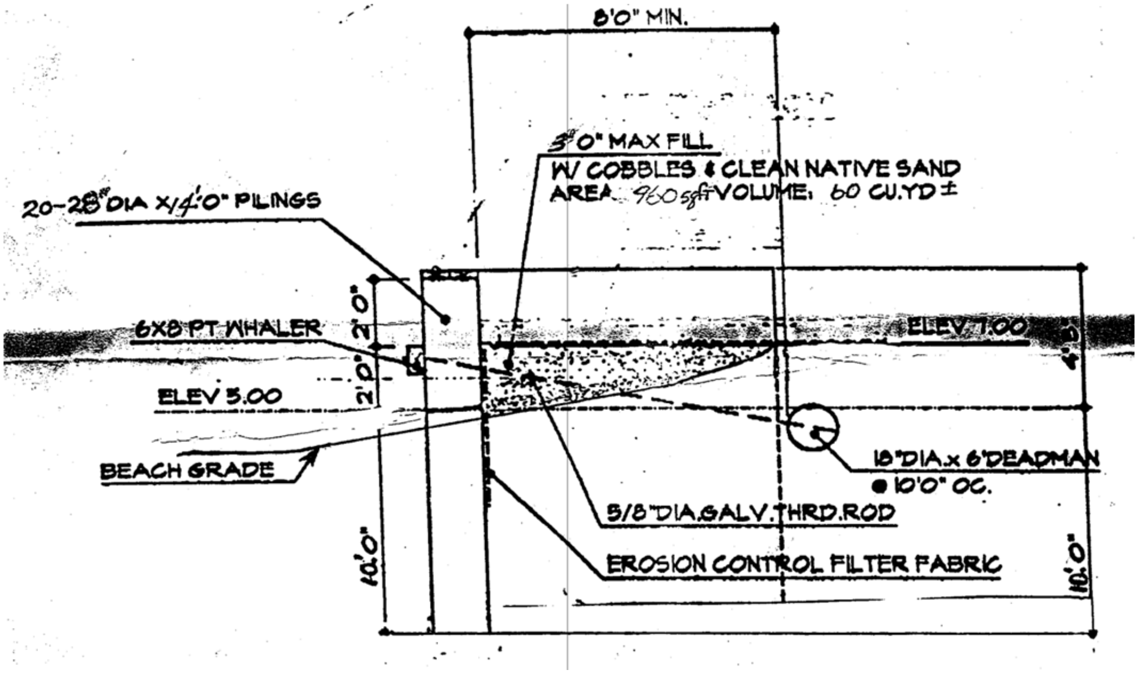
Design

The full 60-ft width of the project site was bulkheaded and lay in the central portion of 800 ft of continuous soldier pile bulkheads. The bulkheads were made of tightly placed, untreated soldier piles averaging 1.6 ft in diameter. Three continuous courses of 6-in by 8-in treated wooden whalers (planks attached to the front of a soldier pile bulkhead), one above the other, ran across the upper portion of the pile wall. Tie-backs, spaced every 10 ft, consisted of ¾-in iron bars running through the whalers and piles landward to anchors which were to be placed 4 ft below the upland grade. Galvanized steel plates, 1.0 by 1.5 ft, were used to secure tiebacks to the face of wall. Geotextile was placed on the landward side of the wall up to the height of the tie-backs.

Piles extended approximately 5 to 6 ft above the beach grade, and were topped with wood runner. The height of the soldier pile wall at the project site profile was 5.25 ft. Piles extended approximately 3.5 to 4 ft above landward grade. The backshore height above grade at the project site profile was 3.7 ft. Design drawings indicated that piles were to extend 9 to 10 ft below beach grade. This depth of burial could not be determined in the field.



Project design drawing (design by Chris Kantola).



Project design cross section (design by Chris Kantola).

Current Conditions

Technique Condition – Soldier piles generally were in good condition, with minor abrasion near beach level but generally sound wood. Piles remained vertical. Small gaps of up to 0.15 ft between piles appeared to have been the source of backfill loss. Some overtopping appeared to have occurred, likely during extreme wind-wave events coincident with very high tides. Corrosion of tie-backs and associated hardware was evident during the site visit.

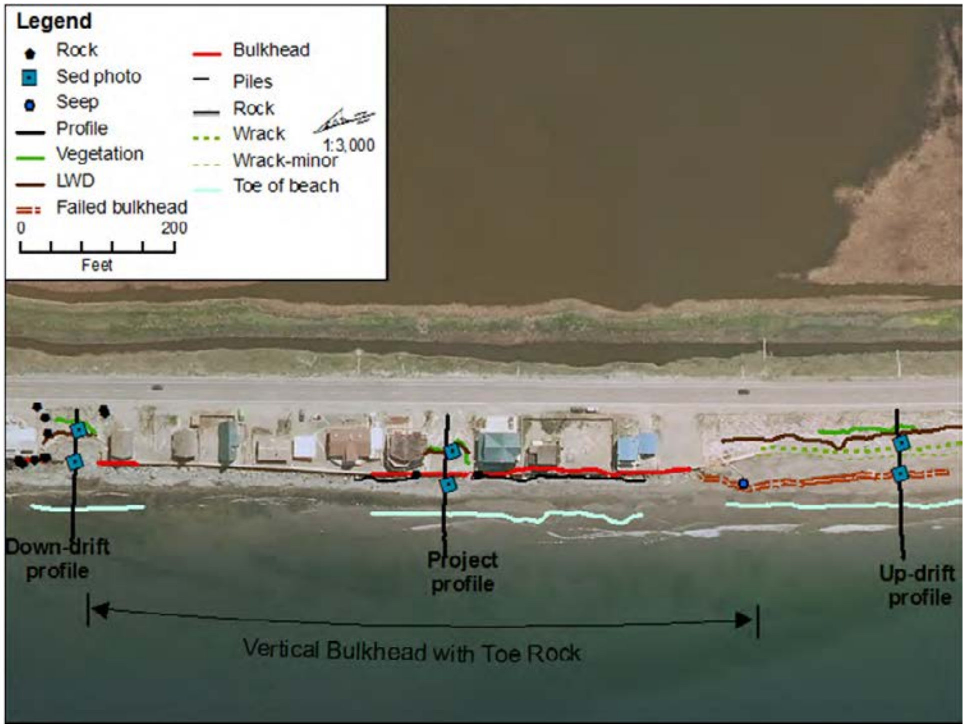
Upland Threats – The property did not contain a house, and therefore no infrastructure was threatened. However, loss of fill behind the bulkhead was evident in the very low elevation landward of the wall and in the exposed geotextile filter fabric and tie-backs. Many drift logs had accumulated on the landward end of the lot by the road shoulder and may have been pushed into the road during storms. The bulkhead was not protecting the lot from coastal erosion.

Beach Characteristics – The mixed gravel and sand beach, with sediment ranging from coarse sand to large cobble, showed no major differences between adjacent bulkheaded sites and the subject property. However, the site's backshore lay far landward of the bulkhead wall and was isolated from the active beach in almost all conditions.

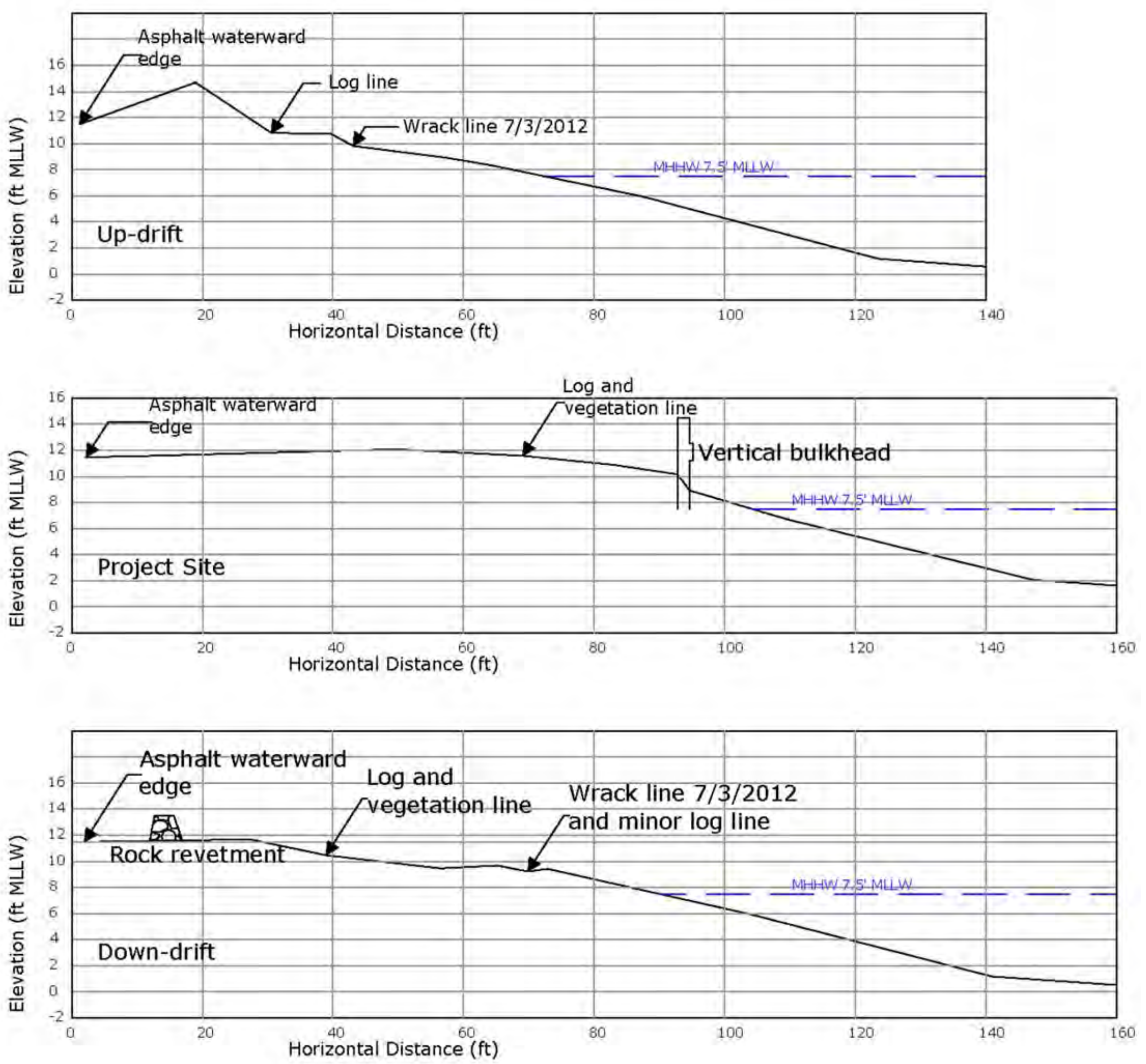
Adjacent Shores – Adjacent bulkheaded sites had varying amounts of drift logs and debris landward of the bulkheads, but most contained less large wood. Houses generally stood only 15 to 20 ft from the line of bulkheads, with some decks even closer. Up-drift and down-drift sites, along with the historical T-sheet, showed that fill had been added to the lots by the time of development.

On-site profile location (indicated by rod) looking up-drift in 2012.

Sandy continuation of the beach, backshore, and drift logs behind soldier pile wall looking waterward in 2012.



Beach characteristics as observed and collected in July 2012, with profile locations. Soldier pile wall on project site is in line with structures on both sides. Up-drift profile was in an area with only small intertidal remnant of a concrete wall; down-drift profile was located in an area without a bulkhead.



Beach profiles measured during the 2012 site visit.

Comparison of beach surface sediment at project and adjacent sites.

Location	Backshore	Difference	Upper intertidal	Difference
Up-drift	SAND, coarse pebble	similar	SAND, coarse pebble	similar
Project site	SAND, fine pebble, coarse pebble	-	SAND, medium pebble, coarse pebble	-
Down-drift	SAND, cobble	similar	SAND, coarse pebble	finer

Performance

The soldier pile wall has not performed well due to significant erosion and loss of fill, enough so that a drift log zone was established landward of the bulkhead. The bulkhead installation buried backshore areas, and the bulkhead disconnected the backshore from the beach, blocking smaller logs from continuing to down-drift. Design performance problems included the following:

- The bulkhead is overtopped during some storms, allowing debris to enter the lot and potentially cause damage.
- Piles have become deteriorated and allow the loss of fill to the beach.
- Geotextile fabric was exposed on the landward side of the bulkhead.
- The pressure-treated wood installed that caps the top of the soldier piles was significantly warped and degraded.
- Wood whalers across the upper face of the wall required replacement in recent years.

Property owners in line with the same soldier pile wall immediately down-drift and up-drift of the project site have placed large boulders for toe protection, and some sand bands landward to abate scarping. This was evidence of the poor performance of the initial design.

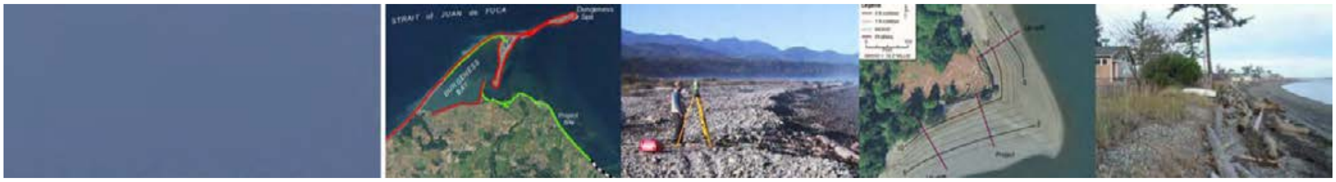
Project performance scoring.

Category	Parameter	Rating	Score	Rationale
Benefits	Effectively mitigated landward erosion	Low*	2	Landward erosion has not stopped as evidenced by the log line far landward of structure
	Sediment volume augmented	None	0	No structure removal or nourishment
	Input/exchange of LWD, detritus	Low	1	Allows some cross-shore exchange to the backshore
	Backshore vegetation enhanced	None	0	No planting occurred
	Marine riparian vegetation enhanced	None	0	No planting occurred
	Low-cost and simple installation	None	0	Assume more expensive than $200/LF
Impacts	Structures bury backshore & intertidal areas	Med	-2	Structure installation buried less than 7 ft (average) of backshore with a minimum of 1.5 ft
	Structures impound littoral sediment	None	0	No bank site
	Coarser/steeper beach profiles created	Med	-2	Project site has 7.8:1 slope while reference sites had 8.5:1 and 8.25:1 slopes
	LWD/detritus recruitment reduced	None	0	LWD band larger on site than on reference sites
	End erosion adjacent	None	0	Project site in line of continuous bulkheads
	Required maintenance interval	Med	-2	Neighbor remembers maintenance in past 15 years on most of the bulkheads along this reach. No specifics were given.
Design-specific benefits	Structural integrity & function maintained	Med	2	Structure has allowed backfill to erode from behind structure through larger-than-installed openings between soldier piles
	Cross-shore location of exposed toe of structure	Low	1	Exposed toe of structure is just above MHHW
Design-specific impacts	Scour at structure	Med	-2	Scour behind structure is less than 0.5 ft
	Debris on beach from structure	None	0	Natural beach sediment present
Total			-2	

*Scores at double other values (e.g., high=6); all others, none=0, low=1, med=2, high=3

Totaling the above scores, benefits equal +6 points and impacts equal -8 points, for a final combined score of -2.

Marine Shoreline Design Guidelines



APPENDIX B

Review of Literature

2013

Prepared for:

The Aquatic Habitat Guidelines Program

Prepared by:

Washington Dept. of Fish and Wildlife

Prepared for:

Washington Dept. of Fish and Wildlife

Appendix B. REVIEW OF LITERATURE

This review covers engineering and geologic literature of shore processes and the design of protection measures. The specific focus is material that supports the development of these guidelines. This is in no way a comprehensive bibliography for the topic. For a more in-depth review of related topics, the **Review of Shoreline Armoring Literature**, Appendix C in **Puget Sound Shorelines and the Impacts of Armoring** (Shipman et al. 2010), covers the geomorphology of Puget Sound, shoreline development and armoring, impacts on nearshore biology, and a short section on engineering and alternatives to shoreline armoring. Portions of the latter section are re-reviewed here with a slightly different emphasis.

Literature on the assessment and design of shore protection measures is often focused on the open coasts with their unlimited fetch, large, long period waves, and sandy beaches (some with cobble berms). This review of the literature did not find any articles that specifically address Puget Sound shores over and above what is part of the common cannon and written largely by the authors of these guidelines. Nevertheless, there are some insights to be gained from the reviewed literature, as discussed below.

Gravel Beaches and Beach Nourishment

Many Puget Sound beaches are steep and composed primarily of gravel and the predominant material for nourishment is also gravel. Studies investigating the behavior of gravel beaches could improve the design methods and success of beach nourishment projects.

The dynamics of gravel beaches are complex and poorly understood. Masselink and Puleo (2006) provide a conceptual model and figure for understanding prevailing sediment transport processes (Figure 1). Despite considerable analysis, they conclude that the net sediment transport in the swash zone, and the resulting changes in morphology, cannot be determined quantitatively.

They make several useful observations:

1. Sediment is mixed into the water column and transported during uprush, but moves close to the bed during backwash.
2. There is a short burst of acceleration during uprush.
3. Flow velocities are similar between uprush and backwash, but with a slightly longer backwash skewing velocity in the offshore direction.
4. There are a number of processes that promote uprush sediment transport that compensate for the net offshore velocity that results in onshore sediment transport.
5. On steep beaches turbulence and suspended sediment are expected to be significant factors.

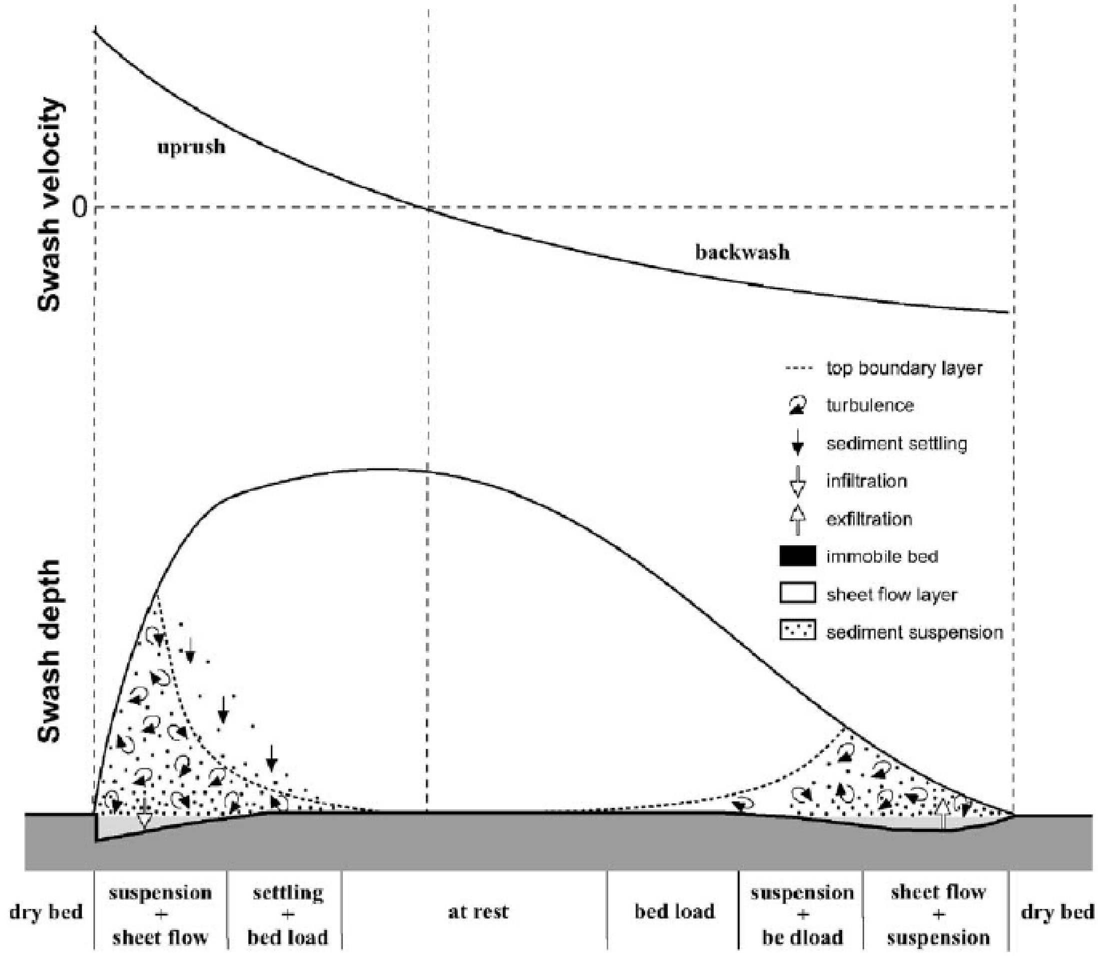


Figure 1. Schematic of the sediment transport processes as a wave breaks and recedes on a gravel beach (Masselink and Puleo 2006)

Buscombe and Masselink (2006) draw a distinction between gravel and mixed beaches. The former is where the whole beach is composed of gravel and the latter where gravel forms a high tide beach and storm berm with a sandy low slope foreshore. One could conceive that nourishment emulated the former and the dynamic revetments (Komar et al. 2003), or cobble berms, are of the latter type.

The step at the toe of the foreshore may control wave energy and make the gravel beach slope independent of wave height and dependent on sediment size. It is not clear what role tides have in this model. In the macrotidal Puget Sound, the step (if it exists) would have diminishing effect on the wave breaking as tide increased. They say that the step is crucial in gravel beach morphodynamics – it acts as a dissipative feature.

Swash asymmetry leads to onshore movement of sediment and berm building. Sediment is moved up the foreshore by the wave which is then stranded at the landward extent of runup because the infiltration into the porous beach reduces competency. There is a modeled dependence of foreshore slope and swash infiltration. This is proposed with more confidence than in Masselink and Puleo's (2006) theoretical analysis.

"Rollover" builds storm berms where onshore sediment transport throws material landward and strands material above the reach of waves. The berm sediment is removed from the active long and cross-shore drift but forms a protective interface between development and the beach – an important feature in the design of protection measures.

Buscombe and Masselink propose that sediment sorting (band of similar sizes) forms mosaics that are analogs to bedforms on sand beaches, such as bars. These mosaics "act as both an expression and control on gravel beach behavior." Whether grading placed materials in beach nourishment projects is theoretically possible (considering our understanding of the processes and forces) or practical is another matter. Currently, beach nourishment consists of placing the same mix of materials over the entire project area and letting natural forces sort the material.

Predicting the effects of both sea level rise and armoring on beach and barrier functions and structure is not easy. Orford and Forbes (2002) show that the way in which changing forces, structures, and materials interplay is complicated and difficult to predict. Orford and Forbs describe the emergence of a gravel beach which depends on an adequate sediment supply and backshore area. "Excess sediment enables the formation of a barrier but only when a barrier crest forms so that a landward dipping back barrier slope can be defined. Barrier crest elevation is defined by the distribution of wave runup as a function of breaker height, beach slope, and bed roughness (attenuation coefficient). Elevation also reflects a balance between runup sufficient to deposit material at the beach crest (overtop) and runup sufficient to exceed the crest and move material onto the back-barrier slope (overwash), the latter leading to barrier transgression via rollover."

Predicting the height of a gravel berm is an important calculation for the design of beach nourishment projects, especially where there isn't an appropriate existing berm to measure. Lorang (2002) evaluated two equations to predict crest height. The first (equation 17) is a force balance equation that estimates the force required to move a stone up the beach versus the submerged weight of the stone. This equation includes several difficult parameters to estimate and would be challenging to apply to practical situations. The second (equation 21) balances the potential energy of the mass of material in the crest versus the energy in the waves: "the height of the breaker as it impinges on the beach divided by the mass per unit area of the crest."

$$h_c = (\rho_w H_{sb}^2)/8m$$

where h_c is the beach crest height (above MHHW), ρ_w is the unit weight of water, H_{sb} is the height of the breaker immediately impinging on the beachface, and m is mass per unit area of the beach crest. This seems like a more practical method and it performed well in their field test, although has some difficult assumptions.

Beach Nourishment

Sand nourishment on the open coast is regarded as a temporary solution to a chronic problem. On threatened coasts more permanent solutions are either retreat (relocation of existing infrastructure landward of the eroding coast) or protection measures (Finkl and Walker 2004). These authors suggest that nourishment be evaluated on the basis of specific objectives to determine success and justify costs. The objectives include some that are familiar to Puget Sound practitioners: creating a recreational beach, protecting coastal infrastructure, and creating and maintaining beach habitat. Criteria for success and measures of performance are associated with each objective. Puget Sound nourishment projects can have a very long lifespan but still warrant careful evaluation.

Globally, there doesn't appear to any simple rule or a general methodology that works everywhere for designing beach nourishment projects because of many site specific differences (Finkl and Walker 2004). Considering the more narrow range of conditions in Puget Sound, a more focused approach is possible.

In addition to the theoretical approaches to gravel beach analysis (above) and design manuals currently available in the U. S. (USACE 1984, USACE 1989, USACE 1995), there are also active programs designing and evaluating beach protection measures in Europe. An extensive collection of case studies of open coast, sandy beach projects can be found in De Pippo (2006). They recognize the recreational value of beaches and how that has been compromised by development as well as the ecological impacts. In this context they view beach nourishment as both protection and restoration of recreational and ecological benefits.

Unique in De Pippo (2006) is a fairly detailed cost/benefit alternative analysis section, although lacking a thorough environmental impacts assessment, or monetization. De Pippo treats the alternatives as investments rather than part of a complex nearshore ecosystem. Alternatively, Speybroeck et al. (2006) created a framework of the ecological effects of beach nourishment. They list biological effects relating to the quality and quantity of sand and construction.

Speybroeck et al. (2006) observe that nourishment is probably more benign than armoring, and that nourishment probably takes place on shores that are already unnatural and it may be difficult to determine effects under these conditions. They also observe that the nourishment sand gradation quickly adjusts to prevailing conditions, but this delays ecological benefits. To maximize immediate benefits, place nourishment using the native gradation and place in winter when intertidal organisms are at their lowest populations and less likely to result in high mortality events.

Pocket beaches (embayed beach) are common in Puget Sound and the use of a terminal sill to create pocket-like beaches on artificial shores is increasingly common. Daly et al. (2011) developed a model to determine the response of embayed beaches to varied wave forcing. In the simulations, longshore currents are active until an equilibrium shape forms, often with rotation, then cross-shore forces take over. Modeling software has been developed by Schiaffino et al. (2013) to calculate the equilibrium shape of an embayed beach (pocket beach) using both sand and gravel.

A detailed case study of a constructed 1000-ft-long gravel beach exposed to large, long period waves on the coast of Italy was done by Cammelli et al. (2006). Most of the coast in the area is armored with seawalls and breakwaters. Nourishment acted as pocket beach in “rocky shore” (groins acting like headlands). Two beaches were constructed between three groins. Thirty-seven cy/ft of 1.6 to 8-inch sediment was placed, and the specific gravity was about 2.6. Sediments were placed in front of the seawall to form an approximately 66-ft-wide platform at 6.5 ft above mean sea level, which was immediately reshaped by waves.

Conclusions from Cammelli include:

1. A gravel beach can protect coastal infrastructure and produce a surface usable for tourist activity.
2. The beach becomes reoriented toward the direction of high-energy wave approach, resulting in a narrowing of the berm in one segment, causing waves to overtop the seawall and deposit gravel landward of it.
3. The efficiency of the beach as a protection structure may be reduced by the volume loss due to sand infiltrating the gravel.
4. Profile deepening in sandy substrate seaward of the gravel beach may occur from wave reflection or strong backwash.
5. Offshore effects of gravel nourishment may be obscured by greater morphologic changes caused by movement of bar systems, where present.
6. The movement of gravel offshore is not likely.
7. Bar systems close to the foreshore may be stabilized by the presence of groins.

Hanson et al. (2002) reviewed beach nourishment projects (beach fill for coastal protection) constructed in Europe. They document a steady change in protection tactics from hard armor to soft approaches since the 1950s, although much hard armor still exists and soft is often a combination of soft and hard. Each major country is evaluated. England is most sophisticated in deciding on the type of defense needed by evaluating,“(1) benefit/cost ratio, (2) feasibility and likely effective lifetime, (3) standard of defense that is appropriate, e.g. the return period of flood events that the scheme is designed to prevent, and (4) environmental.” For nourishment projects they look at (1) cost of materials, (2) height and width of new profile, and (3) long-shore drift. England also does coarse grained fills (e.g., gravel, shingle) and recycles down-drifted sediments back into the project.

Kumada et al. (2010), reports on a beach nourishment project in Japan. This is essentially a pocket beach project facing the Pacific Ocean and was installed to protect the toe of an existing seawall. The gravel is 0.5 inch minus. The equilibrium slope was 1h:8v and experienced minimal cross-shore leakage.

Dynamic Revetments and Cobble Berms

Dynamic revetments and cobble berms are comparatively flexible protection techniques using natural gravel and cobble berms as analogs. Komar et al. (2003) describe a cobble berm on the Oregon coast built as an alternative to a quarry stone revetment or seawall. The berm is in the upper intertidal area above a sandy beach. The concept may work well at high energy sites in Puget Sound as a replacement for rock revetments or vertical bulkheads where there is adequate backshore width.

The design was based on the morphology of natural cobble beaches in the area, not on analysis or modeling, which limits a more general application of the method. The main design elements were the berm slope and a crest elevation required to reduce storm overwash. Slopes, based on existing cobble berms were 1:5 to 1:4 (vertical:horizontal). The elevations were based on measured tides and the runup of storm waves. They determined that, "the cobble berm is playing an important role in dissipating the energy of the storms, particularly in reflecting the incoming waves which then collide with following waves to enhance their breaking and energy loss. Also important is the friction and percolation of the swash runup as it crosses the cobble berm, further dissipating the wave energy."

Allan and Hart (2007) monitored the cobble berm described by Komar et al. (2003) using cross-sections and particle tagging. They found that the berm was "dynamic"; seasonally changing in shape and experiencing net northward sediment transport. Despite several major storms, the berm continued to protect the upland property, although overtopped several times. Particle movement was measured up to 1,100 ft in 16 months. Some cobbles were lost both long- and cross-shore and the berm may require periodic maintenance.

To improve the dynamic revetment design methodology, Allan et al. (2005) examined 13 gravel beaches on the coast of Oregon considering slope (average 11°, 1:5, vertical:horizontal), height (about 20 ft), crest height, grain size (D_{50} = 2.5 inches), and drift, among several other aspects of design and construction.

Everts et al. (2002) examined a California cobble berm that formed above a sand beach exposed to high wave energy. They make an interesting observation concerning the height of a berm used for protection, noting that a lower berm that allows overwash could provide additional stability. "The release of some of the runup beyond the structure reduces backwash stresses during the most energetic and potentially damaging swash cycles and encourages cobble accretion on the top of the berm… The downside to designing overwash into an artificial berm is obviously the necessity of dealing with the movement of water and possibly cobbles onto the region being protected." This could be mitigated by using a wider berm. Backing a berm up with a seawall, on the other hand, is likely to lead to erosion from reflected overwash. They also suggest that the base of the berm be located away from, or isolated from, breaking waves or uprush. The berm should be swash aligned to minimize alongshore losses; a common approach when the sediment source is limited. The stability of a porous berm (absorbing swash volume on the upwash) was documented after a cobble berm was choked with sand and began to erode under conditions in which it had formerly been stable. This article is full of good observations.

Large Wood

Large wood is commonly found on Puget Sound beaches and plays a role in beach morphology, processes, and ecology. Terich (1977) looked at the effects of large wood on the beaches of northern Puget Sound at a time when the intensity of logging was much greater than it is now and the method of transport was different (log booms then, trucks now) and log storage was different (log rafts then, dry storage now). Not surprisingly, he found that the quantity of large wood on beaches is less now than it was when logging practices were more water-oriented. Terich measured log density at a number of sites but didn't describe where on the beach the logs were located (tidal frame), embedment, wave exposure, or aspect. Mean volume of drift logs on beaches in Whatcom and Skagit county was 54 ft^3/ft (range about 210 – 11) and higher in pocket beaches (61 ft^3/ft) than linear (43 ft^3/ft). Seasonal change in density and volume differs with beach type, pocket vs. linear. Logs tend to remain on the pocket beaches over seasons, whereas linear shorelines show more variability in log residency. Density of logs responds to seasonal change in wave and beach conditions with higher density in winter than summer (20 to 40% more logs). Wood density in the cross-shore direction (total volume/length of transect) had a mean 7.8×10^{-5} ft^3/ ft in the summer, a mean 10×10^{-5} ft^3/ ft in winter, range 0.5 to 21×10^{-5} ft^3/ ft. The effect of drift logs is to buffer the upper beach from wave attack and to help trap sediment on the landward side of the logs.

A more recent study from New Zealand by Kennedy and Woods (2012) evaluated the influence of coarse woody debris on gravel beach geomorphology. This was a fairly energetic site (Hs = 8.2 ft, T = 10 s as opposed to Puget Sound Hs ~ 3 to 6 ft, T = 3 s) and micro tidal (5 ft vs. 6 to 14 ft in Puget Sound). They found that coarse woody debris is an important geomorphic agent. On gravel-dominated beaches wood is deposited during high wave events and is positioned at the top of the storm berm. Large wood traps sediment and limits storm-caused overwash. Kennedy and Woods measured the height of beaches with wood and found them to be on average between 1.6 and 3 ft greater that those without, and the slope of beachfaces with wood were almost twice as steep as those without. Wood on gravel beaches acts as a buffer to waves during storm events and is inactive during calm periods.

Kennedy and Woods found that, "On gravel beaches the profiles adjust to high wave energy events primarily at the upper limit of wave swash, while sandy beaches respond through transporting sediment into the nearshore zone. The result for gravel beaches is that wood is deposited at the limit of wave swash and therefore influences sediment transport during a storm event, while on sandy beaches wood is more important in interacting with sediment transport pathways after a storm event."

Rock Armor Design

Europeans follow a different approach to the design of shore protection (CIRIA 2007) than the U.S. Army Corps of Engineers (USACE 1984, 1989, and 1995). CIRIA (2007), the "Rock Manual," covers every aspect of rip rap and coastal design. It includes a simple approach to the design water surface used to determine the height of protection structures that is carefully explained.

In general, rock armor is not designed from a geomorphological point of view, but rather to provide the highest level of protection for the lowest overall cost. Ironically, one of the more common methods to determine the stable mass of a revetment element, the Hudson formula, tends to under-predict this mass because it does not consider the wave period. The period is proportional to wave power. An analysis of the threshold entrainment mass of a boulder (Lorang 2000) produces a new equation with theoretically better predictive power and a connection to beach processes. The equation is complex and attempts to apply it to Puget Sound conditions were unsuccessful because of two variables, K_r and waver run-up. K_r could not be estimated (K_r is a function of a packing coefficient and a shape factor which are dependent on characteristics of the material and its placement) and is not a reliable way to predict wave runup. Once there are some assumed values for K_r and runup techniques, the equation could be used as an aid to better design. Lorang mentions that a more realistic method to determine the entrainment of large rock as a good way to distinguish static and dynamic revetments.

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