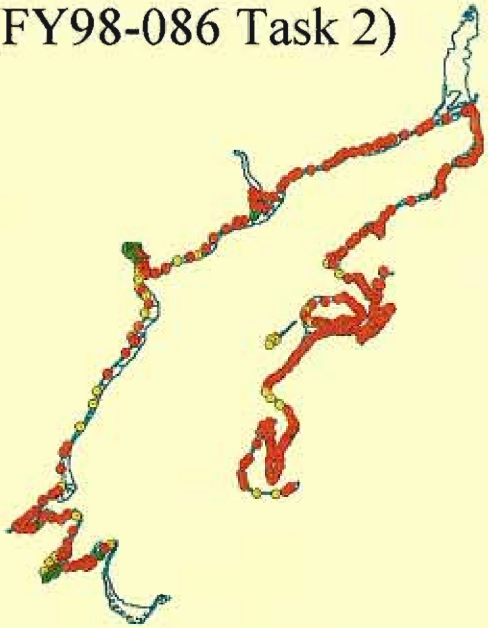
The Physical Classification and Biological Modeling of Nearshore Habitats in Carr Inlet
(FY98-086 Task 2)



G. Carl Schoch
College of Oceanic and Atmospheric Sciences
Oregon State University
Corvallis, OR 97331

Dr. John Harper
Coastal & Ocean Resources, Inc
107 - 9865 W. Saanich Rd
Sidney, BC V8L 5Y8
Canada

Dr. Megan Dethier
Department of Zoology and Friday Harbor Labs
University of Washington
Friday Harbor, WA 98250

Report for the Washington State Department of Natural Resources

January 4, 1999

This report was produced for the Nearshore Habitat Program, a component of the Puget Sound Ambient Monitoring Program. For additional copies, contact:

Washington State Department of Natural Resources
Business Systems Support Division
Nearshore Habitat Program
1111 Washington Street SE
PO Box 47014
Olympia, WA 98504-7014
(360) 902-1100

Executive Summary

This report describes the results of project FY98-086 funded by the Department of Natural Resources. The purposes of the project were to: 1) compare the shoreline classification system currently used in British Columbia to the system used for modeling the biota of Carr Inlet in 1997; and 2) develop a method for integrating the two systems. The method used in British Columbia for shoreline inventory is the Shore-Zone Mapping System implemented by Coastal and Ocean Resources, Inc. The method used in Carr Inlet was the Shoreline Classification and Landscape Extrapolation (SCALE) model. Shore-Zone Mapping is an aerial survey with narrated videography that documents the physical and biological attributes for sections of shoreline called physical units. SCALE relies on a tight coupling between the biota and the physical attributes of the nearshore environment, and extrapolates from a limited series of randomly sampled beaches ("segments") to landscape-scale distributions of intertidal communities. The advantages and disadvantages of these two systems complement each other in such a way that nesting the quantitative SCALE model into the qualitative Shore-Zone Mapping system results in a powerful tool for describing nearshore habitats.

Quantifying the distribution, abundance, and diversity of nearshore algal and invertebrate populations over large spatial scales is problematic since no method currently exists to statistically extrapolate biological data from the scales of sampling quadrats (.25 m^2) to larger areas (landscapes). Thus, only limited inference can be made about local communities and processes beyond single-point monitoring sites. Increasing pressure on the nearshore environment by perturbations at multiple scales of space and time has led to concern for the health of this ecosystem and a desire to monitor intertidal communities for indications of long term change. Early detection of change in the nearshore ecosystem could prompt policy directives to control the effects of perturbations.

The objective of this study was to evaluate a nested hierarchical nearshore classification model, based on a suite of physical factors, for characterizing and predicting the algal and invertebrate community structure over a range of spatial scales spanning 10 m to 100's km. Specific physical factors are linked to causal processes associated with ecological responses in the nearshore environment. At very large scales (100-1000 km) oceanographic processes such as nutrient upwelling, water temperature and meso-scale currents may influence community structure and organism abundance by controlling food supply and the release and distribution of propagules. At smaller scales (10-100 m) the hydrodynamics of the nearshore, substrate size and elevation become more important in determining local distributions. Complex shorelines can be partitioned into relatively homogeneous polygons, and the morphodynamic attributes of the polygons can be described.

The methods presented in this report are intended for general application to any shoreline, but the results are based on work done in Carr Inlet during the summer of

1997. Two nearshore mapping systems (Shore-Zone Mapping and SCALE) were applied to the shores of Carr Inlet in order to compare and contrast the results. Although differences were found in both the physical and biological descriptions, due mostly to the differing scales of observation, we found that these mapping systems complement each other by providing two levels of data resolution. Shore-Zone Mapping relies on aerial overflight and video imagery to produce a qualitative inventory for 100% of the project area of physical and biological features associated with the nearshore environment. SCALE gathers more detailed data on the ground through observers walking the shore, describing beach habitats and quantifying the physical features of the nearshore. These data are used to statistically group similar beaches. Reference beaches are selected from these groups and intensively sampled with quadrats and cores along a 50 m horizontal transect at a series of intertidal elevations. The biological data are then extrapolated to other members of the same group across multiple spatial scales. These results are viewed with a GIS creating a powerful database for analyzing the spatial patterns of nearshore biota and how they change over time.

We used the biological data collected from the field (abundance, frequency, and taxonomic identification) to generate ranked lists of organisms that provide the best statistical representation of the beach biota. These lists were integrated with the GIS database. The lists include all sampled organisms, and are ordered from the best "bio-indicator" to the worst. The organisms listed are identified at the family taxonomic level. Statistically infrequent organisms have very low indicator values. These lists of indicators for each of the sampled habitat types (in all three intertidal sub-zones) can be used to decide which organisms to monitor. The selection criteria should include statistical robustness and ecological relevance. For example, if a rare organism becomes more frequent and/or abundant over time then it is ecologically and statistically meaningful as an indicator, even though its indicator value was initially very low.

The SCALE system of partitioning, quantifying and grouping nearshore habitats provides a means to extrapolate biotic data from localized transects to larger spatial areas. But the system produces biological data for only a portion of the project area. The percent of the shoreline that can be modeled (in terms of predicting the biota) depends on:

1) the number of beach groups selected for sampling (not all habitat types can be sampled, so decisions need to be made based on shore length or area represented by a habitat type);

2) the amount of biological variability acceptable to the monitoring project (this issue was addressed in detail in our earlier report);

3) the spatial extent that SCALE can extrapolate community data, which is limited by the number of beach segments in the clustered habitat groups.

Small groups of habitats, for example, usually do not represent a large percentage of the total nearshore area, therefore these may not be the best choice for sampling if overall shoreline characterization is the objective. However, it may be of ecological interest to sample a small group if, for example, these comprise an uncommon but highly valued shoreline within a project area, such as rocky sites in Puget Sound. In general, the number of beach segments in a cluster group can be modified by changing how narrowly defined is the group (i.e., how many physical attributes are used to define it; see Methods). Narrowly defined groups will have low variability (and thus high predictability) of biota, but will allow only very limited extrapolation to other areas. Broadly defined groups will have more biological variability but allow us to extrapolate more widely (see Schoch and Dethier 1997).

Another method for increasing the spatial extent over which we can make predictions about biota is to extrapolate among Shore-Zone Mapping units (rather than within SCALE groups) of the same shoretype. However, we do not recommend this because the Shore-Zone Mapping units are much larger than SCALE segments and often encompass considerable physical (and thus biological) heterogeneity. As an indication of this heterogeneity, several SCALE segments usually lie within a Shore-Zone Mapping unit. This physical heterogeneity at the scale of the Shore-Zone Mapping unit will result in biological patchiness at any smaller spatial scale of observation. A quadrat or core will sample organisms either not observable from the air, or in numbers or densities not detectable from the air. This illustrates why the Shore-Zone Mapping observations cannot be "telescoped" to smaller spatial scales and why the nested approach is advantageous for multi-scale habitat monitoring.

We advocate nesting the quantitative SCALE model inside the qualitative Shore-Zone Mapping inventory so that each physical unit is partitioned into geophysically homogeneous beach segments. In this way, the two mapping systems combined can produce 100% spatial coverage of physical and biological attribute data at a low resolution, and 40-50% coverage at a very high ecological resolution suitable for use in change detection studies. When used in tandem, the two mapping methods will improve our understanding of biotic patterns and processes as a first step towards understanding what influences marine biodiversity over a range of spatial scales. The recommended modeling and monitoring approach is summarized as follows:

1) Use the Shore-Zone Mapping to map and inventory physical and coarse-scale biological attributes of an area of interest;

2) Use either remotely sensed data or by collecting field data, map the salinity, water temperature, and nutrient/chlorophyll distribution for the project area. Determine the temporal stability of the distribution patterns of these features;

3) Use Shore-Zone Mapping results (e.g. area, shoreline length, and frequency of different shoreline types) to characterize the abundance and distribution of geomorphic shoretypes;

4) Select areas for high resolution SCALE mapping by using the data from (2) and (3) and considering management priorities. All high resolution biota sampling and extrapolation will be limited to the selected areas;

5) Collect SCALE geophysical data from selected areas;

6) Analyze SCALE data, produce a GIS database, and determine the habitat clusters. This would involve consideration of management priorities in order to find a balance between the ability to extrapolate over large areas versus lower biotic variability;

7) Collect (using quadrats and cores along transects) biotic data from randomly selected beaches in the habitat clusters;

8) Extrapolate SCALE data, generate predictions of community distributions, and add to the GIS database;

9) Validate model results. Randomly select new sites from the same groups previously sampled, and (optionally) resample the biota at the original sites (from #7 above) during the following year to assess change.

The intertidal environment is a region of high biological productivity and diversity, but can be heavily influenced by anthropogenic perturbations such as oil spills, other pollution, upland or shoreline development, and recreational uses. An understanding of the relationships between physical features of shorelines and the distribution and abundance of nearshore populations will yield important knowledge about a valued portion of the marine environment. Our recommended nested methodology for mapping and inventory of coastal habitats represents a powerful and relatively low-cost tool for gathering detailed information on these valuable shorelines. The databases resulting from this work should be of very broad utility, not only in detecting ecological change, but in shoreline planning, siting of development projects, choosing locations for other types of marine research, and numerous other ways.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

3. BACKGROUND

4. METHODS

5. RESULTS

The Physical Classification and Biological Modeling of Nearshore Habitats in Carr Inlet

1. Introduction

The diversity of life in the oceans is being dramatically altered by the rapidly increasing and potentially irreversible effects of activities associated with human population expansion (Vitousek et al. 1997). The most critical contributors to changes in marine biodiversity are now recognized to be the following: fishing and removal of the ocean's invertebrate and plant stocks; chemical pollution and eutrophication; physical alterations to coastal habitats; invasion of exotic species; and global climate change. These activities and phenomena have resulted in clear, serious, and widespread social, economic, and biological impacts (National Research Council 1995). Evaluating the scale and consequences of changes in the ocean's biodiversity due to human activities is, however, seriously compromised by critically inadequate knowledge of the patterns and the basic processes that control the diversity of life in the sea.

Considerations of spatial patterns have been prevalent in nearshore and intertidal ecology since the early 1960's (Connell 1961, Paine 1980, and many others). The intertidal zones of rocky shores have been the prototypical systems for ecologists exploring the connection between biodiversity and ecosystem functions. The structure of intertidal communities can vary tremendously over a range of spatial scales due to geophysical gradients and biological interactions. In addition, many intertidal organisms rely on mass dispersion into the nearshore ocean to propagate their populations, and recruitment from the plankton to colonize suitable habitats. The interaction between nearshore oceanographic processes and larval transport is thus important to the understanding of the presence, absence, and distribution of intertidal species. Therefore, nearshore habitats provide an appropriate environment to study the associations between connected populations in open systems.

Many species of marine organisms only utilize particular habitats and are generally found in highest abundance where the physical and biological conditions are optimum for their life history and ecosystem function. Their population success is often dependent on the presence, dimension and distribution of appropriate habitats. These habitats defined by a suite of interacting environmental variables such as substrate size and type, water temperature, salinity, water quality, silt loading, hydrology, and processes and patterns of coastal sediment transport. These variables often act synergistically, producing complex mechanisms that influence the abundance, distribution and diversity of organisms in a given area. Thus it is important to any program concerned with natural resources to acquire a database not only containing lists of species, but also habitat-specific information on abundance, distribution, food sources, and productivity of breeding populations so that statistically valid conclusions may be drawn from the data.

The relative importance of geophysical and biotic factors in regulating community patterns varies across scales of space and time. For example, at small spatial scales, biotic and abiotic factors interact to influence local patterns of community structure through predation, competition, solar aspect, wave forces, and point source perturbations. At larger scales, variations in tides, currents and weather can affect dispersal and nutrient fluxes. At global scales, long term changes in climate can indirectly modify local variables to produce environmental stresses that directly and indirectly influence nearshore populations (Menge & Olson 1990).

A holistic coastal management program requires studies of physical habitats such as the intertidal and subtidal zones, as well as the upland terrestrial fringe and watersheds. Corresponding studies of the biota (communities of coastal flora and fauna) are then needed to assess the effects of marine pollution, changing climatic patterns or other environmental stresses. For a given coastal population, if detailed life history information is known and the species' habitats are inventoried and mapped, then an assessment of its present status and likely fate can be made (French 1991). Critical or sensitive habitats for a variety of species can be identified during such an analysis.

2. Project Objectives

The goal of this study is to develop a hierarchical shoreline classification system that defines nearshore habitats at spatial scales ranging from meters to hundreds of kilometers. The results of the classification can be used to appropriately design a program to inventory coastal organisms and communities, and allow us to model spatial distributions of nearshore habitats as a first step towards understanding biological community structure over large areas. The model is based on the premise that the co-occurrence of specific intertidal populations is predictable, in that many organisms are linked to physical attributes of their habitat (Schoch & Dethier 1996).

There is an increasing emphasis in marine policy towards examining issues at the ecosystem level. Understanding processes at this large scale, however, suffers from the fact that ecosystem scale studies are inherently observational due to the multitude of uncontrolled factors at these scales. Repeatability is problematic because of the difficulty in locating ecosystem "replicates" in nature. One of the applications for a physical classification system is the grouping of similar habitat types, thus creating potential replicates for ecosystem studies.

Classification techniques (discussed below) are often used to map and inventory shoreline habitats. But while these classifications have excellent large area coverage and are relatively low cost in terms of the amount of information collected, they usually lack the data resolution necessary for studies of ecological change. Standard monitoring techniques such as quadrat samples along a horizontal or vertical transect at selected reference stations are good for high resolution change detection of populations or communities, but there is no way to extrapolate these high resolution data to large areas. The methods used to sample and analyze shoreline biota are detailed in Schoch & Dethier (1997). The procedure used to map, classify, and quantify beach habitats are described in this report, along with an analysis of how we can most efficiently extrapolate population and community level data across multiple spatial scales.

3. Background

Nested Hierarchical Systems

Hierarchy theory involves the concept that complex systems can be divided into hierarchical sets of entities, with each level or unit characterized by a particular range of temporal and spatial scales. The discreteness of units within a hierarchy is purely a product of human perception, thus the boundaries are arbitrary; but an attempt is made here to define or justify the selection of scales based on biogeographical attributes with known ecological responses. A nested hierarchy, such as the system proposed here, is one where the units at the apex of the system contain and are composed of all the lower units. In general, the larger and slower-responding units are at the top of the hierarchy while successively smaller and faster-responding units occur at lower levels. The properties of the higher units are not apparent from the properties of the individual parts (Allen & Starr 1982). For example, primary productivity over the inshore shelf at scales of 1-10 km may constrain the abundance of nearshore benthic biota in different ways depending on the specific attributes of small scale (10-100 m) benthic habitats.

Ecological responses to interacting physical and biological processes are manifested across multiple scales of space and time. At large scales (100-1000 km, decades to centuries) physical processes may dominate the structuring of nearshore communities, while at smaller scales (1-10 m, minutes to hours) biological processes may become more important in determining organism distributions. Climatic variations control global distributions of organisms near one end of the space/time continuum, while the rise and fall of the tides determine across-shore distributions at the opposite endpoint. Similarly, concentration gradients of primary productivity are linked to distribution patterns of higher trophic levels. Modeling the landscape-scale distribution of nearshore communities therefore requires quantifying multiple parameters at many spatial and temporal increments.

Geomorphic characteristics of beaches can serve as indicators of prevailing nearshore processes. Coastal classifications based on geomorphology are almost universally centered on describing landforms, and are usually referenced to temporal scales far exceeding those of ecological studies (e.g. Inman & Nordstrom 1971, Shepard 1976). It is in this temporal context that the two disciplines are particularly disparate. In terms of the life history of individual intertidal organisms, geological processes may be essentially static, even though on longer temporal scales the coastal environment is one of the most dynamic places on earth. There are exceptions such as subsidence or uplift caused by earthquakes, catastrophic erosional events such as landslides and slumps, and areas of high sediment transport, erosion or accretion. These areas may appear to change dramatically from one observation to the next, but the changes are often episodic or seasonal, thus not necessarily precluding recruitment, settlement, and reproduction of populations between events. On geological time scales, the physical processes controlling shoreline morphology may not be as critical to intertidal organisms as are the seasonal and annual changes in shoreline substrate and physical environment.

Overview of SZMS and Other Selected Classification Systems

The spatial distribution of nearshore habitats is critical information for marine ecologists studying intertidal populations and community dynamics, and for resource managers having jurisdiction over intertidal lands subject to the effects of development or episodic anthropogenic disturbance. In the United States, resource agencies at the federal, state and local levels have expended considerable funds in developing shoreline classification schemes. Non-hierarchical classification methods include those adopted by the National Oceanic and Atmospheric Administration (NOAA). The purpose of NOAA's Environmental Sensitivity Index (ESI) maps is to predetermine the sensitivity to oil spills of all beaches in the conterminous states and Alaska in terms of the predicted persistence of stranded oil and ecological consequences (Michel et al. 1978, Hayes 1980, and Domeracki et al. 1981). Washington's Natural Resources Damage Assessment (NRDA) classification is similar in purpose to the ESI maps but includes ecological criteria for determining vulnerability to oil spills. The Oregon Department of Fish and Wildlife is currently mapping rocky intertidal habitats with an objective of describing and comparing species distribution and diversity at various spatial scales along the Oregon coast (Fox et al. 1994). The U.S. Fish and Wildlife Service (USFWS) developed a hierarchical shoreline classification for the National Wetlands Inventory (NWI). Other hierarchical classifications include those from regional organizations, such as the Washington State Natural Heritage Program, that developed more detailed shoreline classifications for specific projects such as the mapping of intertidal and shallow subtidal lands for the Puget Sound Ambient Monitoring Program (PSAMP). The British Columbia Ministry of the Environment developed the Physical Shore-Zone Mapping System, a comprehensive classification that relies on qualitative geomorphological descriptions of habitats and processes that influence temporal and spatial variation of biota. The ecological classifications currently used in Washington are briefly reviewed below with the exception of the ESI maps, which are excluded because they do not consider intertidal ecology other than a qualitative biomass estimate.

The USFWS has mapped wetlands and deep water habitats of the United States through the National Wetlands Inventory Program, using a classification system developed by wetland ecologists to provide comparable information over large areas (Cowardin et al. 1979). This hierarchical system was designed to categorically describe ecological units that have certain homogenous natural attributes, and to arrange these units into a system that would aid natural resource management decisions. The habitat classification was originally based on 1:58,000 scale color infrared aerial photography flown during the early 1980's; wetlands were delineated and digitally mapped from visual interpretation of these photographs. Satellite [Landsat Thematic Mapper (TM)] imagery is now used to check for subsequent wetlands changes and losses. The base maps are 1:24,000 scale 7.5' USGS quadrangle maps. The minimum mapping units are 2 acres. Field verification is limited by a preset criteria of a minimum 2.5 field days and 25 wetlands sites per 1:100,000 map area.

The marine and estuarine portions of the NWI are considered to be insufficiently accurate to make land use and resource management decisions (Mumford et al., 1992). The only relevant information presented by NWI is the presence or absence of vegetation within the intertidal areas and the relative degree of tidal inundation. No information is included about whether the aquatic beds are drift or attached vegetation or what species of vegetation are present. Eelgrass beds or nearshore floating kelp beds *(Nereocystis* or *Macrocystis)* are not distinguished from other types of vegetation, and there is no means of indicating the substrate type beneath aquatic beds.

NWI Classification Summary

<u>Objective</u>: To provide a national standard for the classification of wetlands and deep water habitats over large areas
<u>Data source</u>: 1:58,000 color infrared aerial photography and multispectral satellite data
<u>Method</u>: photo interpretation and digital classification with field verification
<u>Basemap Scale</u>: 1:24,000 USGS quadrangles
<u>Resolution</u>: 100m

Advantages	Disadvantages
• standard mapping scale	spatial scale too small to accurately resolve intertidal habitats and associated biota
• large areal coverage	many changes have occurred since data were collected
• standard definitions	limited number of parameters
• hierarchical	not process oriented
• remote sensing techniques (e.g. are used substrate)	only visible coverages are mapped vegetation type, and possibly
• inclusion of dominant plants	lacks biological detail, a single plant is used as a key for each habitat
• provides some biological relevance	no measure of exposure energy
• all types of wetlands are mapped providing a linkage between freshwater and marine systems	

To make effective decisions, land use planners, regulators and agency personnel need information not found in the NWI maps. The Washington Natural Heritage Program produced a hierarchical marine and estuarine habitat classification system that was designed to be compatible with the Cowardin system, but able to identify and describe the full array of nearshore marine and estuarine natural communities in Washington State (Dethier 1990). The purpose was to 1) provide a framework for existing data and future inventory work on the status and distribution of marine and estuarine communities; and

2) to aid the Puget Sound Ambient Monitoring Program in mapping intertidal and shallow subtidal lands by providing mapping units, thus creating a uniform terminology useful to resource managers and planners. The mapping units (the nearshore habitat types, each with a distinct physical regime) are identified from the ground.

This classification system provides sufficient detail for the collection, organization and presentation of information describing the ecological characteristics of nearshore marine and estuarine environments. The Natural Heritage classification builds on the National Wetland Inventory classification of Cowardin et al. (1979), but adds an energy level to the hierarchy to incorporate the critical importance of waves and currents in structuring marine communities. This system also removes the "Aquatic Bed" categories from all levels, making substratum type one of the highest levels in the hierarchy. Marine and estuarine habitats are thus defined by their relative depth, substratum type, energy level and a few additional modifiers. For each combination of these physical variables, species that are diagnostic of the habitat are described, based on surveys from around the state of Washington. This system was modified by the Washington State Department of Natural Resources (WDNR) for implementation to a Puget Sound mapping project (Bailey et al, 1998).

DNR/Dethier Classification Summary

<u>Objective</u>: To provide a regional standard for the classification of subtidal, intertidal and estuarine habitats in Puget Sound
<u>Data source</u>: 1:24,000 color infrared aerial photography
<u>Method</u>: field classification
<u>Basemap Scale</u>: 1:12,000 WDNR orthophotos
<u>Resolution</u>: 10m

<u>Advantages</u>	<u>Disadvantages</u>
• derived from the NWI classification	a classification system rather than a mapping system
• standard definitions	limited number of parameters
• defines physical criteria such as substrate and energy	not process oriented difficult to differentiate estuarine from marine subdivisions
• includes biotic associations	
• includes the subtidal and intertidal zones	energy categories are difficult to apply
• hierarchical	qualitative biotic associations limit ecological usefulness over large spatial scales

Natural resource damages assessment (NRDA) is a process for resource management agencies to determine and collect restoration funds when hazardous material spills harm natural resources. Natural resources include land, fish, wildlife, plants, air, and water that the government manages on behalf of the public. At the federal level the Superfund law (CERCLA) authorizes NRDA when there is a release of a hazardous substance. The Clean Water Act (CWA) authorizes NRDA when there is a discharge of a hazardous substance into navigable waters. The Washington Administrative Code (WAC) 173-183-010 implements the legislation at the state level and provides a framework and standards for this process.

In the event of an oil spill or other hazardous substance, the parties responsible for the spill are liable for damages to natural resources according to a compensation schedule in the NRDA. Federal, State, or Tribal natural resource trustees must use recovered damages to fund restoration of injured resources to baseline (i.e., the condition that would have existed if the release or discharge had not occurred).

A Preassessment Screening was conducted on the coast of Washington for marine and estuarine habitats. An oil spill vulnerability ranking was determined for shore sections to aid in assessing damages to birds, mammals, fish, shellfish, and invertebrates. The marine and estuarine habitats present in the state are classified into thirty-seven types based on substrate type, energy regime and depth of occurrence. The habitats are ranked and scored for vulnerability to oil spills on a 1 to 5 scale, where a habitat vulnerability score (hv) of 5 represents the greatest vulnerability and 1 represents the least vulnerability. Marine and estuarine habitat vulnerability scores are based on the presence of living public resources at risk, where living public resources include only those not otherwise incorporated into the compensation schedule in the marine fish, shellfish, salmon, marine mammal or marine bird vulnerability rankings, and predicted sensitivity to the acute toxicity, mechanical injury and persistence effects of oil based on energy regime of the habitat and propensity to entrain oil.

NRDA Classification Summary

Objective: The purpose of this classification is to provide a marine and estuarine habitat oil spill vulnerability ranking.
Data Source: compilations from various sources
Method: annotated basemap
Basemap Scale: 1:24,000 USGS quadrangles
Resolution: 100 m

Advantages	Disadvantages
• standardized definitions	limited number of parameters
• defines physical criteria such as	not process oriented
• substrate and energy	no vertical zonation
•	not hierarchical
•	poor data resolution

In 1979 the British Columbia Ministry of the Environment set out to inventory and map the physical character of the provincial coastal zone. Howes et al. (1994) developed a classification of the materials, forms and processes that occur or operate along the sheltered mainland and exposed outer-island coasts of British Columbia. The classification was specifically developed to provide an inventory of the physical character of the shore zone and to show the distribution, extent and locations of shore types. The B.C. classification includes a descriptive biological inventory (Searing & Firth 1994, Morris et al. 1995) for mapping visible biota. The biota are cataloged in terms of spatial distribution within bands across the beach face. The data are collected from direct aerial observations and subsequent interpretations of aerial videotape of the shoreline. The aerial platform is usually a helicopter flown at a low altitude and speed so that a narrative description can be recorded. This is the most descriptive hierarchical classification system of those reviewed here. The database has a wide range of natural resource applications including planning, management, impact assessment, and oil spill response. The classification allows systematic recording of shore morphology, shore-zone substrate and wave exposure characteristics. Thirty-four shoreline categories have been defined in terms of substrate type, sediment size, width, and slope (Table 1). Shoreline units are represented by line segments on a map and with a unique identifier. Alternatively, shore units may be represented as polygons or points depending upon the scale of the map representation. Additional information on each unit and the components are recorded in an associated database.

The classification hierarchy first subdivides the shoreline into alongshore units. These are subsequently partitioned into across-shore components. Each component is systematically described in terms of physical characteristics such as morphology, texture and dominant geomorphic processes. As such, the mapping approach is descriptive (the mapper describes what can be seen of the component). There are no functional relationships with ecological processes incorporated into the classification scheme. The component polygons are qualitatively grouped into vertical zones representing the supratidal, intertidal or subtidal elevations. Shorelines are also differentiated by wave exposure. For example, additional shore units are delineated where wave exposure changes significantly. Wave exposure is based on fetch distance, resulting in a categorization summarizing wave exposure over multiple units.

British Columbia Shore-Zone Mapping System (SZMS)

Objective: to provide an inventory of the physical character of the shore zone and baseline data for a wide range of natural resource applications
Data source: vertical aerial photography, aerial videography, field verification
Method: photo interpretation, aerial surveys with narrative documentation
Basemap Scale: scale dependent on selected basemap
Resolution: 10 m at 1:5,000 scale (but variable depending on research scale)

Advantages	Disadvantages (see Results section)
• standard regional definitions	poor resolution at small spatial scales
relies on aerial video imagery and on	qualitative descriptions (except for

Table 1. Geomorphic Shoreline Type Classification (after Howes et al., 1994)

SUBSTRATE	SEDIMENT	WIDTH	SLOPE	SHORELINE TYPE	CLASS
ROCK	n/a	WIDE (>30m)	STEEP(>20°)	n/a	
			INCLINED(5-20°)	Rock Ramp, wide	1
			FLAT(<5°)	Rock Platform, wide	2
		NARROW (<30m)	STEEP(>20°)	Rock Cliff, narrow	3
			INCLINED(5-20°)	Rock Ramp, narrow	4
			FLAT(<5°)	Rock Platform, narrow	5
ROCK & SEDIMENT	GRAVEL	WIDE (>30m)	STEEP(>20°)	n/a	
			INCLINED(5-20°)	Ramp w/gravel beach, wide	6
			FLAT(<5°)	Platform w/gravel beach, wide	7
		NARROW (<30m)	STEEP(>20°)	Cliff w/gravel beach, narrow	8
			INCLINED(5-20°)	Ramp w/gravel beach, narrow	9
			FLAT(<5°) -	Platform w/gravel beach, narrow	10
	SAND & GRAVEL	WIDE (>30m)	STEEP(>20°)	n/a	
			INCLINED(5-20°)	Ramp w/gravel & sand beach, wide	11
			FLAT(<5°) -	Platform w/gravel &sand beach, wide	12
		NARROW (<30m)	STEEP(>20°)	Cliff w/gravel and sand beach	13
			INCLINED(5-20°)	Ramp w/gravel and sand beach	14
			FLAT(<5°) -	Platform w/gravel and sand beach	15
	SAND	WIDE (>30m)	STEEP(>20°)	n/a	
			INCLINED(5-20°)	Ramp w/sand beach, wide	16
			FLAT(<5°) -	Platform w/sand beach, wide	17
		NARROW (<30m)	STEEP(>20°)	Cliff w/sand beach	18
			INCLINED(5-20°)	Ramp w/sand beach, narrow	19
			FLAT(<5°) -	Platform w/sand beach, narrow	20
SEDIMENT	GRAVEL	WIDE (>30m)	FLAT(<5°) -	Gravel flat, wide	21
		NARROW (<30m)	STEEP(>20°)	n/a	
			INCLINED(5-20°)	Gravel beach, narrow	22
			FLAT(<5°) -	Gravel flat or fan	23
	SAND & GRAVEL	WIDE (>30m)	STEEP(>20°)	n/a	
			INCLINED(5-20°)	n/a	
			FLAT(<5°) -	Sand & gravel flat or fan	24
		NARROW (<30m)	STEEP(>20°)	n/a	
			INCLINED(5-20°)	Sand & gravel beach, narrow	25
			FLAT(<5°) -	Sand & gravel flat or fan	26
	SAND/MUD	WIDE (>30m)	STEEP(>20°)	n/a	
			INCLINED(5-20°)	Sand beach	27
			FLAT(<5°) -	Sand flat	28
				Mudflat	29
		NARROW (<30m)	STEEP(>20°)	n/a	
			INCLINED(5-20°)	Sand beach	30
			n/a		
ESTUARIES					31
ANTHRO-POGENIC	MAN-MADE	n/a	n/a	Manmade, permeable	32
				Man-made. impermeable	33
CURRENT-DOMINATED				Channel	34

	calculations of fetch) define attributes
• overflight narratives	the shoretypes are lumped so that much of Puget Sound is defined by a few classes
•	
• hierarchical	poor estimates of area
	does not identify cryptic or burrowing organisms
• comprehensive regional coverage	
• physical and biological inventory	

The *Exxon Valdez* spill prompted the development of a classification scheme that integrates ground observations with low altitude aerial photography, and focuses on describing the physical features and conditions controlling ecological responses (Schoch 1994). This system was applied to National Parks in southcentral Alaska and to the Olympic Coast National Marine Sanctuary from Neah Bay to the Copalis River, Washington. Conventional geomorphological parameters such as sediment size and shape and landform descriptions are combined with physical factors generally thought to control the abundance and distribution of macroalgae and macroscopic sessile invertebrates. This classification scheme is applied to each intertidal zone to vertically differentiate the shoreline. Vertical differentiation is an important consideration in regions such as the Pacific Northwest, where large intertidal areas can be exposed at low tide. Many of the parameters utilized by this classification scheme are correlated. Although the specific geomorphic mechanisms and beach processes are not evaluated, all of the parameters combined provide, through association, indicators of the beach processes that may define biotic patterns. More importantly, these parameters characterize the shoreline in terms that can be statistically analyzed. The objective was to create a hierarchical shoreline classification for large spatial assessments of intertidal habitats and assessments of coastal processes for use in intertidal habitat modeling.

Schoch Classification Summary

Objective: to define the physical character of the coastal zone for intertidal habitat modeling
Data source: ground surveys and 1:12,000 aerial photography
Method: field assessment of geomorphic features, surveyed shoreline profiles, and subsequent GIS analyses
Basemap Scale: 1:12,000 or scale of available aerial photography
Resolution: variable depending on research scale, 10 m at 1:12,000 basemap

Advantages	Disadvantages (see Results section)
• high physical and biological data resolution	method requires detailed ground surveys
• quantitative criteria	spatial extent of modeled biota depends on the number of segments sampled
• can be used for habitat modeling	

- nearshore process oriented
- characterizes process indicators
- hierarchical

4. Methods

Intertidal shorelines are a complex mosaic of habitats, with spatial and temporal patchiness across many scales of observation. Physical and biological factors strongly influence the distributions and interactions of marine plants and animals, so that biotic communities generally are linked to factors such as substrate type, wave exposure, and other physical characteristics (Dethier 1990). These physical parameters contribute not only to horizontal patchiness but also to intertidal zonation. On small to moderate scales, physical factors contributing to spatial variation of organism abundance and diversity include wave exposure and associated forces of wave breaking (e.g. Seapy & Littler 1978, Lewis 1964, Paine & Levin 1981; Underwood & Jernakoff 1984, Denny et al. 1985), rock type (Raimondi 1988), desiccation (Johansen 1972, Menge et al. 1983), shade (Carefoot 1977), and disturbance from logs, ice, and sand scour (Daly & Mathieson 1977, Paine & Levin 1981, Littler et al. 1983, Wethey 1985). All of these factors may act in a patchy fashion, creating locally variable assemblages, because of cm- to km-scale differences in rock aspect, local topography, slope, and wave exposure. The influence of each factor may vary between seasons or over multiple years (Foster et al. 1988). At landscape scales, species composition is affected by oceanographic conditions such as current patterns (affecting dispersal and nutrient delivery), salinity, and water temperature (Roughgarden et al. 1988).

Biological factors similarly contribute to spatial and temporal variation in intertidal assemblages. Key processes include competition (Connell 1972), biotic disturbances such as predation (Paine 1974) and grazing (Underwood & Jernakoff, 1984; Duggins & Dethier, 1985; reviewed in Steneck & Dethier, 1994), and recruitment (reviewed in Menge & Farrell, 1989; Menge, 1991; Santelices, 1990). Modeling and field work suggest that on local spatial scales, such biotic factors interact with physical factors to produce community patterns (Menge & Olson, 1990; Dayton et al., 1984). On larger scales, the role of oceanographic processes and environmental variation become increasingly important, affecting community structure indirectly rather than directly. Thus any predictive model of community ecology must be hierarchical, with local-scale models nested within more complex larger-scale models.

A hybrid model was developed that combines parameters of the B.C. Shore-zone classification with quantitative field observations of the Schoch classification in a nested hierarchy that can be tailored to the specifics of time and funding for any given project. This new classification focuses on characterizing geomorphic features and processes, and quantifying those generally cited as affecting the abundance and distribution of macroscopic algae and sessile invertebrates in the nearshore zone. This hybrid system provides high resolution data for modeling habitat distributions and biological associations. Predicting the distribution, abundance, and diversity of intertidal fauna and flora over landscape scales based on biological sampling transects is described in Schoch and Dethier (1997).

We apply hierarchy theory to solve issues of biological variability and scaling in the marine realm by systematically quantifying and eliminating geophysical gradients among biological sample sites. Minimizing gradients in the physical environment can enhance our ability to detect an actual change from natural variation, because at least in some systems, sampled communities show significant fidelity to their physical habitat types. Application of the SCALE model (Shoreline Classification and Landscape Extrapolation) increases biological homogeneity by partitioning a shoreline into a spatially nested series of geophysically uniform segments.

Field mapping using the SCALE approach consists of the following steps:

1. Map an area using the SZMS protocols: analyze the low altitude aerial videography of the coastal zone for large scale (100-1,000 m linear) partitioning of the shoreline into beach units, based on shore geomorphology, geophysical and biological characteristics of the nearshore, and characteristics of the upland watershed as in Howes et al. (1994);

2. Block the shore units into nearshore cells based on regions of oceanic homogeneity, especially in chlorophyll, nutrients, salinity, and sea surface temperature at scales greater than 1 km (grid);

3. Analyze the SZMS results to determine characteristics and distribution patterns of nearshore habitats, and how these patterns relate to monitoring concerns;

4. Select and prioritize habitats of interest for high resolution SCALE modeling;

5. Field map the shoreline (on the ground) to partition the beach units identified in Step 1-3 into geophysically homogeneous segments (10-100 m linear), quantifying the geophysical attributes known to force biological communities in the nearshore;

6. Sample selected reference shore segments (from geophysically similar segment clusters) for macroalgae and macroinvertebrates, or other organisms of interest (see below).

7. Statistically scale-up these community or population data by extrapolating among segments within geophysically similar clusters within an oceanic cell. These communities can also be scaled up among cells but with a loss of resolution to detect ecological change.

8. Validate the model results by sampling randomly selected segments from within the clustered groups.

In 1997, the Washington Department of Natural Resources (WDNR) funded a pilot project to apply the SCALE model to the shores of Carr Inlet, the first major embayment south of the Tacoma Narrows in the Puget Sound Trough (Figure 1). Field mapping using the SCALE approach has been detailed in the report "Analysis of Shoreline Classification and Bio-physical Data for Carr Inlet" (Schoch & Dethier 1997). This model is represented in Figure 2 under the branch labeled "Nearshore Cell" (formerly called "Block" in Schoch and Dethier (1997)). Following that work, an independent aerial survey was flown by Coastal and Ocean Resources, Inc. to map the same shoreline using the B.C. Physical Shore-zone Mapping System, illustrated in Figure 2 under the branch labeled "Nearshore Shoretype". Task 1 of this project details the results of that effort.

The current study proposes and evaluates a spatially comprehensive system combining the physical and biological attributes of the B.C. Physical and Biological Shore-Zone Mapping System (SZMS) with the quantitative aspects of high resolution statistical modeling allowed by SCALE. This model is represented by Figure 2 in its most basic form as consisting of six levels. We advocate nesting the quantitative model inside the qualitative inventory at the third level (as shown by the dashed line) so that each physical unit of the qualitative inventory is partitioned into quantified geophysically homogeneous alongshore segments. This model produces a low resolution (100-1000 m) physical and biological inventory with 100% coverage of the project area, and a higher resolution database of measured physical attributes and modeled biota (10-100 m) for a smaller subset of selected habitats. Habitats selected for modeling were those that best characterized the project area in terms of shore length, shore area, or ecological significance. The six levels of the model are described as follows from the smallest scale to the largest:

Level 1. Coastal Ocean: The coastal ocean includes the inshore (continental) shelf and the nearshore surf zone.

Level 2. Nearshore Ocean: The nearshore ecosystem is characterized by general shore configuration (linearity and aspect) and the inshore (deep water) wave energy regime. Komar (1997) defines the nearshore as the area extending seaward from the shoreline to just beyond the region where the waves break. The depth limit is where the sediment is less actively transported by surface waves, in general this is 10-20 m.

Level 3. Nearshore Cells: Gradients of attributes such as salinity, water temperature, nutrients, wave energy and sediment transport in the nearshore ocean can be quantified to define areas that are ecologically distinct.

Level 4. Shoretype Class: The shoretype characterization is derived from a comprehensive aerial bio-physical shoreline inventory such as the SZMS. The shoretype includes descriptive information about the supra-tidal, intertidal, and subtidal zones.

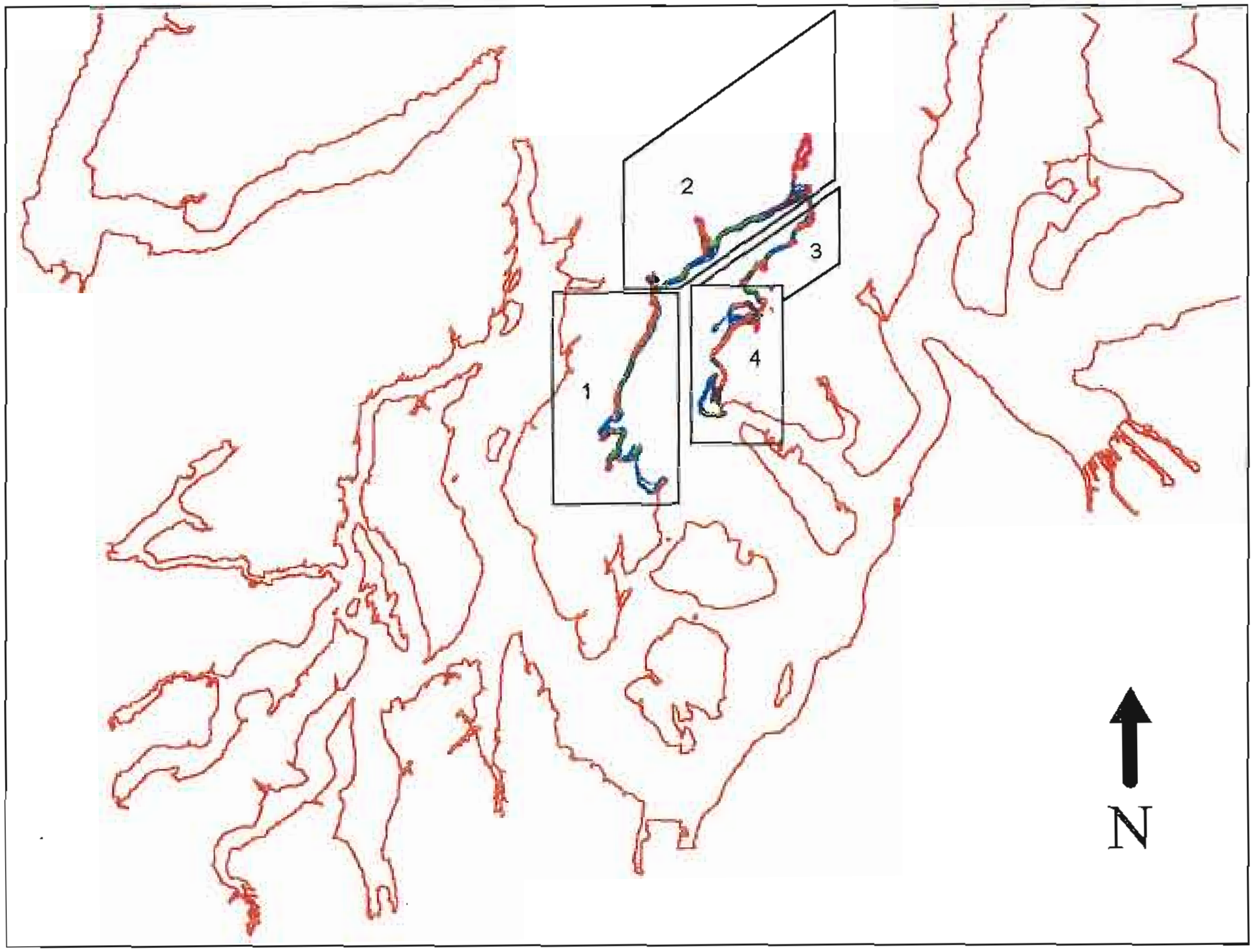


Figure 1. Map of South Puget Sound, Carr Inlet is highlighted by the color coded SZMS Shoretype Classes. The nearshore cells are annotated.

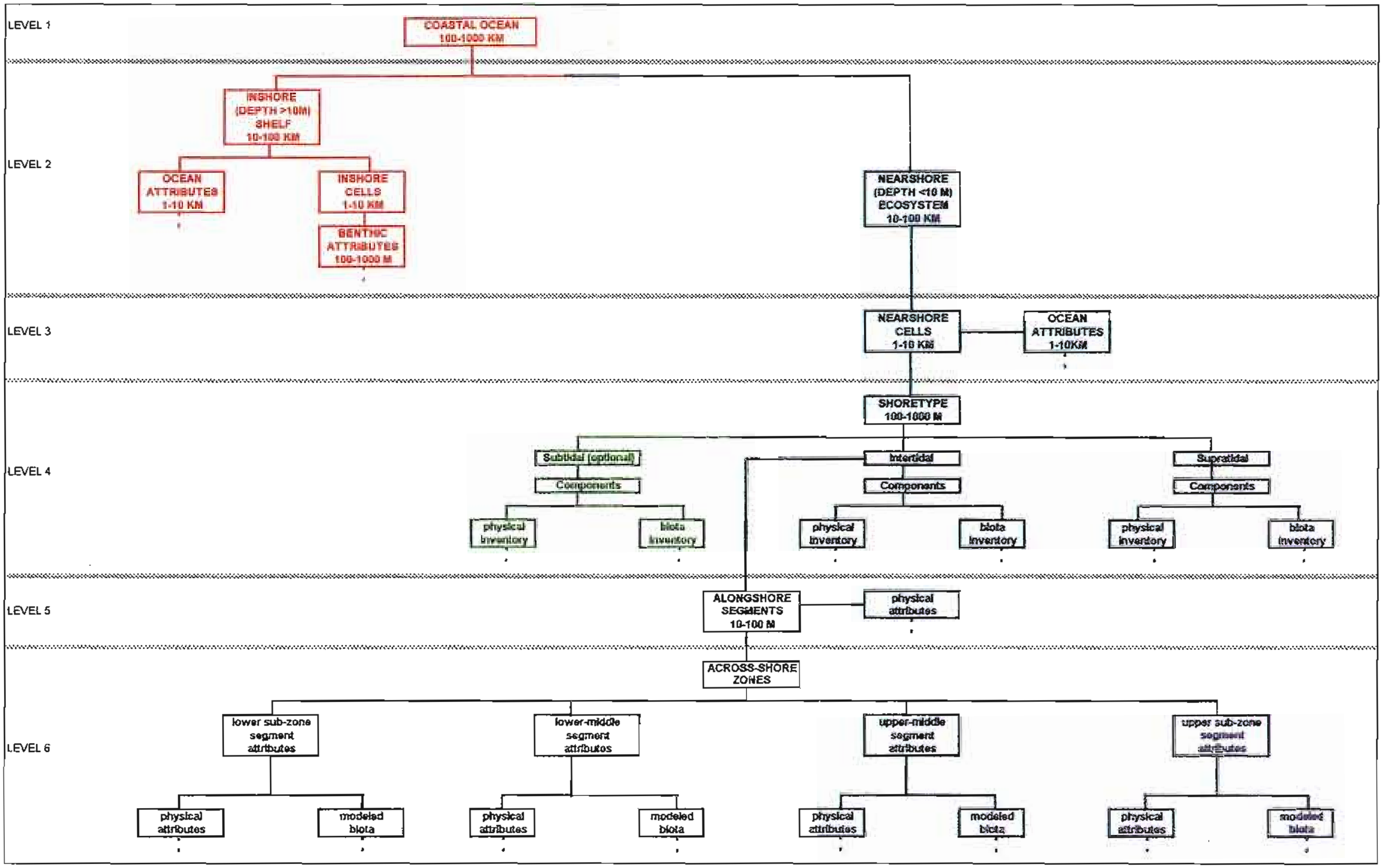


Figure 2. The nested hierarchical Shoreline Classification and Landscape Extrapolation (SCALE) model. The red portion of this diagram was not included in the Carr Inlet study. The green portion of the model represents the subtidal zone which is not always classified.

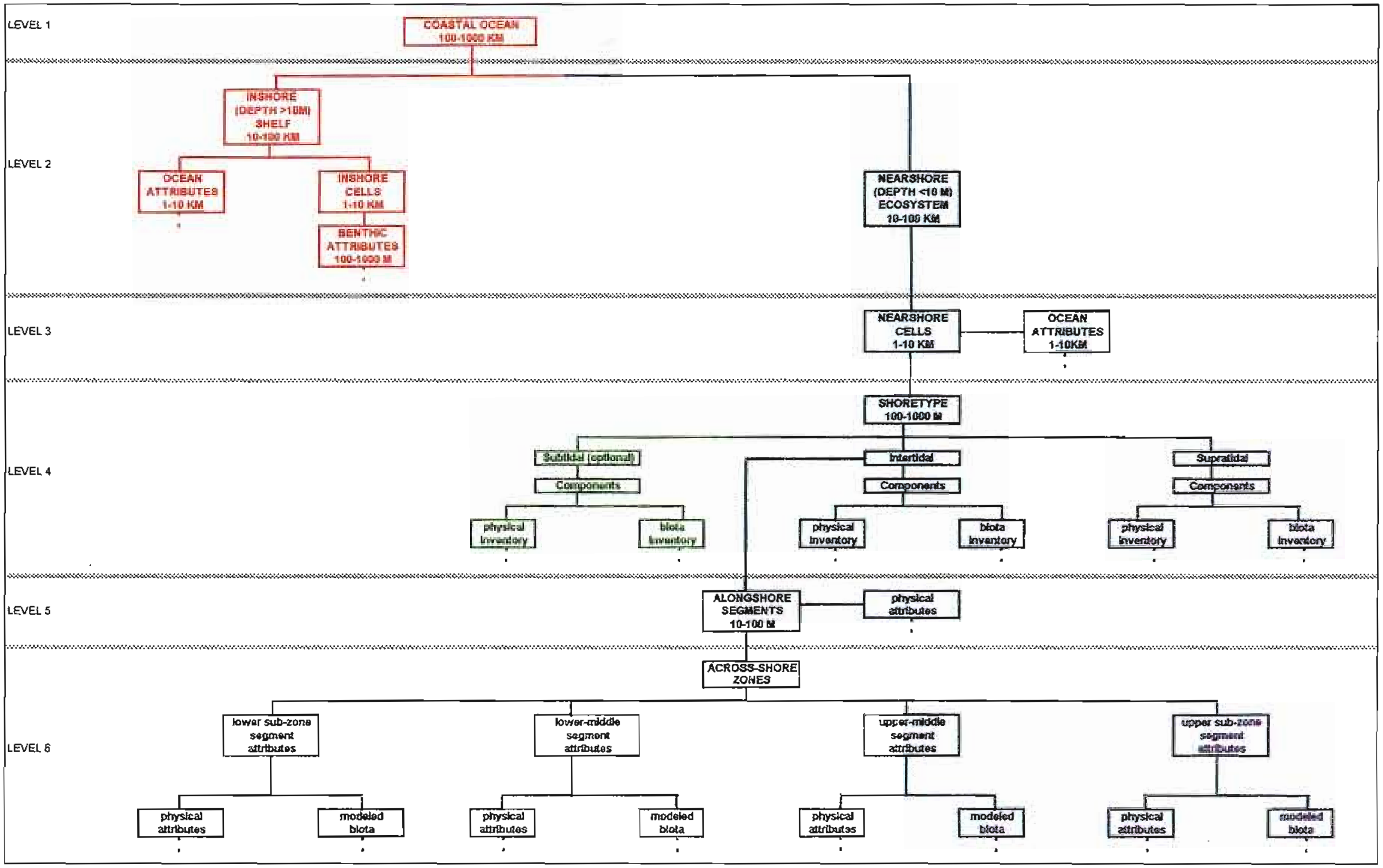


Figure 2. The nested hierarchical Shoreline Classification and Landscape Extrapolation (SCALE) model. The red portion of this diagram was not included in the Carr Inlet study. The green portion of the model represents the subtidal zone which is not always classified.

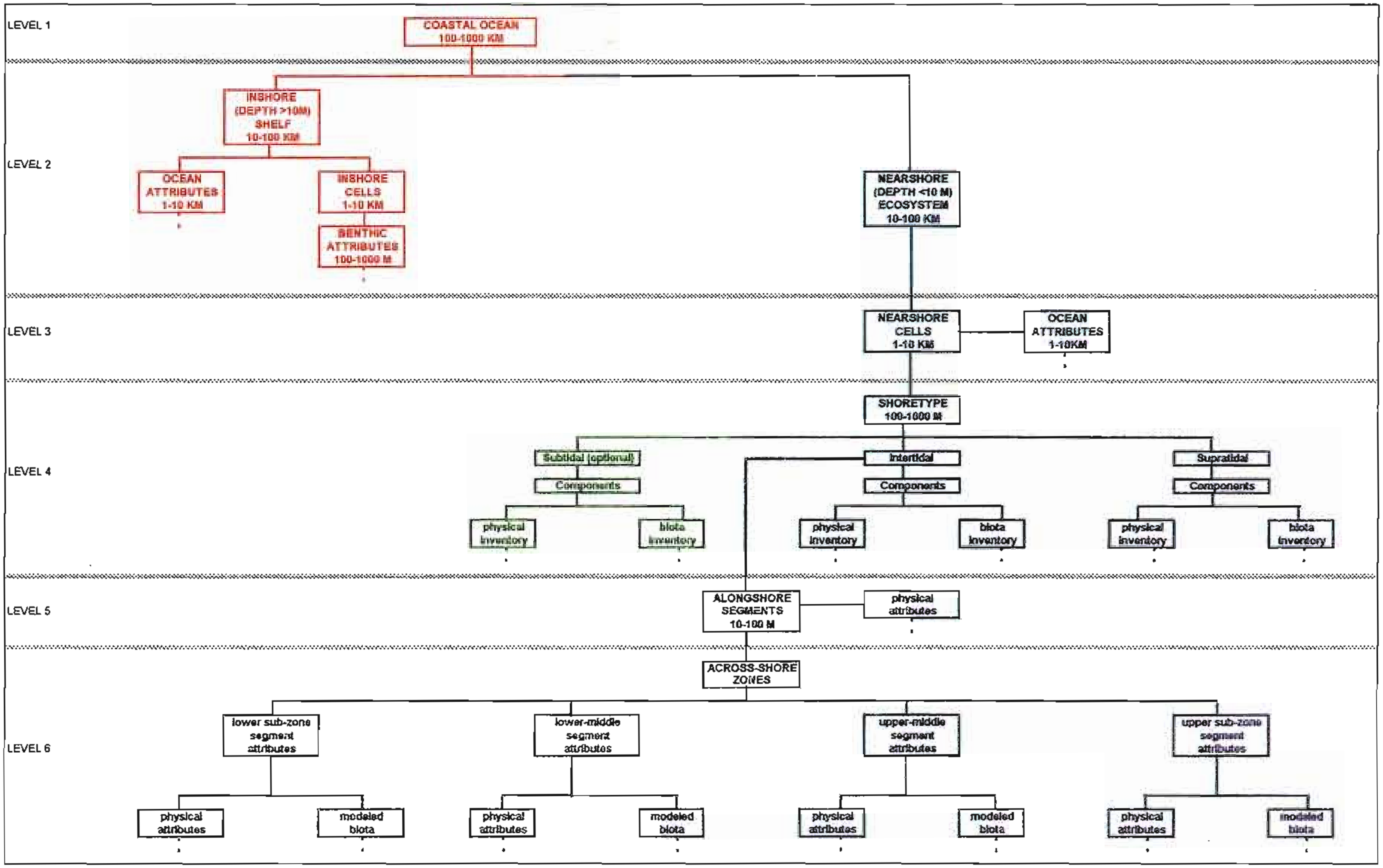


Figure 2. The nested hierarchical Shoreline Classification and Landscape Extrapolation (SCALE) model. The red portion of this diagram was not included in the Carr Inlet study. The green portion of the model represents the subtidal zone which is not always classified.

Level 5. Alongshore Segments: Each segment contains vertical partitions of the intertidal zone that reflect the daily immersion time of substrate and associated biota. Segments are distinguished based on horizontal geomorphic homogeneity.

Level 6. Across-shore sub-zones: These are the smallest spatial units and are defined by polygons delineating each sub-zone within the alongshore segments. Physical attributes are measured and the biota can be either sampled or modeled for each sub-zone within the segment.

The combined nearshore habitat model is described below for general application. The specifics of how this was applied to Carr Inlet are described in the following section and in Schoch & Dethier (1997). The physical attribute definitions and segment grouping protocols described here supersede definitions and methods of earlier reports. See Figure 3 for a diagram of these attributes and how they fit into the SCALE model. Table 2 summarizes the attribute categories used for Carr Inlet. Note that attribute categories are used to classify the full range of expected values. The range for each category is based on measured or calculated extreme values to set the high and low endpoints, then intermediate intervals are assigned to whole number increments. The number of increments is determined by an interpretation of the ecological sensitivity to the specific attribute. For example, particle size is a continuous variable with values of grain diameter ranging from the very fine grains of clay to refrigerator sized boulders. The increments we chose to use categorize all possible values into 10 discreet sizes. Many of the organisms we sample are known to respond to changes among these categories. The number of increments can be modified for any particular area or ecological question of interest requiring more or less resolution.

Ocean Attributes

On landscape scales, species composition is affected by broad oceanographic conditions such as current patterns (affecting larvae dispersal and nutrient delivery) (Alexander & Roughgarden, 1996), salinity, water temperature (Roughgarden et al., 1988), and wave climates (Denny, 1995).

Nutrients

The ecology of the nearshore benthos (from the intertidal to water depths of 10 m) has been studied in detail in many locations in the U.S.. However, the processes that couple the intertidal regions with those in the nearshore ocean are poorly understood. For example, it is not apparent if production in some intertidal communities is regulated by the delivery of nutrients from the coastal ocean or by drainage from nearby rivers and estuaries. Such "edge" communities at the transition between one regime and another have rarely been studied as an integrated system. However, it is clear that there is strong physical and biological coupling between the nearshore and the intertidal.

Our understanding of how wind-driven oceanic processes such as upwelling play a role in structuring the biology of the nearshore has improved. Menge et al. (1997) demonstrated a correlation between nearshore concentrations of chlorophyll-a and growth rates of

Table 2. The SCALE Nearshore Segmentation and Classification Model

Physical Units (see Howes et al., 1994)													
Alongshore Segments 10-100 m			Across-shore Zones 10-100 m										
Orientation	Wave Power (watts/m^2)	Drift Exposure	Zone	Area (m2)	Size	Iribarren	Mean Vertical Runup	Seepage	Slope	Dynamism	Permeability	Roughness
1 = N	1 = 50	1 = same direction	1 = Backshore (uplands)	1 = 100-1,000	1 = clay	1 = <.5	1 = < 0.5m	present	1 = 1 - 2°	1 = < 1.0	1 = > 10 min	1 = very smooth (sand)
2 = NE	2 = 250	2 = 135 degrees	2 = Supratidal (spray zone)	2 = 1,000 - 10,000	2 = mud	2 = .5 - 1.0	2 = 0.5 - 1.0m	absent	2 = 2 - 4°	2 = 1.0 - 2.0	2 = 5 - 10 min	2 = smooth (small pebbles)
3 = E	3 = 1,000	3 = 90 degrees	3 = Upper Intertidal (MHHW)	3 = 10,00 - 100,000	3 = silt	3 = 1.0 - 2.0	3 = 1.0 - 2.0m		3 = 4 - 7°	3 = 2.0 - 5.0	3 = 2 - 5 min	3 = gnarled (cobbles)
4 = SE	4 = 5,000	4 = 45 degrees	3 = Upper Middle Intertidal (MSL-MHW)	4 = 100,000 - 1,000,000	4 = sand	4 = 2.0 - 3.0	4 = 2.0 - 3.0m		4 = 7 - 10°	4 = 5.0 - 10.0	4 = 1 - 2 min	4 = rough (boulders)
5 = S	5 = 10,000	5 = opposite direction	4 = Lower Middle Intertidal (MLW-MSL)	5 = > 1,000,000	5 = granules	5 = >3.0	5 = > 3.0m		5 = 10 - 15°	5 = > 10	5 = < 1 min	5 = crevices (blocks)
6 = SW	6 = 25,000		5 = Lower Intertidal (MLLW)		6 = pebbles				6 = 15 - 20°			
7 = W	7 = 50,000		6 = Upper Subtidal (< 10 m)		7 = cobbles				7 = 25 - 35°			
8 = NW	8 = 100,000		7 = Lower Subtidal (>10 m)		8 = boulders				8 = 35 - 45°			
	9 = 200,000				9 = blocks				9 = 45 - 65°			
	10 = 400,000				10 = basement				10 = > 65°			
	11 = 600,000											
	12 = 1,000,000											

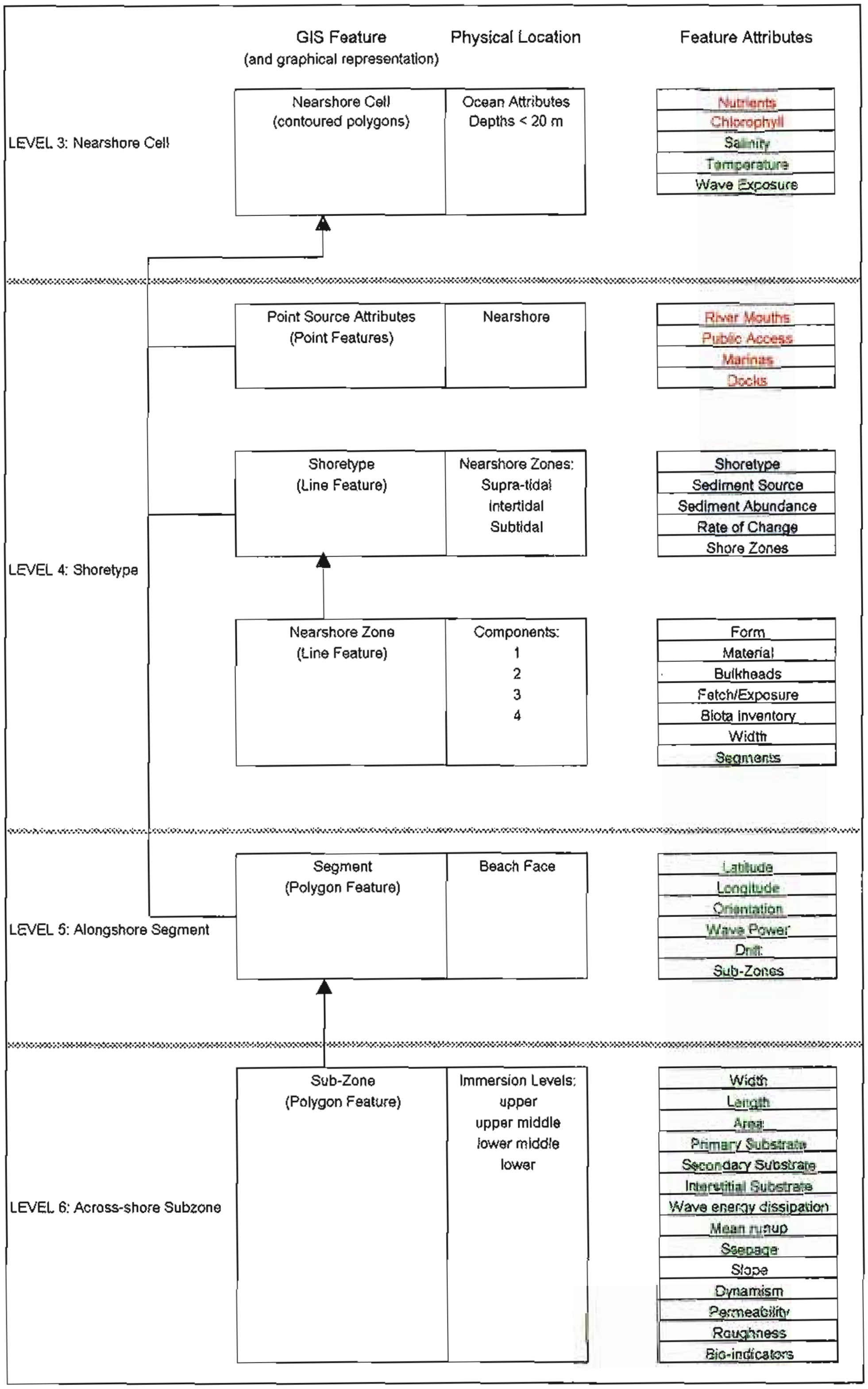


Figure 3. The benthic and ocean attributes measured for SCALE input. Attributes in red were not measured for the Carr Inlet study but are recommended for general inclusion. Attributes marked in blue are from the SZMS and those marked in green are from the SCALE field observations. See text for attribute descriptions.

rocky-shore organisms at 2 sites within an upwelling region but 10's of km apart. They suggest that oceanic processes (e.g., local water-exchange rates alongshore or inshore-offshore) may be driving these site differences. Inshore nutrient levels can directly affect productivity of nearshore algae (Bustamente et al., 1985; Ormond & Banaimoon, 1994), and the feeding and growth rates of a variety of suspension-feeding organisms are generally enhanced in higher flow conditions (e.g., Frechette & Bourget, 1985; Eckman et al., 1989, Sanford et al., 1994, Lesser et al., 1994). The nutrient regime was not determined for Carr Inlet but future modeling work should consider this attribute on an experimental basis. The parameters of interest are nitrates, nitrites, ammonia, and phosphates, and it is advisable to collect chlorophyll concentration as well. See Strickland and Parsons (1972) for detailed information on collecting and analyzing water samples.

Salinity and Water Temperature

Differences in salinity and water temperature are often reflected in the composition of intertidal and nearshore flora and fauna communities. It is difficult to quantify boundaries of salinity or water temperature due to the large temporal and spatial changes caused by precipitation, surface runoff, groundwater flow, and evaporation. But most nearshore regions have characteristic patterns that can be quantified. Many intertidal organisms are extremely sensitive to the salinity range of the water. Some can survive by adaptation of osmotic mechanisms that protect them against damage from salinity changes. Since some organisms are better adapted to lower salinity than others, the entire community structure of one beach may differ from that of another beach having similar morphology but different salinity. Typically the open ocean has a mean salinity of 35 $^{0}/_{00}$, but large salinity gradients can occur at the scale of individual organisms due to the effects of river plumes and groundwater seeps. Because of potentially dramatic salinity gradients across space and time, it is important to recognize that here the intent is to characterize the salinity climate rather than determine through exhaustive monitoring the exact salinity regime of the local waters. For purposes of ecological modeling, the salinity is based on values measured at the time of biological sampling from a depth of 1 meter.

Exposure

Wave exposure can aid in the delineation of shorelines having approximately the same wave energy impinging on the coast. The nature of deep water waves reaching a coast is the basis for several similar wave environment classifications. The classification proposed by Davies (1980) is useful for a very general categorization of wave climates. A low-energy environment occurs where coasts are protected from the full force of the waves. Protection may be provided by a short sea fetch resulting from the distribution of landmasses, sea ice, or reefs. The waves of this environment can only be generated within sheltered waters. At the opposite end of the energy spectrum are the storm waves which dominate the high latitudes. Strong west winds in the North Pacific, North Atlantic, and the Southern Ocean generate high and relatively steep waves that can be destructive to coastal areas. Coastlines subject to these waves generally show evidence of erosion such as cliffs and platforms. The swell wave environment lies between the two above end points. These waves travel long distances from their generating areas, usually from the stormy west wind belt (Owens 1982). Howes et al. (1994) suggests the following six wave exposure classes to characterize the wave climate over shoreline distances of 10-100 km: very protected (< 1 km), protected (1 - 10 km), semi-protected (10 - 50 km), semi-exposed (50 - 500 km), exposed (500 - 1000 km), and very exposed (>1000 km). The wind fetch criteria limits the ecological usefulness of this classification in the nearshore since there is no consideration for wave energy or attenuation, but when restricted to large areas the categories provide a qualitative approximation of exposure.

Point Features

Large volumes of fresh water runoff can significantly influence the structure and distribution of nearshore communities. Many cumulative impacts result from the movement of water and sediments through the nearshore environment. Rivers, for example, are the primary sources of environmental pollutants to the coastal zone. The processes controlling the extent and magnitude (e.g. spatial and temporal scale) of cumulative impacts are often a function of the mode of dispersal. Dispersal can either increase or decrease the effects of the materials. For example, pollutants can be transported by rivers and collected in lakes and reservoirs, where they become concentrated over time and result in increased effects to biotic communities. Coastal ecosystems continue to be threatened by the insidious indirect impacts of watershed land use including timber harvesting, agriculture, and urbanization. Materials associated with these activities are transported by rivers, causing perturbations to the marine nearshore and estuarine environments (Beatley 1991). Forest practices in the Pacific Northwest have been associated with increased sedimentation of streams, increased stream temperatures and a larger influx of heavy metals suggested by the analysis of tissues in marine benthic organisms (Sindeman 1988). Therefore, in terms of seasonal precipitation, the local weather can be an important consideration when major rivers and estuaries are present within the bounds of this spatial increment. Rivers and streams are located and mapped as point features (this was not included in the current project but is recommended for the future). When stream flow and water quality data are available, the map symbology should reflect the size and quality of the stream characteristics. Other point features already included in the database are public access points, marinas, and large dock structures.

Physical Units

Shoretype

These are linear map features representing generally homogeneous shore morphology (100 - 1000 m). Shoreline type (shoretype) refers to the descriptive classification of the general geomorphological landform represented by the predominant physical shoreline structure (e.g. lagoons, deltas, dunes, bars, spits, sea cliffs, reefs, wave-cut terraces, etc.). Many coastal geomorphology studies rely on descriptive terminology of predominant short and long term physical processes to identify shoreline types (Inman & Nordstrom 1975, Hayes 1980, Domeracki et al. 1981, Wright and Short 1983, Carter 1988, Michel & Hayes 1991, Howes et al. 1994). While some processes occur continuously such as the transport of sand, others affect the intertidal zone seasonally or only during the rise and fall of the tide such as the rolling of cobbles and the saltation of sand and pebbles by waves. Sediment transport influences shoreline morphology and dynamism by shifting the sediment along, away from, or onto the shoreline. The rate of sediment transport affects the dynamism of the beach. These characteristics are evaluated for each alongshore unit in terms of sediment sources, and a relative assessment of abundance. The shoreline change characterization is based on observations of landform features, prevailing currents, and accumulations of debris. For ecological purposes, the most useful shoretype classification temporally integrates the significant processes of wave and sediment interactions affecting the predominant nearshore biota at spatial scales of 100 - 1000 meters. The 34 shoretype classes used here are from Howes et al. (1994).

Shore Zones

The physical units are divided into four across-shore zones: the backshore, supratidal, intertidal, and the subtidal. For the SCALE model the divisions are based on physical and biological characteristics between the high and low water lines. The zones are defined by elevations relative to the high and low water lines as predicted by the National Ocean Survey (NOS) in the United States. The subtidal zone is adjacent to the lower elevation margin of the intertidal and is never exposed. The intertidal zone is the maximum area exposed during the daily tidal cycle. The supratidal zone is generally the spray zone (the area of infrequent inundation achieved by only the most extreme tide and storm events). The backshore is the area beyond the supratidal zone and generally beyond the influence of extreme tides, but may be episodically flooded during severe storms.

Form and Material

The analysis of sediments from coastal landforms is an indispensable part of a geomorphological assessment. These analyses serve two main purposes: first the prediction of sediment movement, and therefore the development of the landforms, and second, the interpretation of historic geomorphological processes (Snead 1982). Very often, coastal processes are difficult to document within the spatial and temporal scales of direct observations. Predominant processes may not be operating, or they may be too slow or infrequent. Such processes may be inferred by examining the size and distribution of the populations of sediment grains that have been produced. Thus sediment analysis serves to provide clues to environmental processes (Pethnick 1984). The morphological form of a shoreline is described by Howes et al. (1994) using 12 primary and 86 secondary categories. Note that a morphological form description consists of only one primary category, but more than one secondary category. Qualitative descriptions of the material makeup of the shoreline include 3 primary categories and 18 secondary categories. The primary and secondary material types include composition and origin, which are important in terms of porosity, fracturing, weathering and structural integrity of the substrate.

Bulkheads

Bulkheads are hard stabilization structures that armor the coastline in response to the threat of damage to artificial features following shoreline erosion. Bulkheads usually occur in the upper intertidal sub-zone but may extend well into the middle sub-zone.

They are constructed of many different materials. For this project, bulkheads were described as linear features within each physical unit and length estimates were made based on a percentage of the physical unit that was armored. Additional details of how the bulkheads were treated are included in the Task 1 report.

Modified Effective Fetch and Maximum Fetch

The Army Corps of Engineers, Coastal Engineering Research Center (CERC, 1984) provides a standard method for calculating effective wave fetch:

$$F_e = [\Sigma(\cos \alpha_i)][F_i/(\Sigma \cos \alpha_i)] \tag{1}$$

where F_e = effective fetch
α = angle between the shore normal and direction i
F_i = fetch distance in km along direction i

Harper et al. (1991) describes a simplified method of calculating effective fetch to integrate more than one fetch direction (this is a corrected version from the equation appearing in the British Columbia Shore-Zone Mapping System manual (1994)):

$$F_m = [F_{45L}(\cos 45) + F_N + F_{45R}(\cos 45)]/[1 + 2(\cos 45)] \tag{2}$$

$$= [F_{45L}(0.707) + F_N + F_{45R}(0.707)]/2.414 \tag{3}$$

where F_m = modified effective fetch in km
F_{45L} = fetch distance in km along direction 45^0 left of the shore normal
F_N = fetch distance in km along the shore normal
F_{45R} = fetch distance in km along direction 45^0 right of the shore normal

Note that estimates of wave energy based on fetch do not take into consideration the duration of wind forcing, or the cumulative effect of ocean swells. Harper also measures maximum fetch for each physical unit to estimate effects from open ocean waves. But note that this does not account for the effects of refracted, diffracted, and reflected waves. Harper's modified effective fetch is particularly useful for estimating wave exposure for protected embayments and inland shores subjected primarily to locally generated wind waves. Howes et al. (1994) define a classification based on Harper's fetch calculation where wave exposure increases with increasing fetch distance (see the description for exposure above). This is useful for differentiating wave climates in areas of minimal fetch such as the many small bays and inlets of Puget Sound.

Biota

The aerial survey of the shoreline includes direct observations of visible biota and subsequent interpretation of aerial videotape and aerial photographs. Only large surface biota (algae, vascular plants, and invertebrates) of distinctive color or texture, and infaunal invertebrates that leave a large surface signature (such as ghost shrimp) can be detected using these methods. Groundtruthing of each biotic signature (e.g. barnacles, sand dollars, salt marsh vegetation) is desirable. Searing & Firth (1994) and Morris et al. (1995) provide details for the aerial mapping of intertidal biota.

Alongshore Segments

The spatial heterogeneity of physical environments generates diversity in intertidal communities. A morphodynamically homogeneous shoreline, or a physically uniform environment, should have minimal variation of organism abundance provided that biological factors such as population dynamics, predation and competition, or anthropogenic factors are not creating small scale spatial anomalies (but see Foster 1990). The spatial heterogeneity of the physical variables in shoreline structure can be quantified by partitioning a contiguous shoreline into relatively discrete segments having generally homogenous characteristics. The term "homogenous segment" is used here to mean a spatial region that is morphodynamically uniform as defined by a suite of abiotic attributes. Within homogenous segments, biotic processes often produce an aggregation of specific organisms, following various spatial-temporal scales, and these can be measured (Legendre et al. 1989). For this shoreline model, geomorphologically homogenous segments become the fundamental unit for the statistical analysis of spatial variations and distributions of shoreline habitats. The degree of homogeneity is subjective, since in reality there are seldom clearly defined boundaries between segments but rather gradients of abiotic and biotic features. Therefore, the classification relies considerably on the experience and heuristic analysis of the observer to define and delineate the segments. Hurlbert (1984) points out that the degree of heterogeneity permissible or desirable will affect the magnitude of random error and the sensitivity of the experiment, and thus the interpretation of the results. In terms of the spatial distribution of organisms, the scale of the geomorphic classification is critical to the desired sensitivity of the model to detect biotic homogeneity.

Populations and communities of intertidal biota can be more accurately compared when environmental variables are similar, or homogeneous, both within and among the units being compared. The predominant environmental attributes controlling organism abundance and distribution at this scale (10 - 100 m) are substrate size and wave energy. However for purposes of modeling community structure, greater predictive power can be gained by considering more physical attributes. Many parameters can be measured directly, others can be determined from indicators that act as proxies to a host of variables too difficult or costly to acquire for each shore segment.

Orientation

Orientation or aspect is the shore-normal compass direction of the shoreline segment. It is important in terms of solar insolation, volume of debris accumulation, wave energy input and wind-induced desiccation. South-facing shorelines receive more sunlight, which warms and causes evaporation from organisms directly exposed to its rays. North-facing shores generally retain moisture longer than south facing shores. The floral components of the community are especially subject to the effect of day length, sun angle and azimuth, and the time of exposure (Lobban & Harrison, 1994). Floral abundance may, in turn, affect faunal components of the ecosystem. Therefore, some flora and fauna are more common on north facing beaches (or on north facing boulders) than on south facing aspects.

Wave Power

Hydrodynamic forces have a profound impact on the biotic composition of a beach or shoreline (Denny et al. 1985, Denny 1988, 1995). Availability of bare space for recruitment from the plankton is generally the limiting factor governing community structure in the rocky intertidal. Wave forces often create space during extreme storms on any type of substrate. Denny (1995) discusses in detail how to estimate the actual forces imparted on individual organisms and the effects of those forces for selected taxa.

A key physical feature of the nearshore is wave energy, which affects community structure both directly through episodic disturbance events and indirectly by controlling substrate dynamics over short and long temporal periods (Denny et al. 1985). Indirect effects include current propagation and the frequency of substrate movement. The wave climate has a profound impact on the biotic composition of a beach. Unconsolidated substrates can be moved by the direct impact of waves, by wave run-up, and by wave generated currents. On beaches with mobile substrates, the particles can be rolled or entrained continually, seasonally, or episodically in high wave energy environments. Mobile substrates typically harbor fewer organisms than stable substrates. For example, rounded cobble and pebble beaches are typically depauperate of biota, while stable substrates such as bedrock and large boulders are relatively species rich. Nearshore fauna in heavy surf must have thick shells and strong muscular attachments (limpets and snails), permanent attachments (barnacles), or the ability to seek refuge in crevices or interstitial spaces (crabs). The floral community must likewise adapt to the forces of the nearshore surf and swash zone, and in the intertidal must also tolerate long hours of desiccation. The measurement of wave energy is therefore fundamental to the structuring of nearshore communities. Wave energy is also the most difficult attribute of the intertidal zone to quantify, mostly because the wave energy field is constantly changing, but also the ability to make observations over long periods is often hampered by weather.

At the spatial scales considered here, we begin to link the processes of the nearshore ocean to the biota of the shore. Indices of exposure described earlier no longer provide the required mechanistic link to nearshore biota. Wave forces need to be measured or calculated for episodic, mean monthly, seasonal, and annual wave conditions in order to study the effects of wave climate on nearshore biota. Implementing this over large spatial scales is a daunting task, but a nested approach is again advocated to make this simpler without sacrificing data resolution. The SCALE model uses higher order estimates of wave energy with each incremental increase in spatial resolution beginning with estimates of exposure described earlier, progressing to estimates of wave power at the alongshore segment scale, and finally estimating the effects of shore morphology on wave energy and runup for each across-shore zone.

The amount of energy arriving at a beach in the form of waves is related to the wave height but also to the wave length and period. Ideally measurements of wave statistics can be obtained from buoy data of the Coastal Data Information Program (CDIP), and from the National Data Buoy Center (NDBC) of NOAA. Also available are U.S. Army Corps. Of Engineers daily wave hindcast from the Wave Information Study (WIS) although Shih et al. (1994) have shown that hindcasts for the west coast can be unsatisfactory. Unfortunately, these wave statistics are seldom available over large areas, particularly in the relatively sheltered environment of Puget Sound.

In terms of the nearshore biota, the power (wave energy per unit area) generated by a wave, rather than wave height, is a better indicator of the local wave climate because wave height alone does not correlate as well with wave generated forces. Wave power is a function of the wave height and wave period impinging on the shoreline. North Pacific winter storm systems have large pressure differentials causing strong winds with associated large wave heights and long periods. These episodic extreme storm events can cause catastrophic erosion and movement of massive volumes of sediment. Very low frequency waves, or infragravity waves are generally responsible for the severe coastal erosion and storm damage to natural and man-made structures on the outer coasts (Komar, 1997). Denny (1995) discusses the forces generated by extreme waves on intertidal organisms in terms of patch dynamics, one of the most important processes by which rocky intertidal communities are structured. But these extreme waves are generally not expected uniformly along the coast and may focus on headlands by bathymetric refraction.

The statistical height variation of a random wave field generated by a distant storm approximates a Rayleigh distribution. The significant wave height represents the largest 33% of all measurements, and is close to the wave heights that are easily observed in the field. These relatively large waves contribute to the highly variable nearshore abiotic and biotic characteristics of the Pacific Northwest. These waves drive the oscillating swash that provides the required nutrient perfusion and prevents desiccation of marine organisms in the intertidal zone. Thus, wave power is a primary factor influencing the physical makeup of nearshore intertidal habitats (Denny 1995).

The constant wave power curves shown on Figure 4 illustrate the relationship between wave power and a range of significant deep water wave heights (H_s) and wave periods (T). The endpoint power value selected for curve 12 is based on the maximum mean annual significant wave height and corresponding period from statistical analyses by Tillotson (1995) on wave data measured by an offshore buoy located near Grays Harbor, Washington.

The deep water energy flux or wave power for these endpoint values was calculated using the following equations fully described in Komar (1997):

$$P = ECn \tag{4}$$

where P is the energy flux (watts/m^2), E is the wave energy (Joules/m^2):

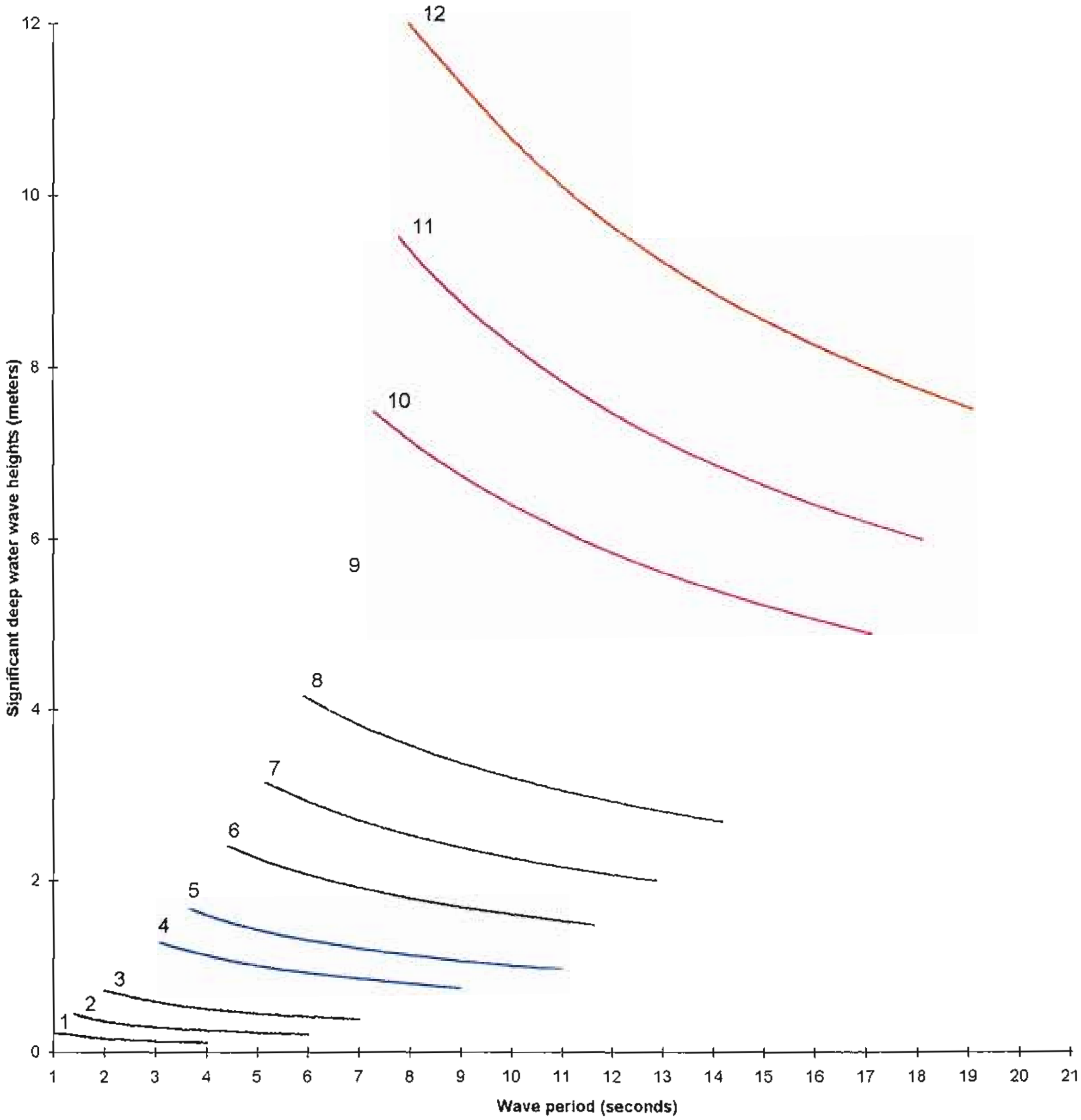


Figure 4. Constant power curves for deep water waves over a range of wave heights and periods.

$$E = 1/8\rho g H_s^2 \tag{5}$$

ρ is water density (1020 kg/m^3), g is the acceleration due to gravity (9.8 m/sec^2), H_s is the significant deep water wave height (m), C is the wave celerity:

$$C = gT/2\pi \tag{6}$$

and n equals ½ in deep water . So P becomes:

$$P = (1/8\rho g H_s^2)(gT/2\pi)(1/2) \tag{7}$$

and T is the corresponding wave period in seconds.

Category 1 represents the low endpoint for the most protected waters in Puget Sound. The intermediate values are estimates based on 12 arbitrary wave power values incrementally spaced between the endpoints. A range of probable wave heights and periods was calculated for each wave power estimate.

Table 3 lists the twelve categories of wave power used for the SCALE model to approximate wave heights in different marine systems. Algorithms from the Shore Protection Manual (CERC 1984) were used to convert wave heights and periods into fetch distances and wind velocities. The maximum fetch was measured for each alongshore segment using Arcview GIS software and the appropriate wave power classification was assigned. A correction was calculated for the tabulated wave power categories to account for the local (segment) exposure to high velocity winds. Beaches facing the direction of highest wind velocities can expect large waves more frequently than beaches facing the opposite direction even if the fetch distances are the same. The CERC conversion assumes that the wind blows along the axis of the maximum fetch. In situations where this does not occur a smaller than expected wave height should be calculated. Since the largest waves generally occur during the winter, for this project the mean monthly wind velocities at the Seattle-Tacoma Airport for November through February from 1990 to 1997 were tabulated and ranked according to eight compass directions. For each beach segment, the wave power class was decreased by one category for segments facing the direction of the four lowest velocities (east, northeast, north, and northwest).

Drift

Exposure to alongshore currents and drift is based on the orientation of the shoreline with respect to the prevailing seasonal wave and current direction. This parameter, together with the net sediment transport direction, provides an indicator of how exposed the segment is to drift logs and debris, to sediment accumulation or erosion, and potentially to settlement of propagules and delivery of nutrients to organisms. In the Pacific Northwest a substantial number of logs tend to drift down rivers as a result of logging operations, bank erosion, and blowdowns. Coastal currents transport these logs and other debris in the alongshore direction. Logs occasionally collide with rocky headlands, batter

Table 3. Wave parameters derived from fetch categories.

SCALE Wave Power Category	Wave Power (watts/m^2) P	SZMS Exposure Equivalent	Maximum Fetch (km)	Maximum Condition Wind Speed (km/hr)	Significant Wave Height (m) H_s	Wave Period (s) T	Wave Length (m) L
1	50	very protected	1	10	0.1 - 0.3	0.5 - 3	1 - 15
2	250		5	20	0.2 - 0.5	1 - 5	2 - 40
3	1000	protected	10	20	0.4 - 0.7	2 - 7	6 - 75
4	5000		25	30	0.6 - 1.6	2 - 9	6 - 125
5	10000	semi-protected	50	30	1.0 - 1.8	3 - 11	15 - 175
6	25000		100	35	1.5 - 3.0	3 - 12	15 - 225
7	50000		200	35	1.9 - 3.5	4 - 14	25 - 300
8	100000		300	35	2.5 - 5.0	4 - 16	25 - 400
9	200000		400	40	3.0 - 7.0	4 - 20	25 - 600
10	400000	semi-exposed	500	50	4.5 - 9.0	5 - 20	40 - 600
11	600000	exposed	1000	60	5.5 - 11.0	5 - 20	40 - 625
12	1000000	very exposed	>1000	70	7.0 - 12.0	7 - 20	75 - 650

intertidal communities in the surf zone, and eventually may strand on shorelines to become a functional component of a nearshore habitat. Particular combinations of currents, coastal configuration, and shoreline morphology result in some beaches acting as collection areas for debris. Here, large accumulations of logs, drift kelp, algae, and plastic material may occur with potential effects particularly to sessile intertidal populations. Drift is categorized according to the orientation of the beach face with respect to the prevailing current direction (see Table 2).

Across-shore Sub-Zones

Elevation, length, width, area

Intertidal communities exhibit distinct patterns of zonation based on elevation or immersion time (Kozloff, 1993). Each alongshore segment was vertically separated into four across-shore polygons centered at specific elevations that correspond to immersion times during the daily tidal cycle, based on the mean tidal statistics for Carr Inlet. The upper zone ranges from extreme high water (> 4.5 m) down to mean high water (3.8 m); we characterized its geophysical parameters at mean higher high water (4.0 m) where the substrate is immersed 10% of the time. Much of the project shoreline is armored by protection structures (seawalls) in this sub-zone. The middle zone, from mean high water to mean low water (0.9 m), has previously been characterized at mean sea level (about 2.4 m) where the substrate is exposed 50% of the time. But in Carr Inlet, the middle zone comprises the majority of the exposed beach face at low tide and is generally vertically heterogeneous, so we separated it into an upper-middle zone, characterized at 3.0 m, and a lower-middle zone characterized at 1.5 m. These elevations generally avoided slope breaks and substrate transitions. The lower zone is from mean low water down to extreme low at -1.0 m, and we characterized it at 0.0 m where the substrate is immersed at least 90% of the time. Note that elevations will depend on the tidal range of the study area. The length, width and area of a segment are measured from the GIS database. The dimensions of the sub-zone polygons are important attributes for determining the spatial extent of individual polygons and of polygon groups. Communities inhabiting small beaches can be influenced by edge effects from neighboring beach types, such as the generally detrimental effects of sand scour on bedrock communities.

Particle Size

Characteristics of the substrate are a major influence controlling the distribution of benthic populations. A fairly sharp distinction exists between the types of fauna found on hard substrates such as bedrock or large boulders, and soft substrates such as pebbles and sand. Larger substrates may provide more shelter in the form of crevices and interstitial spaces, and also provide a solid surface for organisms to cling to. Slow growing algae, for example, require stable substrates such as large boulders. Sand and silt substrates may support higher populations of burrowing fauna, particularly if the silt is rich in organics. Clay substrates, when compacted into "hardpan", may support an epibenthos but are generally too hard for an infaunal community (Dethier, 1990). The greatest number of species, or high diversity, is usually associated with a complex mixture of bedrock, cobbles and sand.

Sediment characteristics can serve as indicators of the frequency of sediment movement, the local energy regime, shoreline stability, and therefore the evolution of the landform and the interpretation of past processes (Snead 1982). Thus, sediment analyses serve to provide clues to environmental processes and are sometimes referred to as a surrogate variable or proxy for more complex processes (Pethnick 1984). Particle size is described here using the Wentworth scale (Pettijohn 1949). The size classes are as follows: (8) boulders >256 mm, (7) cobbles 64 - 256 mm, (6) pebbles 4 - 64 mm, (5) granules (coarse sand to pea gravel) 2 - 4 mm, (4) sand 1/16 - 2 mm, (3) silt 1/256 - 1/16 mm, (1) clay < 1/256 mm. In addition, this classification distinguishes substrates larger than boulders and also fine particle mixtures. Blocks (9) are very large boulders that are essentially immobile yet unattached fragments of rock (e.g. > 2 m). Mud (2) is a mixture of very fine clastics and organic material generally found only in protected energy environments. Bedrock (10) is the final category for a total of ten substrate classes. Three particle size estimates are made according to the percentage of areal coverage, with primary size covering > 60% of the area, secondary size covering < 40%, and interstitial size if between particle voids are filled.

Traditional particle size analyses involve substrate sampling and sieving to sort the particles by size fractions, but this is too laborious and time consuming for landscape scale characterization. The surface substrate can be quantified by photographing a quadrat laid over a representative section of the beach segment. Replicate photos can be taken as necessary to capture the substrate characteristics of the beach. We use a .25 m^2 quadrat with a 10 cm grid made of stretched nylon twine. The particle sizes are sampled from each of the 16 grid intersections. The longest axis of the particle under each grid intersection is measured from the scanned photo and ranked by size class and count as shown in Steps 1 through 4 in Figure 5.

The subsurface particle size distribution is important when biological sampling extends to the infauna. Estimates can be made from a sample collected with a coring tool or a shovel to the depth of interest. The sample is spread out on a flat surface, then photographed and treated as described above and on Figure 5.

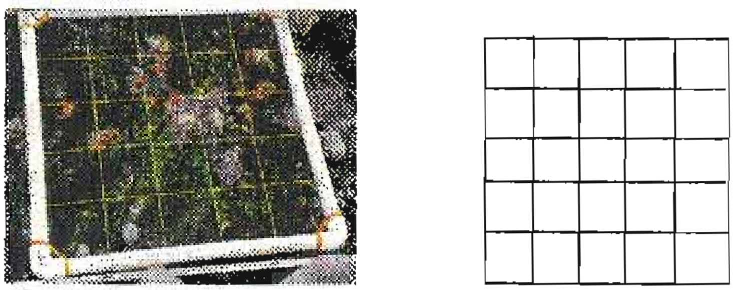
Wave Energy Dissipation

The wave energy is evaluated again at this scale to account for the dissipation of energy as waves break across the beach face. The effect of waves on beaches is best represented by surf characteristics. Battjes (1974) developed a surf similarity parameter defined by the Iribarren number:

$$\xi_b = \frac{S}{(H_s/L_\infty)^{1/2}} \qquad (8)$$

where S is the beach slope (e.g. tan α), and L_∞, the deep water wave length in meters is:

$$L_\infty = gT^2/2\pi \qquad (9)$$



a) Step 1
Field Photography

b) Step 2
Photo-analysis

c) Step3
Categorize particle
sizes at intersections

C P C P
C C S P
C C S P
C C C C

d) Step 4
Tabulate Size Distribution

C = Cobbles	10	63%
P = Pebbles	4	26%
S = Sand	2	1%
Total	16	100%

Figure 5. Example of how beach substrate sizes are quantified.

Dissipative or low angle shorelines (e.g. slope = 0.03) correspond to very low Iribarren values (e.g. $\xi < 0.2$ to 0.3), and reflective or high angle shorelines yield $\xi > 2$. Values in between generally represent highly dynamic shorelines if the substrate is unconsolidated (Wright & Short, 1983). Calculations were made for each across-shore zone since for any segment an upper intertidal seawall is generally highly reflective and a lower intertidal sand flat is highly dissipative. There are no published wave statistics for most of Puget Sound, so for Carr Inlet we used the wave height and period values calculated from estimates of wave power (Table 3).

Organisms living in the nearshore are subjected to constantly changing wave forces, immersion periods, and swash oscillations as wave characteristics change with the fluctuations of the tides across the beach face. The energy driving the swash bore oscillations across the intertidal zone is what remains after turbulent dissipation of the random wave field in the surf zone. The height attained by the swash bore is a function of the slope, the substrate size, roughness, and permeability. Wave runup is a measure of the swash excursion across the intertidal zone. In relatively protected areas such as Carr Inlet, wave runup is practically non-existent and large waves are infrequent, such that wave runup does little to directly structure the intertidal community. On more exposed shores, wave runup is useful as a measure of wave penetration across shore zones. Runup directly effects intertidal organisms by providing water to elevations above the still water level, thus continuing the supply of food or nutrients and preventing desiccation. This affects the growth rates and abundance of many intertidal organisms (Menge 1995). In areas of high runup many species can extend their vertical range, thus considerably raising the community above normal elevations. Therefore, in terms of predicting the occurrence of particular species over large spatial areas, runup is an important attribute of the nearshore. The empirical relationship used to calculate wave runup is:

$$\frac{R_{2\%}}{H_s} = C\xi_b \qquad (10)$$

(Battjes 1974, Holman 1986, Van der Meer & Stam 1992, Shih et al. 1994, Tillotson 1995, and others) where $R_{2\%}$ is the runup exceeded only 2% of the time in a 20-30 minute interval, and C is a constant (Battjes 1974). Holman (1986) found that for combinations of set-up due to radiation stress and the runup, the C coefficient equals 0.90. This relationship was successfully used by Shih et al. (1994) to calculate extreme wave runup for cliff erosion studies on the Oregon coast. Van der Meer & Stam (1992) used empirical data to refine the basic formula by considering new values for C when substrate roughness and permeability vary along with slope.

Quantitative evaluation of wave runup is usually limited to experimental studies on planar sand beaches using various techniques explained in the literature (Sallenger et al. 1983, Guza 1988, Holman et al. 1993, Holland et al. 1995, and others). For large scale assessments, spanning dozens of kilometers and including hundreds of beach segments, these techniques are not feasible. For the purpose of this classification, wave runup is quantified to a first order approximation by either the direct measurement of extreme runup elevations or the calculation of extreme runup from equation 7.

Measurements of runup are based on the elevation of biological and physical indicators. These indicators are variable but can be evaluated in the field at the required alongshore resolution of the SCALE model. For example, on sandy shores the lower extent of *Elymus mollis* (dune grass) colonization is a good indicator of the maximum runup elevation attained during the extreme high tides or storms. On exposed rocky shores, the upper extent of *Littorina* sp. (snail) or *Chthamalus* sp. (barnacle), or the lower edge of *Verrucaria* sp. (lichen) can provide good indicators of the swash extent. Other indicators depend on the geomorphology but include the upper edge of the storm berm, the level of drift debris, the level of terrestrial vegetation, etc. The extreme range of the biological indicators is usually attributed to the salinity or immersion tolerance.

For the upper intertidal zone, this classification uses estimates of wave runup obtained from field surveys of height and slope of storm berms, and biological evidence (e.g. elevations of terrestrial vegetation, the upper extent of marine fauna/flora, etc.). For the middle and lower zones, approximations of mean wave runup are calculated based on the slope for each zone, corrected wave heights based on runup and wave power estimates for the upper zone, and the following values for C under the appropriate conditions (from van der Meer & Stam 1992). Mean runup is used as a conservative estimate for substrate perfusion rather than the conventional $R_{2\%}$ used for engineering studies of erosion and overtopping. The mean runup for impermeable substrates is given by:

$$\frac{R_m}{H_s} = 0.47\,\xi_b \qquad \text{(for smooth beaches with low Iribarren } (\xi_b \leq 1.5) \qquad (11)$$

$$\frac{R_m}{H_s} = 0.60\,\xi_b^{0.34} \text{ (for rocky slopes with high Iribarren } (\xi_b \geq 1.5) \qquad (12)$$

The mean runup for rough, permeable slopes is limited to:

$$\frac{R_m}{H_s} = 0.82 \qquad (13)$$

We use a measure of horizontal wave excursion (ω), or the distance the swash travels up the shore slope in meters, to categorized the mean runup:

$$\omega = R_m(1/\sin \alpha) \qquad (14)$$

Seepage

The seepage of fresh water, or water with low salinity, through intertidal substrates during low tides may influence the abundance and distribution of species (Lewis 1964). Seeps are identified by discoloration of the substrate and typically by biotic indicators such as certain foliose green algae. This parameter is categorized as either present or absent.

Slope

Slope influences wave characteristics such as dissipation or reflection (e.g. spilling, plunging, or surging), and the distance of wave runup. Flat intertidal zones generally dissipate wave energy further offshore, providing a more sheltered environment than moderate or high angle shores. The surface area exposed during low tides also varies with the slope angle, as does the degree of solar insolation. The average slope angle of each segment sub-zone can be estimated with an inclinometer or surveyed with a rod and level. Figure 6 shows an across-shore profile and examples of slope estimates for the different sub-zones.

Dynamism

Dynamism is a measure of aggregate stability. Sediment transport influences shoreline morphology and dynamism by shifting the sediment along, away from, or onto a shoreline. The rate of sediment transport affects the stability of the beach. Dissipative beaches have been shown to support higher numbers of macroinfauna compared to reflective beaches (McLachlan, 1990) because wave action on exposed sand beaches creates a morphodynamically unstable condition for organisms inhabiting those environments (Brown & McLachlan, 1990). These stability characteristics are evaluated for each across-shore sub-zone in terms of substrate stability.

Shorelines with low dynamism generally exhibit a highly consolidated (e.g. immobile) substrate not subject to disturbance even during intense winter storms. This includes bedrock, deeply embedded boulders and armored beaches. Highly dynamic beaches are indicated by loosely consolidated mobile particles, shifting sands and unstable slope angles; even large boulders can exhibit dynamism on extremely high energy shores. Dynamism can be estimated or quantified by measuring the change in volume of beach material over time. High resolution shoreline profiles can determine the volume of sediments in the beach prism. Repeated measures can thus be compared for volumetric analyses. The frequency of profile surveys is dependent upon the mobility of the substrate and the prevailing forces acting on the substrate particles. For example, shifting sand by waves and wind would perhaps require daily profile measurements, while a boulder beach may only require annual surveys. Dynamism can also be calculated using:

$$D = \frac{\text{predicted water velocity} \quad V_p}{\text{critical rolling velocity} \quad = V_r} \qquad (15)$$

where d is the grain diameter perpendicular to the rolling force, and

$$V_p \approx .3[g(H_s+h)]^{1/2} \qquad (16)$$

from Gordon et al. (1992). The velocities are calculated from:

$$V_r = 0.155 \sqrt{d} \qquad (17)$$

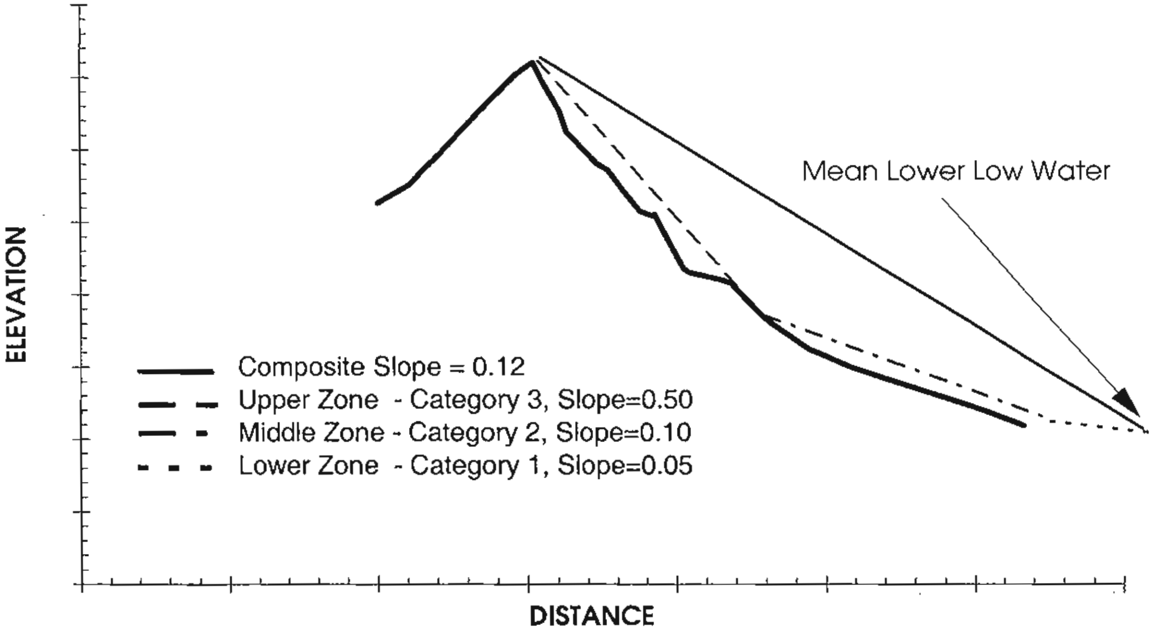


Figure 6. Example of across-shore sub-zone and composite slope classification

where g is the gravitational acceleration (9.8 m/sec^2), H_s is the significant wave height, h is the local water depth, (Denny 1995). Clays and muds are usually found in low energy, low water velocity conditions and dynamism will be practically non-existent. Clay particles frequently flocculate, increasing substrate stability not accounted for by the above calculations. Figure 7 summarizes the settling characteristics of various particle sizes relative to water velocities.

Permeability
Permeability is the property of allowing the passage of fluids without displacement of the substrate particles (Pettijohn 1949). For the purposes of this classification, a substrate is considered to be "permeable" when water passes through the gravel prism, and "impermeable" when the rate of passage is negligible. This was determined by digging a hole in the beach face and timing how long it takes a 2 liter container to fill with water. Note that permeability is used here to describe the structure underneath the armor layer and not the armor layer itself.

Roughness
Roughness characterizes the surface texture of the beach segment (as opposed to individual rocks) thus controlling wave runup distances. Roughness also provides an indication of the quantity and size of microhabitats. Crevices in bedrock, and spaces between boulders and tidepools on bedrock platforms can modify the environment at small spatial scales, creating additional habitats for organisms (for examples see Foster et al., 1988). An armored beach, where fine particles have been removed from the surface layer, also has numerous microhabitats.. In riparian systems, Davis and Barmuta (1989) state that roughness appears to be an excellent habitat descriptor since it combines the effects of water velocity and substrate type. Relative roughness can be approximated by the following relation:

$$r_{rel} = \frac{k}{D} \qquad (18)$$

where k is a measure of roughness (e.g. particle size protruding above the embedded surface) and D is the water depth (Gordon et al. 1992). The parameter k can be measured by stretching a 50 m tape over the substrate surface and marking the endpoints. Then allow the tape to collapse onto the surface making sure to depress the tape into all the major surface depressions. Mark the new endpoints and then measure the difference between the first and second endpoint markers. Large distances indicate rougher surfaces. For the SCALE model, roughness was categorized based on a calculated range of roughness values for ideally homogeneous beaches with the following particle sizes: 1) skimming flows on smooth surfaces such as found on sand and small pebble beaches (r_{rel} < .05), 2) isolated roughness flows where velocity eddies dissipate between roughness elements such as around isolated pebbles and cobbles (r_{rel} = .05 - .1), 3) wake interference flows when elements are close together creating turbulence as found on cobble and boulder beaches (r_{rel} = .1 - .5), 4) turbulent flow where conditions create very complex flow patterns and appears as "whitewater" (r_{rel} = .5 - 1), 5) and extremely rough conditions

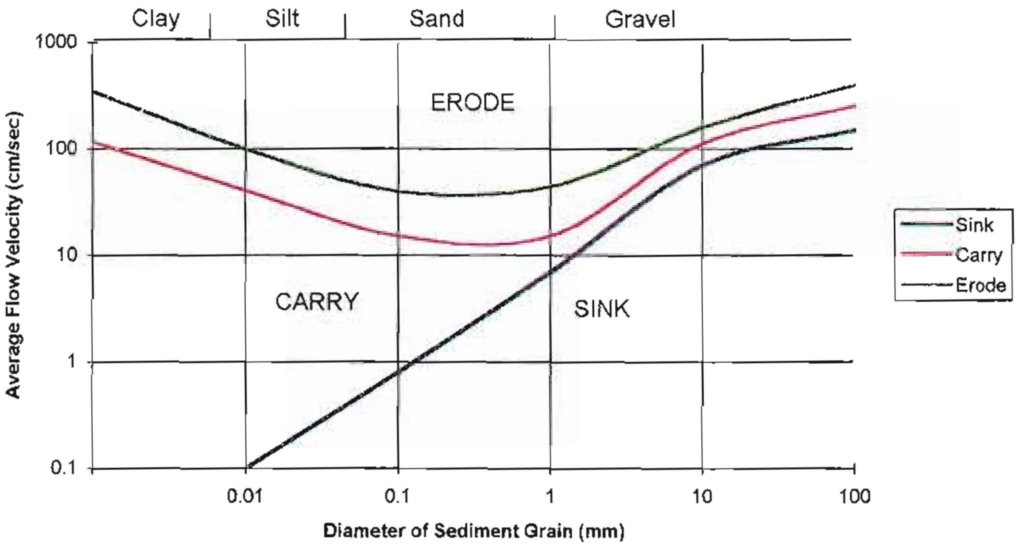


Figure 7. Substrate dynamism based on water velocities and particle sizes

where large voids are present between very large boulders or where crevices exist in bedrock and between blocks ($r_{rel} > 1$).

Bio-indicators
Dufrene and Legendre (1997) provide a method for calculating the 'reliability' of each species within a given set of samples. Their "indicator value" for each species combines information on the evenness of species abundances in a particular group of samples and the fidelity or faithfulness of occurrence (frequency) of a species in that group. The result is a value for each organism sampled indicating how well it represents a habitat group. A maximum value of 100 indicates the organism is a perfect indicator and would be found in every sample unit. Details of these calculations are given in Schoch & Dethier (1997).

5. Results

Quantitative Comparison of the SZMS and SCALE

As opposed to the nested scheme outlined above, the Carr Inlet project was mapped in two independent steps: first the SCALE method was implemented, followed a year later by the SZMS. Task 1 of this project evaluates and compares the methods separately, detailing the results and highlighting some of the difficulties with a direct comparison of the two systems.

The foremost incompatibility lies in the way data are represented. The SZMS shoreline information was mapped with a line representing the mean high water line as provided by WDNR. The SCALE model uses polygons to represent the intertidal beach face. The polygon map is created by screen digitizing the beach face at a scale of 1:2000 using digital orthophotos as a background reference. Color infrared aerial photography (CIR) is used to interpret the areal extent of the beach at an extreme low tide. The high water line (HWL) is interpreted from the vegetation line clearly shown on the CIR by the chlorophyll signature of supratidal plants. The low water line (LWL) is also easily interpreted from the CIR since water absorbs all infrared wavelengths. Intermediate lines depicting estimates of middle intertidal zone boundaries were digitized from tic marks annotated during field surveys.. The results of the polygon mapping were a series of 4 lines stacked vertically across the beach face, delineating the lower, lower-middle, and upper-middle intertidal sub-zones. The digitized lines are intended to serve as estimates of the areal extent of shore habitats, not to infer the location of tidal datum, although in most cases the locations will be close to mean lower low water (MLLW), mean low water (MLW), mean high water (MHW), and the mean higher high water line (MHHW). But since none of the lines represent actual elevations they are not intended to delimit jurisdictional boundaries associated with the various tidal datum lines. To avoid this confusion we chose to label the highest and lowest lines as HWL and LWL.

The original comparison of the SZMS with the SCALE model described in Task 1 used the WDNR MHW shoreline and an intermediate line derived from the SCALE polygons that approximated MHW. The WDNR shoreline was digitized at an interpreted elevation representing the MHW. The SCALE line used for the comparison was at the top of the middle sub-zone polygon which comes closest to representing MHW. This line was digitized at 1:2000 and is considered more accurate in following the small spatial scale convolutions of intertidal beaches such as recurved spits and small inlets. The SCALE mapping project of 1997 did not include Burley Lagoon, thus omitting a substantial portion of the Carr Inlet shore length.

Other discrepancies are derived from the placement of the MHW on the beach face. For example, Minter Lagoon, which dries at tide levels below MHW does not show on the SCALE "MHW" shoreline, but the WDNR shoreline includes the full outline of the inlet (apparently digitized at the extreme high water line). The differences in shore length resulting from the Task 1 comparison of the two systems are therefore mostly a function of the different lines used to map the shoreline rather than differences in the mapping systems.

To realistically compare the systems, the SZMS classes, the DNR/Dethier classes, and the NRDA were re-mapped to the HWL of the SCALE shoreline. Each physical unit of the SZMS system was mapped to the HWL. The summary on Table 4 shows the shoretype frequency and percentage of the total shore length represented by each shore class. The DNR/Dethier and NRDA classes were assigned to each physical unit in order to make comprehensive comparisons across the systems. The data column labeled "DNR Shoreline" lists the lengths associated with the original WDNR shoreline, while SCALE "MHW" and "HWL" are the lines derived from the mapped polygons. All three linear shoreline classification systems categorized equal numbers of mud, estuarine, and man-made shoretypes. More diversification of shoretype occurred within the sand and gravel beach types. As expected, the greatest difference in shore lengths among the three lines was in the estuary class. This is where the DNR shoreline traces the extreme high water line while the MHW is actually considerably lower along the shore.

To facilitate the comparison between the SZMS and the SCALE system, the SCALE polygons were renumbered in the same order as the physical units. Also, the SZMS shoreline was truncated at Penrose Point, thus shortening the total shoreline length but making the line compatible with the project area mapped by SCALE. The physical unit endpoints of the SZMS system were adjusted to coincide with the SCALE segment endpoints (based on the premise that the SCALE delineation is of higher resolution). Approximately 50% of the original SZMS physical unit endpoints had to be moved from 10 to 80 meters to coincide with the SCALE endpoints. The larger distance corrections (>20 m) were always because of inaccurate shore representation around sand spits by the DNR shoreline.

Shoretype areas were calculated for the SZMS classes by adding the component widths and multiplying by the physical unit lengths. Caution is advised however when using these values since few of the beach faces are actually rectangles. Table 5 lists a summary of physical unit lengths and areas, and SCALE segment lengths and areas for each nearshore cell and shoretype. Cells 1 and 4 have the most segments per physical unit

Table 4. Summary of classification data from Task 1 comparing the Shore Class lengths using the shoreline mapped by DNR, the shoreline mapped by SCALE at MHW, and the shoreline mapped by SCALE at HWL.

Classification System	Shore Class	Shoretype Description	Shore Frequency	DNR Shoreline		SCALE "MHW"		SCALE HWL	
				meters	%	meters	%	meters	%
SZMS Classes	24	wide S&G flat	19	7557	10	7789	11	7977	10
	25	narrow S&G beach	26	15238	20	15526	22	15606	19
	27	wide sand beach	3	3267	4	3385	5	3266	4
	28	wide sand flat	43	21640	29	19653	28	22411	28
	29	wide mudflat	12	6040	8	5851	8	6250	8
	30	narrow sand beach	19	7687	10	7892	11	8650	11
	31	estuary	19	12908	17	8380	12	14697	18
	32	man-made permeable	1	11	0	104	0	13	0
	33	man-made impermeable	1	1264	2	1253	2	1271	2
DNR/Dethier Classes	9	semi-protected mixed coarse	29	11143	15	11787	17	11880	15
	11	partially exposed gravel	1	914	1	817	1	892	1
	12	exposed and partially exposed sand	1	548	1	546	1	565	1
	13	semi-protected sand	62	33534	44	34127	49	35577	44
	14	semi-protected & protected mixed fine	15	8755	12	6491	9	8511	11
	15	mud	13	6535	9	6327	9	6736	8
	16	man-made	2	1275	2	1357	2	1284	2
	17	estuary	19	12908	17	8380	12	14697	18
NRDA Classes	4	semi-protected cobble and mixed coarse	32	14880	20	15489	22	15606	19
	7	semi-protected mixed fine	76	40015	53	38280	55	41819	52
	8	mud	13	6535	9	6327	9	6736	8
	9	man-made	2	1275	2	1357	2	1284	2
	10	estuary	19	12908	17	8380	12	14697	18
Total Shoreline			144	75613		69833		80142	

Table 5. Summary of lengths and areas for SZMS shoretypes and SCALE segments after corrections for total project length and endpoint matching.

Nearshore Cell and Shoretype	SZMS Physical Units			SCALE Segments		
	Frequency	Lengths (m)	Areas (m^2)	Frequency	Lengths (m)	Areas (m^2)
Cell 1 Shoretype 24	10	4014	275435	22	4017	558819
Cell 1 Shoretype 25	9	6093	195980	19	6095	534888
Cell 1 Shoretype 27	1	671	57035	2	672	263452
Cell 1 Shoretype 28	11	7422	754218	30	7422	1365341
Cell 1 Shoretype 29	4	2214	186586	10	2211	126251
Cell 1 Shoretype 30	7	2000	54225	17	2013	106002
Cell 1 Shoretype 31	5	2441	143184	8	2438	55974
Cell 1 Total	47	24855	1666663	108	24867	3010728
Cell 2 Shoretype 24	1	293	19045	3	293	38885
Cell 2 Shoretype 25	3	3543	158940	17	3544	458435
Cell 2 Shoretype 27	2	2521	121733	11	2520	363424
Cell 2 Shoretype 28	11	5680	351505	6	4337	156804
Cell 2 Shoretype 29	1	821	98520	0	0	0
Cell 2 Shoretype 30	4	1847	80035	1	271	26098
Cell 2 Shoretype 31	7	8550	1622300	0	0	0
Cell 2 Total	29	23255	2452078	38	10965	1043646
Cell 3 Shoretype 24	2	1511	111889	4	1517	179780
Cell 3 Shoretype 25	3	1118	35777	6	1119	93076
Cell 3 Shoretype 28	9	3258	369644	13	3266	428408
Cell 3 Shoretype 31	2	902	89960	4	1424	182767
Cell 3 Total	16	6789	607270	27	7327	884031
Cell 4 Shoretype 24	7	3384	128150	20	3362	445987
Cell 4 Shoretype 25	11	3986	134730	22	3985	315238
Cell 4 Shoretype 28	12	6200	296432	46	6228	696553
Cell 4 Shoretype 29	7	3383	142565	18	3383	161937
Cell 4 Shoretype 30	9	4817	128448	31	4818	246996
Cell 4 Shoretype 31	5	2749	101844	11	2749	38922
Cell 4 Total	51	24519	932169	148	24525	1905634
Sum	143	79418	5658180	321	67684	6844038
Sum excluding Burley Lagoon	143	67646	3839655	321	67684	6844038

(108/47 and 38/29 respectively). In Cells 2 and 3 the number of SCALE segments is much closer to the number of physical units (38/29 and 27/16 respectively). This shows that habitat diversification increases significantly when observations are made at smaller spatial scales (higher resolution). The total shoreline length difference is due to Burley Lagoon not being mapped by the SCALE method in 1997. Note that even though Burley Lagoon is not included in the SCALE length or area totals, the total SCALE area still exceeds the SZMS total area. The table also lists the total shore length excluding Burley Lagoon from the SZMS. Note that the shore lengths are very similar with a difference of 40 meters (.05%). However, the shore areas are very different, with the SCALE area 44% larger. This illustrates the weakness of SZMS for estimating shore area based on component widths.

Figure 8 shows the difference in shore area with respect to shore length for both the SZMS shoreline and the SCALE polygons. This graph helps to show where the largest differences in area occur. Note that the greatest deviations take place in Cells 1 and 2 and in Cell 4. The rate of area increase near Cell 2 is reduced, again due to the omission of Burley Lagoon from the SCALE data. The SZMS mapping project included Burley Lagoon so the lines intersect. But in general the figure clearly shows that the nearshore area represented by the SCALE polygons far exceeds the SZMS map. This could be explained by systematic errors in the width estimates for beach face components in the SZMS classification.

Spatial Extrapolation of Biological Data

The SCALE system models the biological community structure based on the premise that populations coexist in spatially predictable patterns. If the physical forces controlling ecological responses can be quantified for every beach over an area of interest, then similar beaches can be statistically grouped and the biota compared among group members. Beach members within a group should have more similar communities than members among groups. If biota are sampled from randomly selected group members, then the data can be inferred to all the remaining group members. Therefore the method used to group beach segments becomes critical when using this statistical extrapolation technique. When the beaches are exactly the same, the probability of finding the same biota are greatly improved. But very few (if any) beaches are exactly the same. Slight changes in any of the attributes described above can effect a change in community structure. Linked to these biophysical interactions are changes caused by biological interactions, compounding observed differences.

A number of grouping options are available, one of which is described in detail in Schoch and Dethier (1997). Clustering algorithms, as well as other multivariate techniques that group units based on biological or physical attributes (or both such as TWINSPAN) make assumptions of linearity and multivariate normal distributions. These assumptions, while attractive to apply to ecological data, are usually violated. Data transformations or other manipulations tend to improve the data towards meeting the assumptions but the underlying problem of linearity cannot be circumvented. In addition, the physical attributes controlling community structure do not act equally and should not be assumed

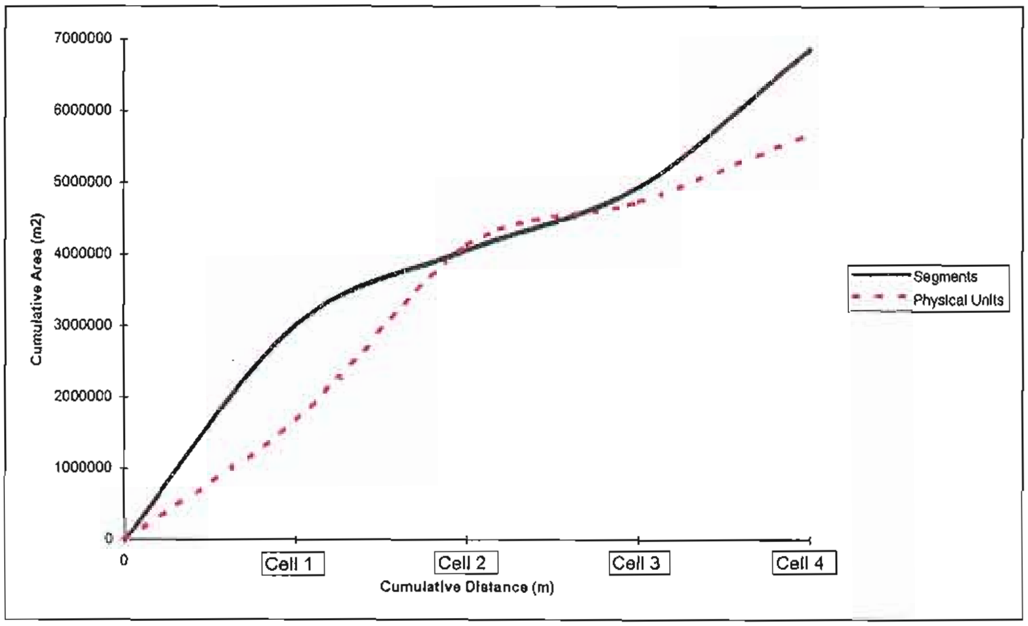


Figure 8. The accumulation of intertidal area with shoreline distance, a comparison of the B.C. physical units to SCALE segments

to behave linearly. We know, for example, that attributes such as substrate size and properties of the nearshore ocean are the predominant physical forces structuring intertidal communities. Therefore, grouping of segments should proceed with consideration given to the relative importance of an attribute in controlling community structure.

The attribute ranking we propose is listed in Table 6. We chose to form groups based on intertidal elevation, three dominant substrate sizes, and oceanic attributes represented here by the nearshore cells and wave energy. Area was chosen next to separate habitats by size, since we know that small habitats are confounded by edge effects and small populations are generally more at risk to perturbations. The remaining attributes were ranked according to the number of groups formed, as shown in Figure 9 by the slope of the plotted line. Attributes causing the largest number of groups to form are represented by steeper slopes of the plotted line. For these attributes the data controls the ranking so other data sets will result in different attribute orders.

The advantage of this method is that any number of groups can be chosen for the final spatial extrapolation, allowing for spatial inference ranging from the most restrictive (many small groups) but most precise in terms of the ecological predictions, to the least restrictive (few large groups) but also least precise. The extent of spatial extrapolation is limited to the number of members in a group, so larger groups will allow for greater spatial inference. For example, if the lower intertidal primary particle size is the only grouping variable, then five groups are formed (Table 6c). The 303 segments assembled into five groups results in a large number of members per group, thus allowing for the largest spatial extrapolation of the sampled biota. But the cost is a loss of ecological precision since we know that the other attributes were not considered. This leads to a low probability of actually finding the predicted community in other group members even though certain populations may be robust enough to tolerate differences in the remaining beach attributes. Barnacles (Balanus glandula), for example, occur where the primary particle size is large enough to withstand rolling by wave action. This organism is tolerant of a wide range of other environmental variables, so a spatial extrapolation based on a primary particle size criteria may be appropriate. However, very few of the other organisms sampled in the lower zone are as robust, so the probability of finding them over the same spatial range as the barnacle is very low. When all 12 attributes are considered, the 303 lower sub-zone polygons are combined into 211 groups; thus each group has relatively few members, and spatial extrapolation is limited to only a small percentage of the total project area. But the group members will be so similar that the probability of finding the sampled community is relatively high. So a tradeoff needs to be made between high precision and extrapolation over a small spatial extent, and large spatial extrapolation but with low ecological precision.

The graphs in Figure 9 show which attributes are the most important for grouping the Carr Inlet segment polygons. Very few groups are added after seepage is considered as a grouping variable. But this will vary depending on the range of habitats considered by the model. Slope and roughness may be an important grouping attribute when harder

Table 6. Summary of grouped variables

A. Upper-middle sub-zone groups

Attribute	#groups	%total
primary substrate	6	2
secondary substrate	15	5
interstitial substrate	32	10
nearshore cell	62	19
wave energy	129	40
area	173	54
aspect	227	71
seepage	228	71
slope	231	72
dynamism	232	72
permeability	232	72
roughness	232	72

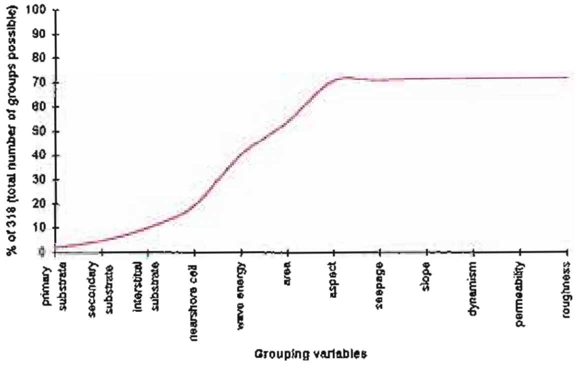
B. Lower-middle sub-zone groups

Attribute	#groups	%total
primary substrate	5	2
secondary substrate	18	6
interstitial substrate	34	11
nearshore cell	69	22
wave energy	137	43
area	175	55
aspect	221	70
seepage	260	82
slope	262	83
dynamism	262	83
permeability	262	83
roughness	262	83

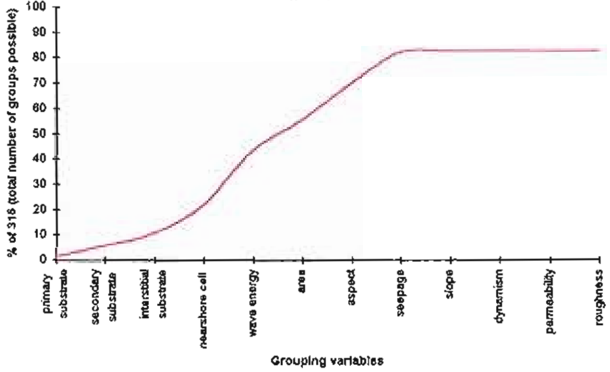
C. Lower sub-zone groups

Attribute	#groups	%total
primary substrate	5	2
secondary substrate	20	6
interstitial substrate	32	10
nearshore cell	56	18
wave energy	108	35
area	145	47
aspect	204	66
seepage	206	67
slope	210	68
dynamism	210	68
permeability	211	69
roughness	211	69

A. Upper-middle sub-zone groups



B. Lower-middle sub-zone groups



C. Lower sub-zone groups

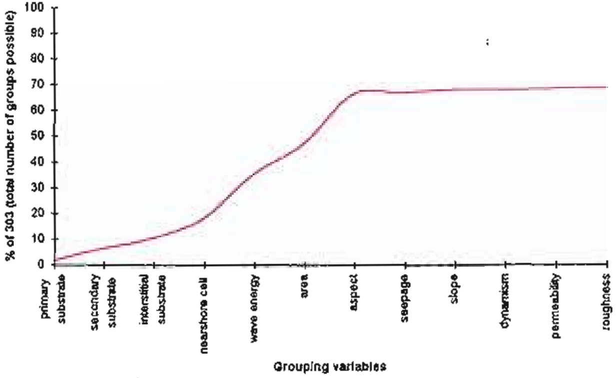


Figure 9. Ranked response of the number of segments per group for each additional attribute

Table 6. Summary of grouped variables

A. Upper-middle sub-zone groups

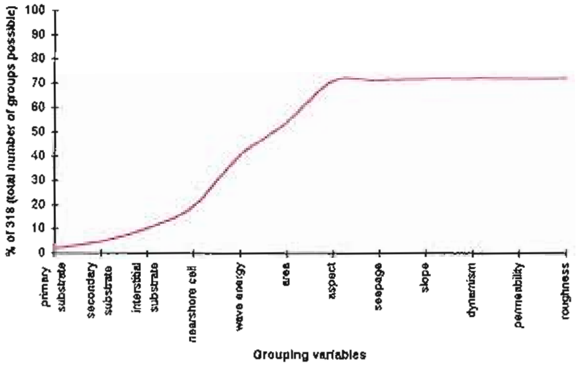
Attribute	#groups	%total
primary substrate	6	2
secondary substrate	15	5
interstitial substrate	32	10
nearshore cell	62	19
wave energy	129	40
area	173	54
aspect	227	71
seepage	228	71
slope	231	72
dynamism	232	72
permeability	232	72
roughness	232	72

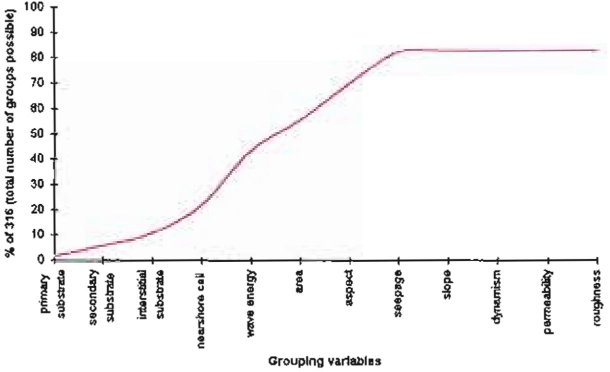
B. Lower-middle sub-zone groups

Attribute	#groups	%total
primary substrate	5	2
secondary substrate	18	6
interstitial substrate	34	11
nearshore cell	69	22
wave energy	137	43
area	175	55
aspect	221	70
seepage	260	82
slope	262	83
dynamism	262	83
permeability	262	83
roughness	262	83

C. Lower sub-zone groups

Attribute	#groups	%total
primary substrate	5	2
secondary substrate	20	6
interstitial substrate	32	10
nearshore cell	56	18
wave energy	108	35
area	145	47
aspect	204	66
seepage	206	67
slope	210	68
dynamism	210	68
permeability	211	69
roughness	211	69


A. Upper-middle sub-zone groups


B. Lower-middle sub-zone groups

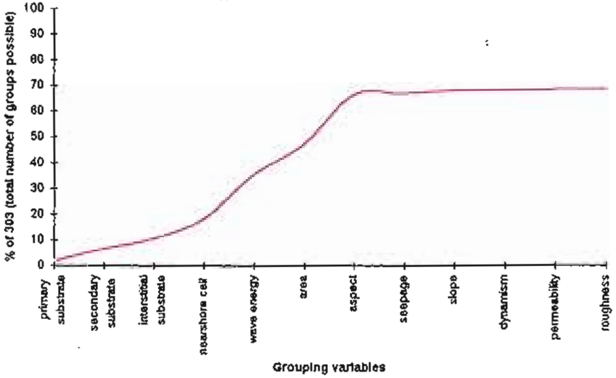

C. Lower sub-zone groups

Figure 9. Ranked response of the number of segments per group for each additional attribute

Table 6. Summary of grouped variables

A. Upper-middle sub-zone groups

Attribute	#groups	%total
primary substrate	6	2
secondary substrate	15	5
interstitial substrate	32	10
nearshore cell	62	19
wave energy	129	40
area	173	54
aspect	227	71
seepage	228	71
slope	231	72
dynamism	232	72
permeability	232	72
roughness	232	72

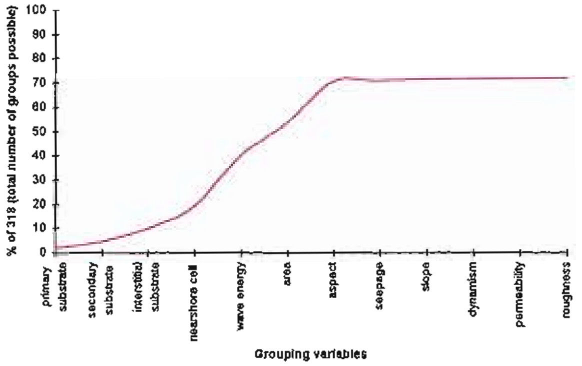
B. Lower-middle sub-zone groups

Attribute	#groups	%total
primary substrate	5	2
secondary substrate	18	6
interstitial substrate	34	11
nearshore cell	69	22
wave energy	137	43
area	175	55
aspect	221	70
seepage	260	82
slope	262	83
dynamism	262	83
permeability	262	83
roughness	262	83

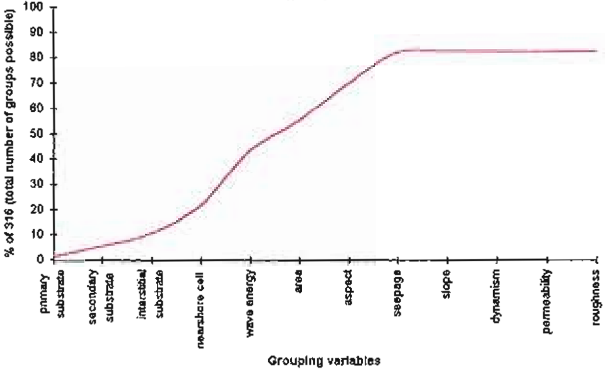
C. Lower sub-zone groups

Attribute	#groups	%total
primary substrate	5	2
secondary substrate	20	6
interstitial substrate	32	10
nearshore cell	56	18
wave energy	108	35
area	145	47
aspect	204	66
seepage	206	67
slope	210	68
dynamism	210	68
permeability	211	69
roughness	211	69

A. Upper-middle sub-zone groups



B. Lower-middle sub-zone groups



C. Lower sub-zone groups

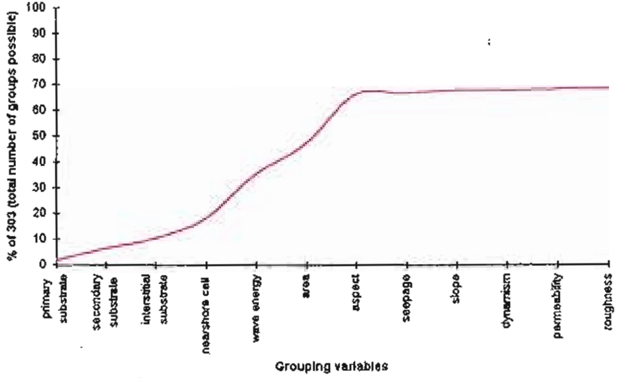


Figure 9. Ranked response of the number of segments per group for each additional attribute

substrates are included in the range of nearshore habitats. Carr Inlet is predominantly composed of soft nearshore substrates so the graphs reflect the controlling attributes for this system only. In areas where beaches are configured linearly and are composed mostly of pebbles, stronger gradients in slope angle and permeability may cause more groups to form.

The decision of how many groups to generate depends on the resources available and the ecological resolution required for the level of change detection desired by the investigators. For this study we chose the groups formed by all three substrate sizes and the nearshore ocean attributes. Table 7 summarizes the distribution of the resulting groups. The total lengths and areas of each group are listed. These data are useful for selecting which groups are important for biological characterization in terms of shoreline length and area criteria.

A number of factors come into play when choosing the beach types for conducting intensive biological sampling. Biological data extrapolation will be limited to the segments within the sampled beach group. Therefore if the goal is to characterize a large area, then selection can be based on the cumulative shore area represented by a habitat group. However if ecological criteria are considered, then perhaps statistically infrequent but ecologically interesting beach types should be considered. A rocky beach among many soft sediment beaches could be of ecological interest even if it is not spatially characteristic. Figures 10 through 12 show the frequency, shore length and area distributions for each sub-zone and the groups generated when all three substrate sizes and the nearshore ocean attributes are considered. Also shown in green are the groups selected for modeling.

The selection criteria for this project were based on the lower sub-zone shore length, area and the range of habitat types. Figure 10 shows the distributions for the lower sub-zone habitat groups. The groups are arranged so that the lower numbered groups represent the finer sediment sizes, increasing to the larger sediment sizes with higher group numbers. Segments for sampling were selected from mud, sand, pebble, and cobble groups as shown. The groups with the longest shore length were selected so that the greatest spatial extrapolation by shore length was possible. The lower-middle and upper-middle groups were sampled by default (i.e. depending on which lower zone polygon was selected). Therefore the modeled groups shown on Figures 11 and 12 may not be the best selection for characterizing the project area. But mud, sand, pebble, and cobble habitats are still represented at these levels, although particularly for the upper-middle zone, the sampled groups do not represent the longest shore length or the greatest surface area. The selections were made in deference to the lower sub-zone since the greatest biodiversity was expected there and the least diversity in the higher sub-zones. This was shown to be correct by Schoch and Dethier (1997).

A score code was derived to represent the degree of physical similarity between the sampled segment and each of the remaining group segments. Although the substrate size and nearshore ocean variables were held constant by group membership, the remaining

Table 7. Lower sub-zone segment group summary by Cell number. Groups result from sorting on primary, secondary, and interstitial substrate sizes, and on Nearshore Cell which are the collective oceanic attributes. Shoretype refers to the SZMS shore classification. Group area is a summation of polygon areas, and group length is a summation of the area divided by the average polgon width.

	SCALE Upper Middle Zone					SCALE Lower Middle Zone					SCALE Lower Zone				
Nearshore Cell	Group Number	Number of Shoretypes	Number of Segments	Total Group Lengths (m)	Total Group Areas (m^2)	Group Number	Number of Shoretypes	Number of Segments	Total Group Lengths (m)	Total Group Areas (m^2)	Group Number	Number of Shoretypes	Number of Segments	Total Group Lengths (m)	Total Group Areas (m^2)
1	1	2	4	1147	29759	1	3	5	405	6813	2	5	30	2796	109152
1	3	3	5	540	13130	4	2	5	482	11099	10	5	8	1218	81737
1	5	1	2	79	8710	6	2	4	504	6706	13	2	3	773	51611
1	8	3	5	754	12230	9	3	6	607	8288	16	1	3	886	42121
1	11	4	9	1464	24696	13	1	1	210	19317	17	1	1	182	13824
1	15	2	4	579	5266	16	2	2	178	1472	20	4	24	8988	1080075
1	17	4	12	2026	33372	20	1	11	3370	138097	24	1	1	126	3283
1	23	1	5	411	10339	25	1	3	432	7281	27	3	6	1263	90983
1	26	6	38	8372	127645	27	2	3	223	21771	32	1	2	135	2168
1	33	2	2	421	3916	30	5	11	2015	51255	36	3	12	3740	268249
1	35	2	2	711	12981	34	1	1	130	1696	43	1	3	566	18248
1	39	1	2	86	946	37	2	2	111	1031	46	1	1	135	5793
1	40	2	7	3367	51101	38	1	2	112	1736	50	2	3	427	56677
1	45	3	5	1008	14477	40	3	9	1729	137611	52	2	4	969	27869
1	49	3	4	768	16986	46	3	3	393	12601	56	1	2	807	27516
1	54	1	2	393	6195	50	2	4	995	29082					
						53	4	15	5237	160543					
						57	1	1	131	3926					
						62	2	3	377	19560					
						63	4	12	3712	113406					
						68	3	4	691	23855					
Cell 1 Total	16		108	22126	371749	21		107	22044	777146	15		103	23011	1879306
2	6	1	1	1222	12217	10	2	2	742	25413	18	2	2	504	23580
2	9	1	1	261	3908	17	1	1	323	68504	21	2	13	3080	237667
2	12	2	3	1620	37526	21	1	2	246	26788	28	2	6	1308	124942
2	18	2	3	346	6739	41	1	1	117	2343	40	2	2	806	64137
2	21	1	1	78	1168	44	2	4	1223	39407	48	1	1	55	6165
2	27	3	10	1608	24845	47	1	5	1117	49792	51	1	2	179	7640
2	31	2	4	1155	13495	54	2	5	1217	44877	53	2	5	1028	20563
2	36	2	5	844	12071	59	1	1	103	3082					
2	46	1	2	490	7148	60	1	1	68	5049					
2	55	1	2	209	3105	64	4	9	1487	55271					
2	59	3	5	713	12359	67	2	5	1324	60525					
						69	1	1	230	36348					
Cell 2 Totals	11		37	8545	134578	12		37	8197	417399	7		31	6960	484694
3	19	1	1	98	21334	28	1	1	646	16786	3	2	3	253	39565
3	24	1	1	1884	20727	35	1	1	94	17980	11	3	10	2667	221259
3	28	1	1	397	5165	48	1	1	297	6822	14	3	5	1426	55906
3	37	2	4	852	13411	55	1	1	130	4017	21	1	1	637	29296
3	41	3	9	3754	63400	65	4	4	1167	45605	25	1	1	367	9898
3	47	1	1	428	7708						33	1	1	202	17980
3	50	2	3	1583	28254						37	1	1	146	5836
3	56	1	1	124	993						44	1	1	234	6071
3	60	4	6	1479	22990						54	2	2	359	10814
Cell 3 Totals	9		27	10599	183963	5		8	2334	91210	9		25	6291	396625
4	2	1	4	352	6819	3	3	8	882	15366	1	1	1	132	5281
4	4	2	2	244	1185	5	2	5	1403	19730	4	5	22	2507	99458
4	7	2	4	441	4813	7	3	4	473	4653	5	1	1	129	3625
4	10	1	2	193	860	8	1	1	152	1371	6	5	10	1942	56755
4	13	1	1	65	719	12	5	24	2594	35527	7	1	5	1057	92087
4	14	1	3	595	3891	15	3	4	1071	16974	8	1	1	116	4647
4	16	1	1	106	739	18	1	2	180	2568	9	1	2	217	7298
4	20	4	7	641	4960	22	2	5	928	25005	12	5	17	1758	105968
4	22	1	1	164	3290	23	1	1	109	1636	15	4	14	2403	86753
4	25	4	16	1393	9167	24	2	2	313	8903	19	4	12	2360	309989
4	29	6	24	4015	41257	26	1	1	109	1087	22	2	7	1128	69622
4	30	1	2	131	806	29	1	4	312	6223	23	2	4	1307	41765
4	32	5	11	2187	17156	31	4	17	2005	45508	26	4	26	3497	107044
4	34	1	1	79	473	32	2	2	271	7526	29	4	5	624	30987
4	38	4	30	4496	28566	33	1	2	128	1436	30	1	1	81	1450
4	42	3	11	1553	12770	36	1	2	136	1453	31	1	1	340	11907
4	43	1	1	154	1383	39	2	6	1348	18363	34	1	1	44	2774
4	44	2	2	256	1398	42	3	19	2444	46322	35	1	1	171	16279
4	48	2	5	443	2897	43	1	1	70	1742	38	1	1	467	42921
4	51	2	10	2168	18173	45	1	1	205	1846	39	1	2	580	50617
4	52	1	1	128	1150	49	1	1	164	3601	41	1	1	184	12681
4	53	1	1	220	2196	51	3	3	508	12514	42	1	1	186	3727
4	57	1	1	149	1193	52	1	2	269	3904	45	2	2	468	45880
4	58	1	1	377	2261	56	3	11	2491	54971	47	2	3	601	25934
4	61	2	3	420	6256	58	1	4	751	19941	49	1	1	47	2370
4	62	1	1	72	502	61	1	1	29	1948	55	2	3	1042	33138
						66	2	12	2986	99675					
Cell 4 Totals	26		146	21040	174884	27		145	22331	459793	26		145	23388	1270957

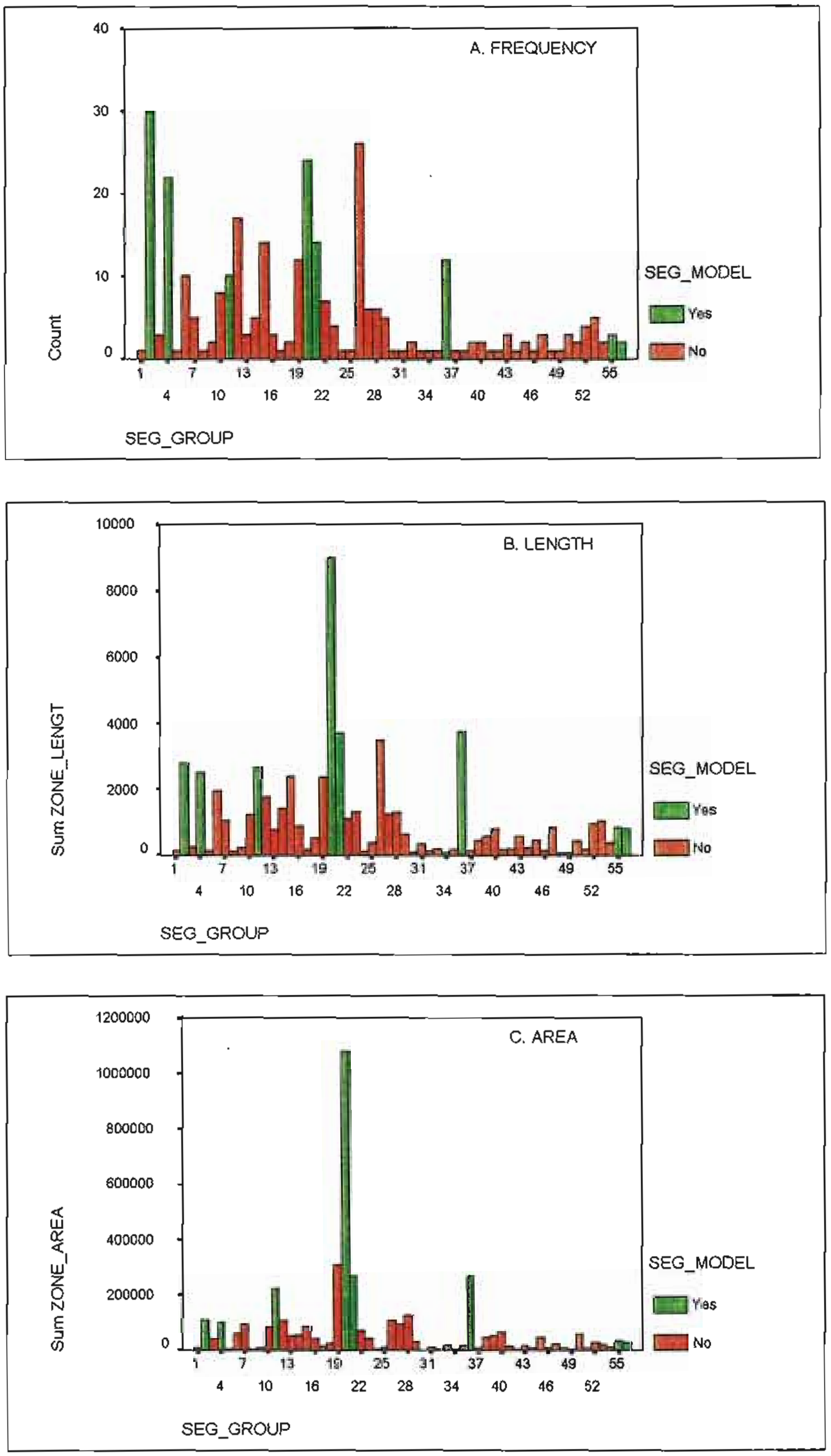


Figure 10. Lower sub-zone segment group distribution by A) frequency, B) cumulative polygon area, and C) the cumulative shore length. Also shown in green are the groups modeled. Note that low numbered groups represent smaller substrate sizes.

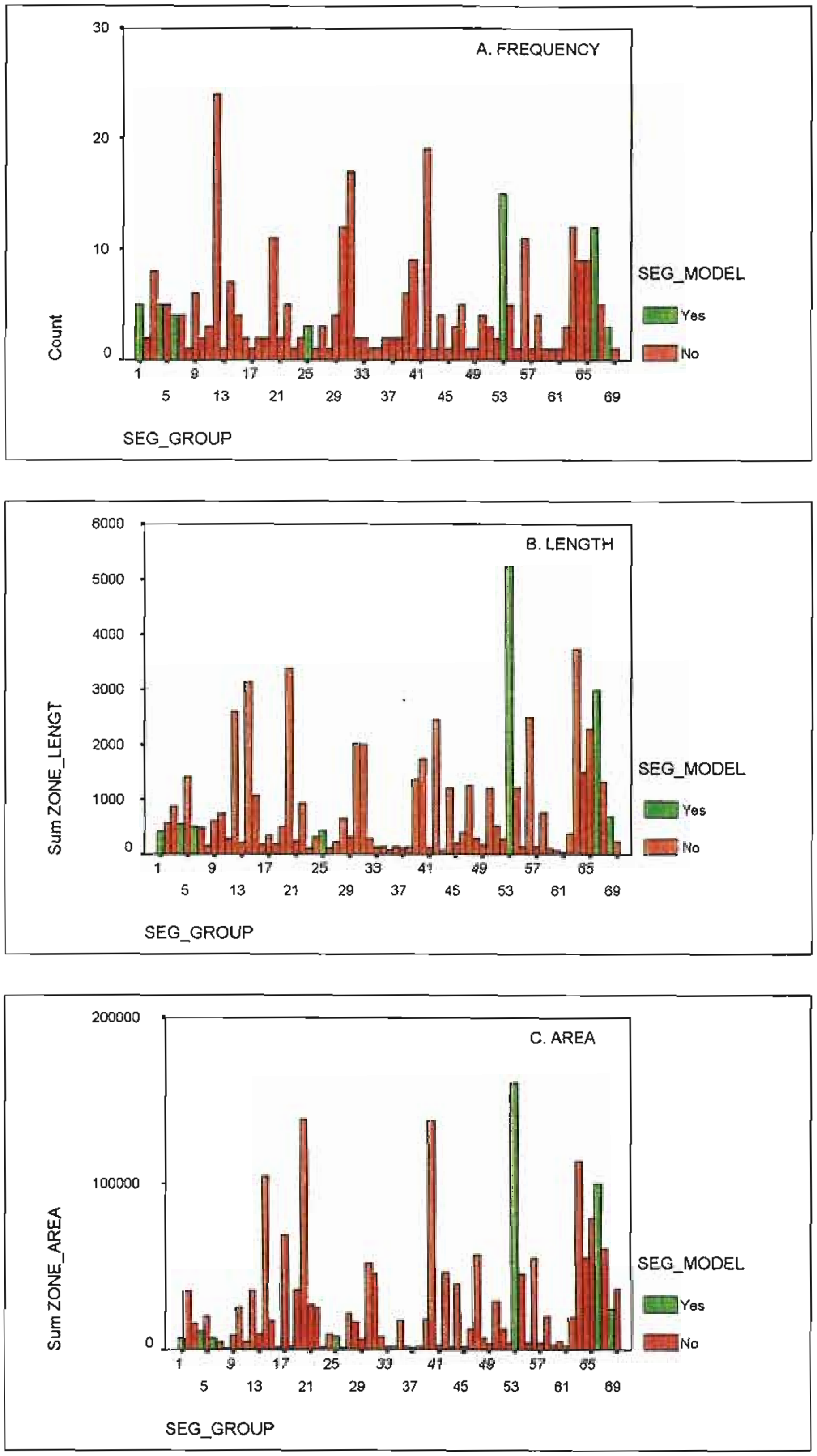


Figure 11. Frequency (A), shore length (B), and polygon area (C) distributions for the lower-middle sub-zone groups

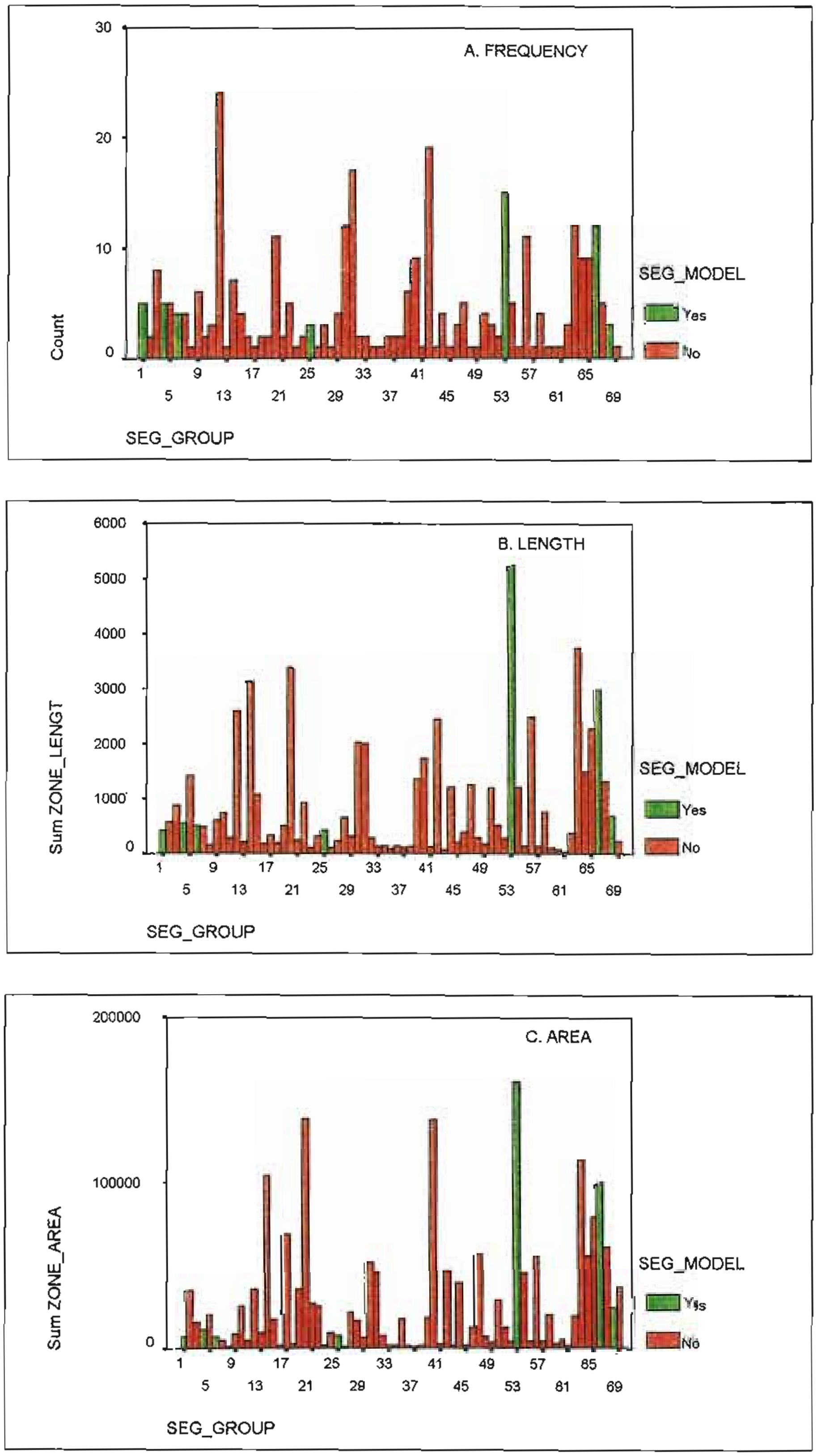


Figure 12. Frequency (A), shore length (B), and polygon area (C) distributions for the upper-middle sub-zone groups

physical attributes varied among segments in each group. This variability is likely to lead to increased difference between the predicted and actual bio-indicators values. To reflect this added variability among segments that are not exactly the same across all attributes, the score shows the amount of deflection from the sampled segments. Each digit in the score represents the deviation of that particular attribute from the attribute of a sampled segment. All sampled segments have scores of all zeroes. Segments exactly the same with respect to the quantified attributes also have scores of all zeroes. When an attribute of a group member differs from the sampled segment, the digits reflect this deviation by the number of categories removed from the reference segment. For example, any of the sampled segments will have a score of 00000000. The first four digits of the score will be constant since these are the grouping variables. Wave energy dissipation, or the fifth zero will be the first digit to reflect a change from the reference segment. If a group member has a wave energy dissipation value one category different (higher or lower) from the reference segment then that segment score will be 00001000. The scores are useful as a qualitative tool for comparing the similarity of modeled beach segments. The greater the deviation indicated by the score, the greater the probability that the organisms (bio-indicator value) will be different.

Bio-indicator values were calculated for all sampled organisms according to Dufrene and Legendre (1996). The results are detailed in Schoch and Dethier (1997). Table 8 summarizes the results for the community extrapolation. For the lower sub-zone, 31 segments out of 305 (10%) were sampled, representing 7 out of 56 groups. These sampled segments allowed for another 117 segments (35%) to be modeled or extrapolated. The 117 segments represent a cumulative shore length of 26,264 meters or 44% of the project shoreline. This also represents 52% of the project area. Similar statistics are shown for the upper-middle and lower-middle sub-zones. The relatively low total shore length and area modeled in the lower-middle zone reflects the high diversity of habitat types at that beach level. Table 8 also shows the total number of organisms sampled from each group (minus infrequent organisms). This can be compared to the number of organisms observed during the aerial survey of the project shoreline in 1997. Only 9 intertidal organisms were observed were visible from the air during the SZMS survey compared to the 114 taxa from the 1997 SCALE samples. But note that the shoreline coverage from the aerial survey was 100% compared to the 52% modeled by SCALE.

We compared the biota mapped by the SZMS with the predicted occurrence of the same organisms by the SCALE model. Table 8 lists these results. This analysis was done using the ArcView GIS. The data were queried to find the sub-zone polygons where the organism of interest was either predicted (SCALE) or observed (SZMS) present. For example the lower sub-zone database was queried to locate all the segments where barnacles (all Balanoids) were predicted by the SCALE model. We found 52 segments where barnacles were predicted to occur. This subset was then queried again to find those segments where barnacles were actually observed during the SZMS overflight. This resulted in 21 segments (of the original 52) where barnacles were observed from the air. This analysis does not infer error, but merely underscores the differences brought

Table 8. Bio-indicator summary for sub-zone groups in Carr Inlet. Table A list the results from the SCALE modeling and Table B lists the observation summary from the SZMS survey. The sub-zone organism comparisons are explained in the text.

A.

SCALE

Upper Middle Sub-zone Segments: 318

Number of Segments Sampled:		%Sampled
	11	3
Number of Segments Modeled:		%Modeled
	67	21
Cumulative Length (m) Modeled:		%Length
	15125	24
Cumulative Area (m^2) Modeled:		%Area
	234131	27

Group	Substrate	Total #Organisms	#Surface	#Infauna
5	mud	5	4	1
11	mud	4	4	0
26	sand	2	1	1
33	mud	4	4	0
40	sand	7	6	1
54	gravel	8	4	4
57	gravel	6	3	3
61	gravel	4	3	1

Lower-Middle Sub-zone Segments: 316

Number of Segments Sampled:		%Sampled
	11	3
Number of Segments Modeled:		%Modeled
	42	13
Cumulative Length (m) Modeled:		%Length
	10393	17
Cumulative Area (m^2) Modeled		% Area
	309159	16

Group	Substrate	Total #Organisms	#Surface	#Infauna
4	mud	25	6	19
25	mud	12	5	7
53	sand	24	9	15
66	gravel	21	11	10
68	gravel	29	12	17

Lower Sub-zone Segments: 305

Number of Segments Sampled:		%Sampled
	31	10
Number of Segments Modeled:		%Modeled
	117	38
Cumulative Length (m) Modeled:		%Length
	26264	44
Cumulative Area (m^2) Modeled:		% Area
	2105810	52

Group	Substrate	Total #Organisms	#Surface	#Infauna
2	mud	33	7	26
4	mud	30	4	29
11	sand	22	4	18
20	sand	11	4	7
21	sand	15	4	11
55	gravel	39	16	23
56	gravel	32	11	21

B.

SZMS Shore Zone Mapping System

Number of Segments Observed From the Air:		% Observed
	318	100
Number of Organisms Observed From the Air:		
	3	

Upper-Middle Sub-zone Comparison

Organism	Number of Segments SCALE	 SZMS
Fucus	11	3
Barnacles	62	35
Ulvoids	20	5

Number of Segments Observed From the Air:		% Observed
	316	100
Number of Organisms Observed From the Air:		
	8	

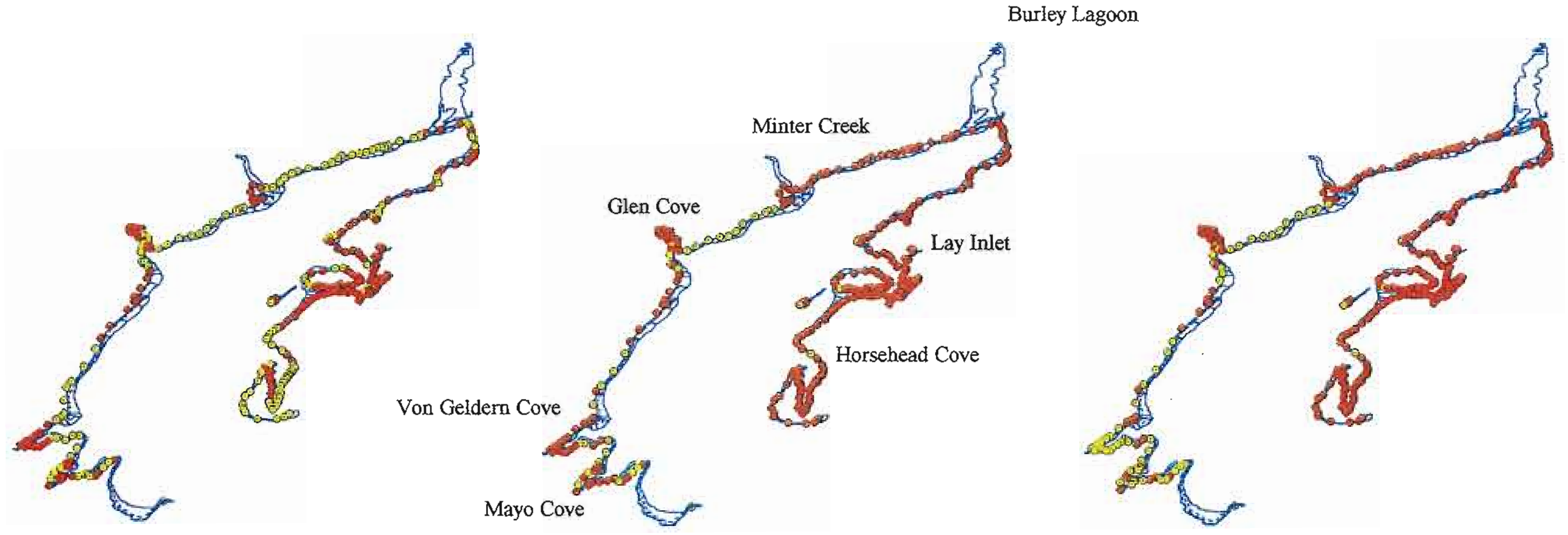
Lower-Middle Sub-zone Comparison

Organism	Number of Segments SCALE	 SZMS
Fucus	8	2
Barnacles	43	27
Ulvoids	26	16
Red Algae	30	6
Dendraster	5	0
Gracilaria	13	0
Callianassa	26	3
Oysters	15	1

Number of Segments Observed From the Air:		% Observed
	305	100
Number of Organisms Observed From the Air:		
	9	

Lower Sub-zone Comparison

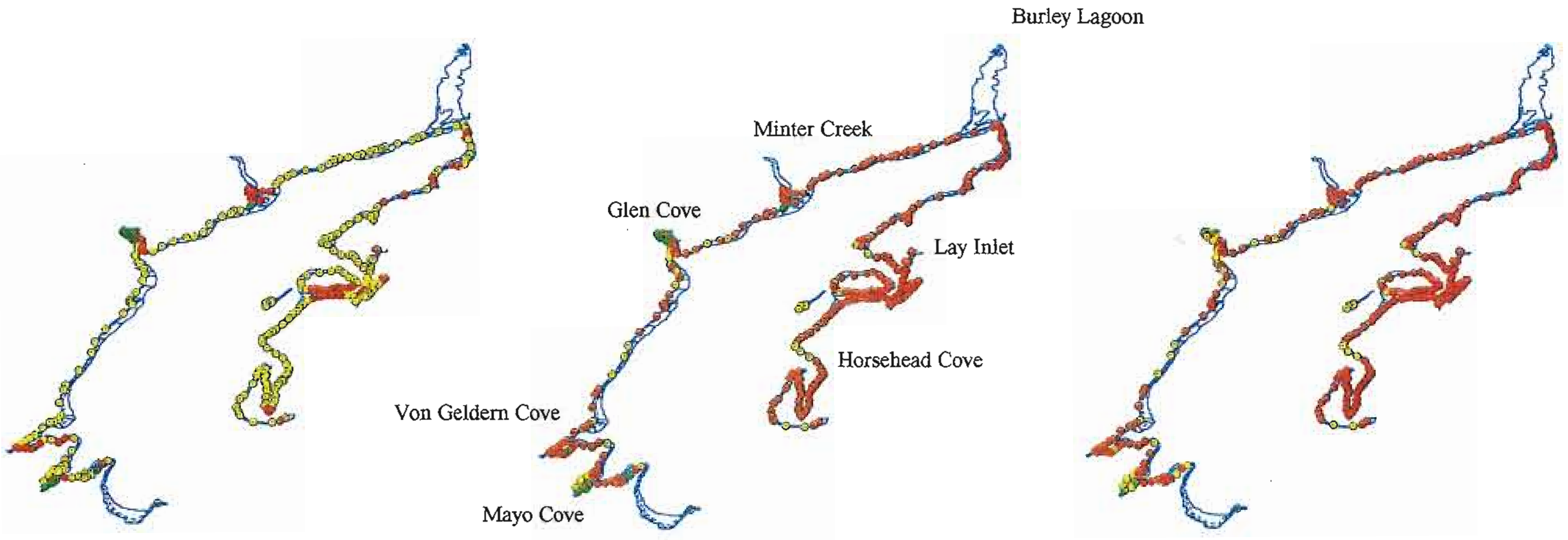
Organism	Number of Segments SCALE	 SZMS
Fucus	0	0
Barnacles	57	21
Ulvoids	105	75
Red Algae	43	1
Dendraster	78	43
Callianassa	27	19
Oysters	0	0
Mussels	30	0
Gracilaria	54	6



Barnacles: Upper-Middle Sub-Zone

A. SZMS Bio-mapping System	B. SCALE/SZMS	C. SCALE
140 observed	34 predicted and observed	62 predicted
22878 (m)	2752 (m)	3797 (m)

Figure 13. Results from an ArcView GIS query of barnacle locations in Carr Inlet. Each dot represents a sub-zone polygon. Yellow dots show where the organism was either predicted by SCALE or observed by SZMS to be present: (A) shows where barnacles were observed during the SZMS overflight, (B) shows the SZMS observation restricted to the segments modeled by SCALE, and Figure C shows where SCALE predicted Balanus glandula will occur. All other dots (red, orange) indicate where barnacles were absent. The total number of segments where barnacles were observed and the associated cumulative shore length are listed for each illustration.



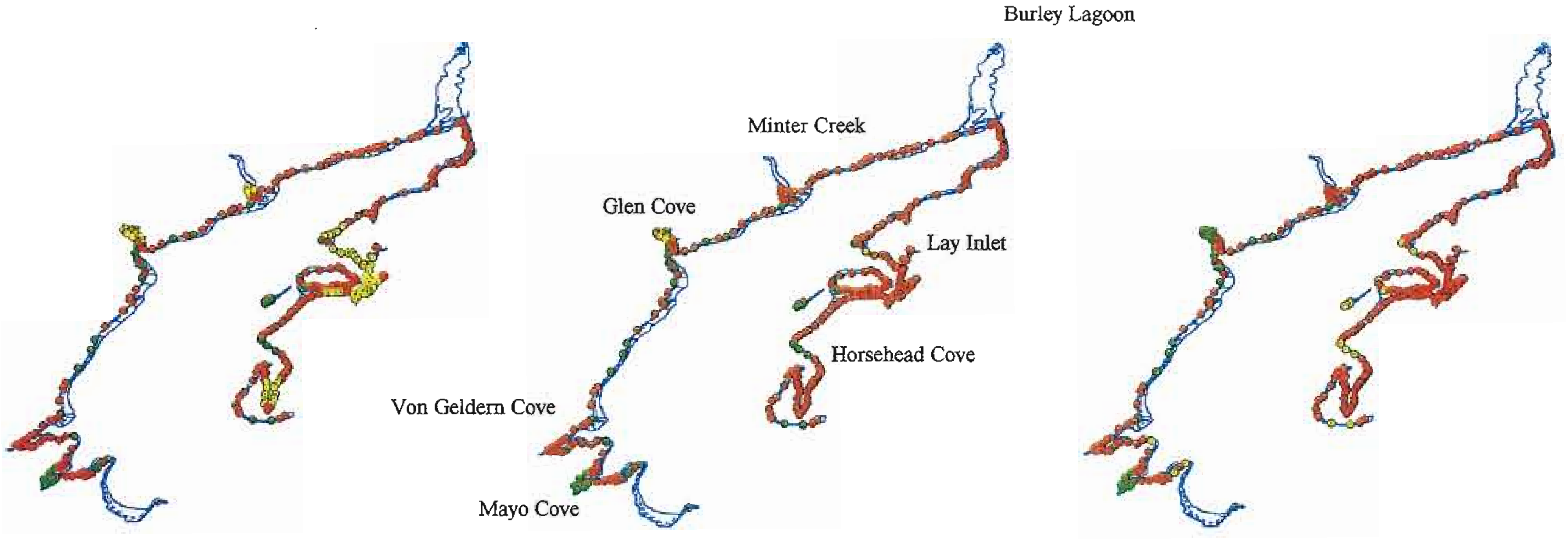
Ulvoids: Lower-Middle Sub-Zone

A. SZMS Bio-mapping System
222 observed
38112 (m)

B. SCALE/SZMS
28 predicted and observed
3911 (m)

C. SCALE
38 predicted
4544 (m)

Figure 14. Results from an ArcView GIS query of ulvoid locations in Carr Inlet. Each dot represents a sub-zone polygon. Yellow dots show where the organism was either predicted by SCALE or observed by SZMS to be present: (A) shows where ulvoids were observed during the SZMS overflight, (B) shows the SZMS observation restricted to the segments modeled by SCALE, and Figure C shows where SCALE predicted ulva and enteromorpha will occur. All other dots (green, orange) indicate where ulvoids were absent. The total number of segments where ulvoids were observed and the associated cumulative shore length are listed for each illustration.



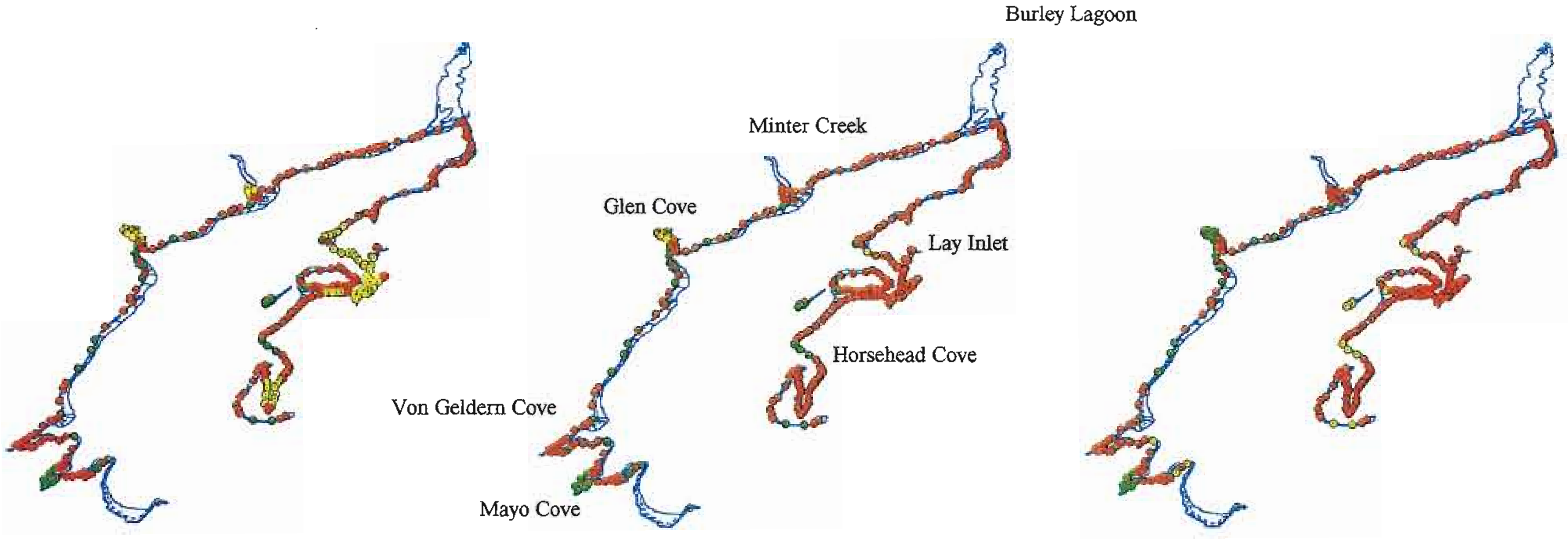
Oysters: Lower-Middle Sub-Zone

A. SZMS Bio-mapping System
79 observed
14959 (m)

B. SCALE/SZMS
26 predicted and observed
2828 (m)

C. SCALE
15 predicted
3108 (m)

Figure 15. Results from an ArcView GIS query of oyster locations in Carr Inlet. Each dot represents a sub-zone polygon. Yellow dots show where the organism was either predicted by SCALE or observed by SZMS to be present: (A) shows where oysters were observed during the SZMS overflight, (B) shows the SZMS observation restricted to the segments modeled by SCALE, and Figure C shows where SCALE predicted oysters will occur. All other dots (green, orange) indicate where oysters were absent. The total number of segments where oysters were observed and the associated cumulative shore length are listed for each illustration.



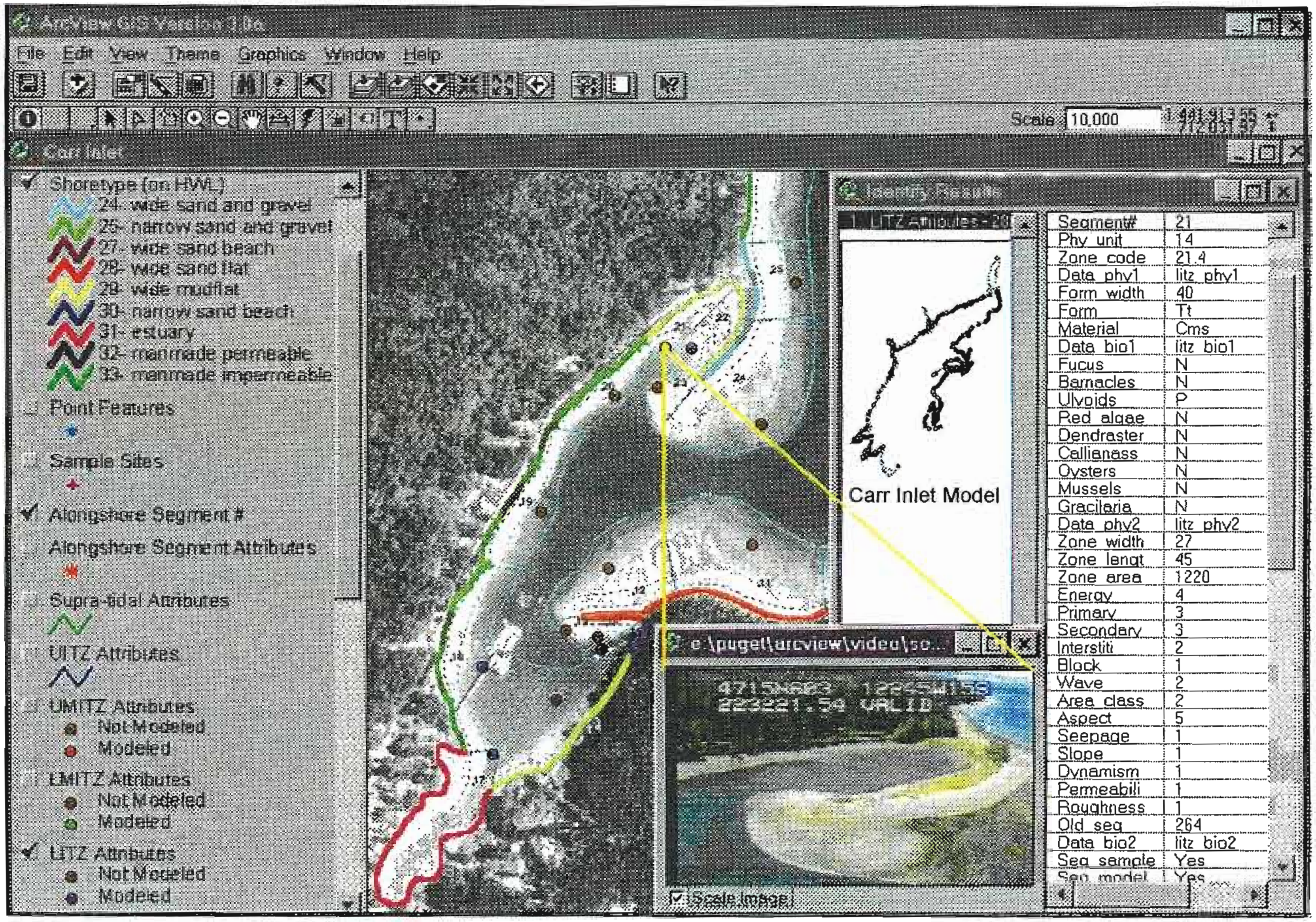
Oysters: Lower-Middle Sub-Zone

A. SZMS Bio-mapping System
79 observed
14959 (m)

B. SCALE/SZMS
26 predicted and observed
2828 (m)

C. SCALE
15 predicted
3108 (m)

Figure 15. Results from an ArcView GIS query of oyster locations in Carr Inlet. Each dot represents a sub-zone polygon. Yellow dots show where the organism was either predicted by SCALE or observed by SZMS to be present: (A) shows where oysters were observed during the SZMS overflight, (B) shows the SZMS observation restricted to the segments modeled by SCALE, and Figure C shows where SCALE predicted oysters will occur. All other dots (green, orange) indicate where oysters were absent. The total number of segments where oysters were observed and the associated cumulative shore length are listed for each illustration.

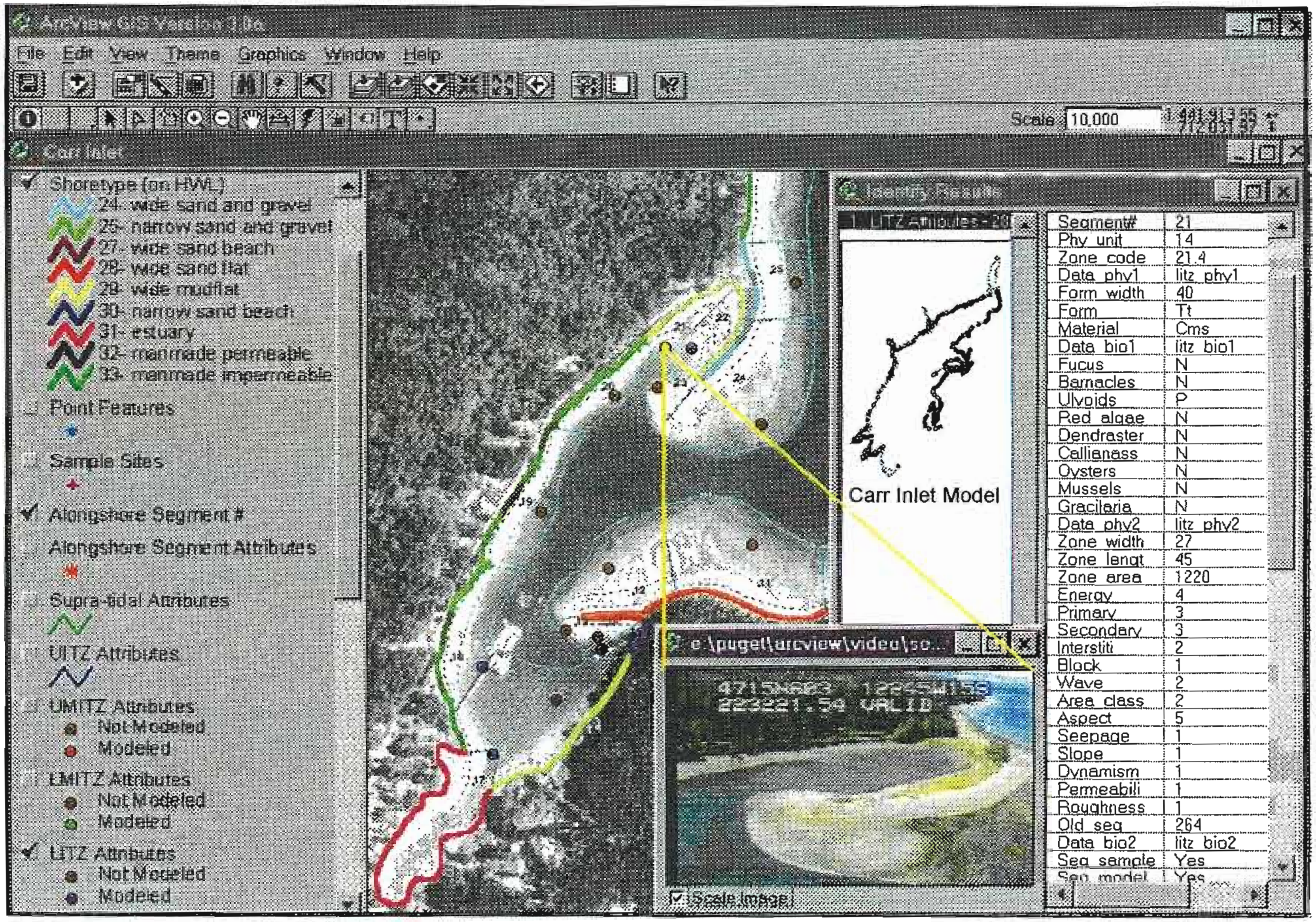


Segment#	21
Phy unit	14
Zone code	21.4
Data phy1	litz phy1
Form width	40
Form	Tt
Material	Cms
Data bio1	litz bio1
Fucus	N
Barnacles	N
Ulvoids	P
Red algae	N
Dendraster	N
Callianass	N
Oysters	N
Mussels	N
Gracilaria	N
Data phy2	litz phy2
Zone width	27
Zone lengt	45
Zone area	1220
Energy	4
Primary	3
Secondary	3
Interstiti	2
Block	1
Wave	2
Area class	2
Aspect	5
Seepage	1
Slope	1
Dynamism	1
Permeabili	1
Roughness	1
Old seg	264
Data bio2	litz bio2
Seg sample	Yes
Seg model	Yes

Figure 19. The GIS data structure in ArcView. Shown are the coverage legend, orthophoto basemap, alongshore segments, across-shore zones, lower sub-zone data attribute table and photo hotlink for Segment 21.

Table 9. GIS data structure and attribute tables. Horizontal lines indicate where data tables are joined.

Coverage Name Feature Type	SHORETYPE LINE	SUPRA-TIDAL LINE	LONGSHORE SEGMEN POINT	UITZ LINE	UMITZ POINT	LITZ POINT	SUB-TIDAL LINE
Data Source	SZMS Aerial Classification	SZMS		SZMS	SZMS	SZMS	
Table Name	Shoretype	Sup_p1		uiyz_p1	umitz_p1	litz_p1	
Table Contents	Physical Unit	Physical Unit		Physical Unit	Physical Unit	Physical Unit	
	Shore Name	Zone Code		Zone Code	Zone Code	Zone Code	
	Shore Type	Data Type		Data Type	Data Type	Data Type	
	Shore Length (m)	Form		Form	Form	Form	
	Exposure	Form Width		Form Width	Form Width	Form Width	
	Sediment Source	Material		Material	Material	Material	
	Sediment Abundance						
	Transport Direction						
	Rate of Change						
Data Source	SZMS						
Table Name	Bulkhead						
Table Contents	Physical Unit						
	Data Type						
	Shore Protection Structures						
	Percent of Physical Unit						
	Total Meters						
Data Source		SZMS		SZMS	SZMS	SZMS	SZMS
Table Name		Sup_b1		uitz_b1	umitz_b1	litz_b1	sub_b1
Table Contents		Physical Unit		Physical Unit	Physical Unit	Physical Unit	Physical Unit
		Segment #		Segment #	Segment #	Segment #	Segment #
		Zone Code		Zone Code	Zone Code	Zone Code	Zone Code
		Data Type		Data Type	Data Type	Data Type	Data Type
		Biota		Biota	Biota	Biota	Biota
Data Source			SCALE	SCALE	SCALE	SCALE	
Table Name			along_p2	uitz_p2	umitz_p2	litz_p2	
Table Contents			Physical Unit	Segment #	Segment #	Segment #	
			Segment #	Zone Code	Zone Code	Zone Code	
			Nearshore Cell	Data Type	Data Type	Data Type	
			Latitude	Zone Width	Zone Width	Zone Width	
			Longitude	Zone Length	Zone Length	Zone Length	
			Area	Zone Area	Zone Area	Zone Area	
			Fetch Length	Primary Size	Primary Size	Primary Size	
			Fetch Class	Secondary Size	Secondary Size	Secondary Size	
			Wave Aspect	Interstitial Size	Interstitial Size	Interstitial Size	
			Wave Power	Energy Dissipation	Energy Dissipation	Energy Dissipation	
			Wave Height	Area Class	Area Class	Area Class	
			Wave Period	Orientation	Orientation	Orientation	
			Wave Length	Seepage	Seepage	Seepage	
			Drift	Slope	Slope	Slope	
			Photo (hotlink)	Dynamism	Dynamism	Dynamism	
				Permeability	Permeability	Permeability	
				Roughness	Roughness	Roughness	
Data Source					SCALE	SCALE	
Table Name					umitz_b2	litz_b2	
Table Contents					Zone Code	Zone Code	
					Data Type	Data Type	
					Segment Sampled	Segment Sampled	
					Segment Modeled	Segment Modeled	
					Segment Group	Segment Group	
					Segment Score	Segment Score	
					Indicator Organisms	Indicator Organisms	
Data Source					SCALE	SCALE	
Table Name					umitz_b3	litz_b3	
Table Contents					Segment #	Segment #	
					Data Type	Data Type	
					More Indicator Organisms	More Indicator Organisms	

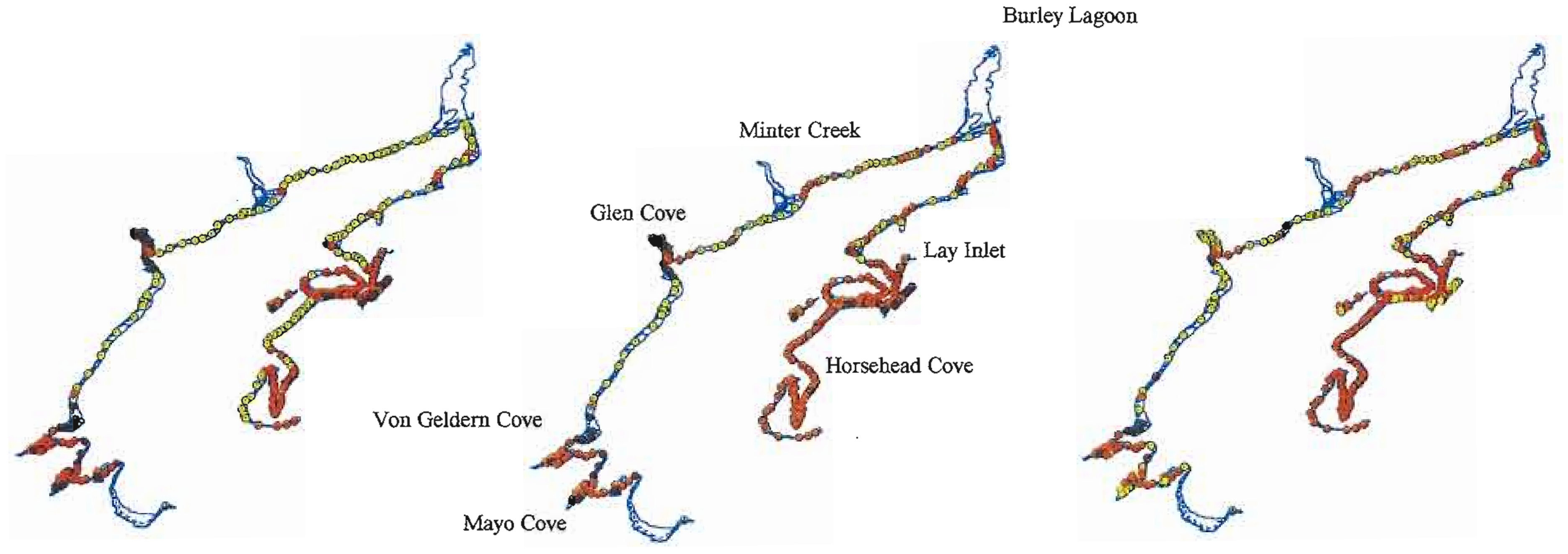


Segment#	21
Phy unit	14
Zone code	21.4
Data phy1	litz phy1
Form width	40
Form	Tt
Material	Cms
Data bio1	litz bio1
Fucus	N
Barnacles	N
Ulvoids	P
Red algae	N
Dendraster	N
Callianass	N
Oysters	N
Mussels	N
Gracilaria	N
Data phy2	litz phy2
Zone width	27
Zone lengt	45
Zone area	1220
Energy	4
Primary	3
Secondary	3
Interstiti	2
Block	1
Wave	2
Area class	2
Aspect	5
Seepage	1
Slope	1
Dynamism	1
Permeabili	1
Roughness	1
Old seg	264
Data bio2	litz bio2
Seg sample	Yes
Seg model	Yes

Figure 19. The GIS data structure in ArcView. Shown are the coverage legend, orthophoto basemap, alongshore segments, across-shore zones, lower sub-zone data attribute table and photo hotlink for Segment 21.

Table 9. GIS data structure and attribute tables. Horizontal lines indicate where data tables are joined.

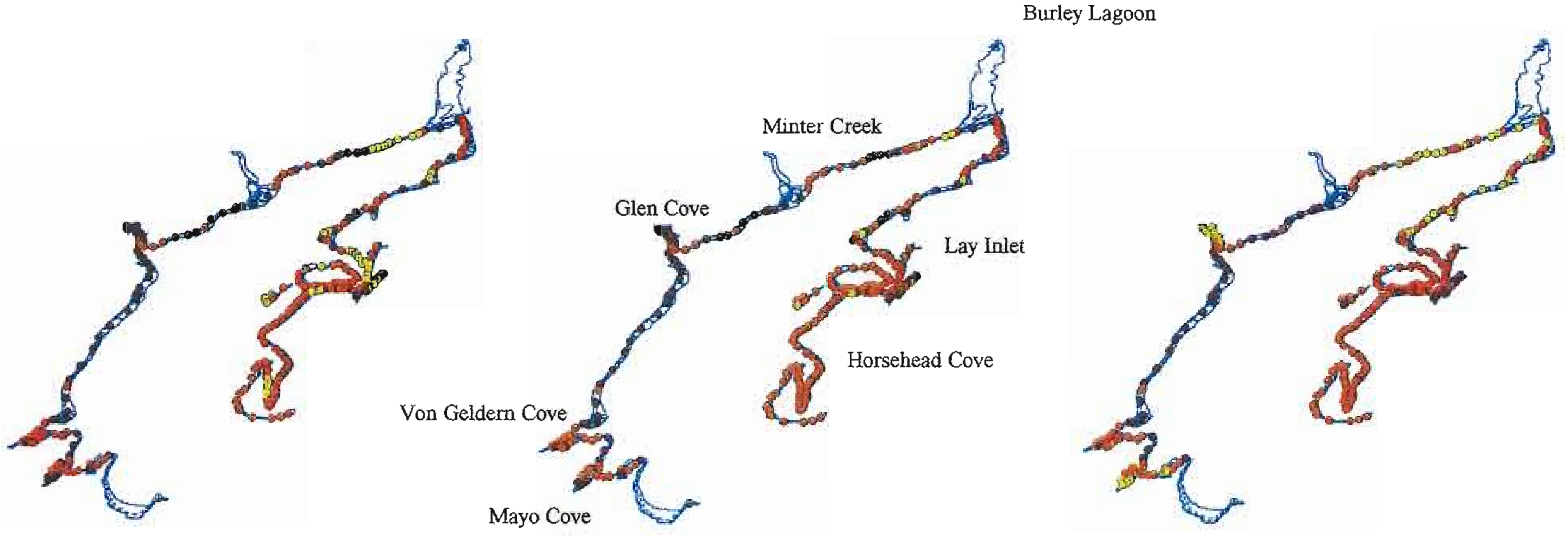
Coverage Name	SHORETYPE	SUPRA-TIDAL	LONGSHORE SEGMEN	UITZ	UMITZ	LITZ	SUB-TIDAL
Feature Type	LINE	LINE	POINT	LINE	POINT	POINT	LINE
Data Source	SZMS Aerial Classification	SZMS		SZMS	SZMS	SZMS	
Table Name	Shoretype	Sup_p1		uiyz_p1	umitz_p1	litz_p1	
Table Contents	Physical Unit	Physical Unit		Physical Unit	Physical Unit	Physical Unit	
	Shore Name	Zone Code		Zone Code	Zone Code	Zone Code	
	Shore Type	Data Type		Data Type	Data Type	Data Type	
	Shore Length (m)	Form		Form	Form	Form	
	Exposure	Form Width		Form Width	Form Width	Form Width	
	Sediment Source	Material		Material	Material	Material	
	Sediment Abundance						
	Transport Direction						
	Rate of Change						
Data Source	SZMS						
Table Name	Bulkhead						
Table Contents	Physical Unit						
	Data Type						
	Shore Protection Structures						
	Percent of Physical Unit						
	Total Meters						
Data Source		SZMS		SZMS	SZMS	SZMS	SZMS
Table Name		Sup_b1		uitz_b1	umitz_b1	litz_b1	sub_b1
Table Contents		Physical Unit		Physical Unit	Physical Unit	Physical Unit	Physical Unit
		Segment #		Segment #	Segment #	Segment #	Segment #
		Zone Code		Zone Code	Zone Code	Zone Code	Zone Code
		Data Type		Data Type	Data Type	Data Type	Data Type
		Biota		Biota	Biota	Biota	Biota
Data Source			SCALE	SCALE	SCALE	SCALE	
Table Name			along_p2	uitz_p2	umitz_p2	litz_p2	
Table Contents			Physical Unit	Segment #	Segment #	Segment #	
			Segment #	Zone Code	Zone Code	Zone Code	
			Nearshore Cell	Data Type	Data Type	Data Type	
			Latitude	Zone Width	Zone Width	Zone Width	
			Longitude	Zone Length	Zone Length	Zone Length	
			Area	Zone Area	Zone Area	Zone Area	
			Fetch Length	Primary Size	Primary Size	Primary Size	
			Fetch Class	Secondary Size	Secondary Size	Secondary Size	
			Wave Aspect	Interstitial Size	Interstitial Size	Interstitial Size	
			Wave Power	Energy Dissipation	Energy Dissipation	Energy Dissipation	
			Wave Height	Area Class	Area Class	Area Class	
			Wave Period	Orientation	Orientation	Orientation	
			Wave Length	Seepage	Seepage	Seepage	
			Drift	Slope	Slope	Slope	
			Photo (hotlink)	Dynamism	Dynamism	Dynamism	
				Permeability	Permeability	Permeability	
				Roughness	Roughness	Roughness	
Data Source					SCALE	SCALE	
Table Name					umitz_b2	litz_b2	
Table Contents					Zone Code	Zone Code	
					Data Type	Data Type	
					Segment Sampled	Segment Sampled	
					Segment Modeled	Segment Modeled	
					Segment Group	Segment Group	
					Segment Score	Segment Score	
					Indicator Organisms	Indicator Organisms	
Data Source					SCALE	SCALE	
Table Name					umitz_b3	litz_b3	
Table Contents					Segment #	Segment #	
					Data Type	Data Type	
					More Indicator Organisms	More Indicator Organisms	



Dendraster: Lower Sub-Zone

A. SZMS Bio-mapping System	B. SCALE/SZMS	C. SCALE
102 observed	46 predicted and observed	78 predicted
27924 (m)	15633 (m)	18168 (m)

Figure 16. Results from an ArcView GIS query of Dendraster locations in Carr Inlet. Each dot represents a sub-zone polygon. Yellow dots show where the organism was either predicted by SCALE or observed by SZMS to be present: (A) shows where Dendraster were observed during the SZMS overflight, (B) shows the SZMS observation restricted to the segments modeled by SCALE, and Figure C shows where SCALE predicted Dendraster will occur. All other dots (green, orange) indicate where Dendraster were absent. The total number of segments where Dendraster were observed and the associated cumulative shore length are listed for each illustration.



Gracilaria: Lower Sub-Zone

A. SZMS Bio-mapping System
41 observed
6921 (m)

B. SCALE/SZMS
12 predicted and observed
1806 (m)

C. SCALE
54 predicted
9180 (m)

Figure 18. Results from an ArcView GIS query of Gracilaria locations in Carr Inlet. Each dot represents a sub-zone polygon. Yellow dots show where the organism was either predicted by SCALE or observed by SZMS to be present: (A) shows where Gracilaria were observed during the SZMS overflight, (B) shows the SZMS observation restricted to the segments modeled by SCALE, and Figure C shows where SCALE predicted Gracilaria will occur. All other dots (green, orange) indicate where Gracilaria were absent. The total number of segments where Gracilaria were observed and the associated cumulative shore length are listed for each illustration.

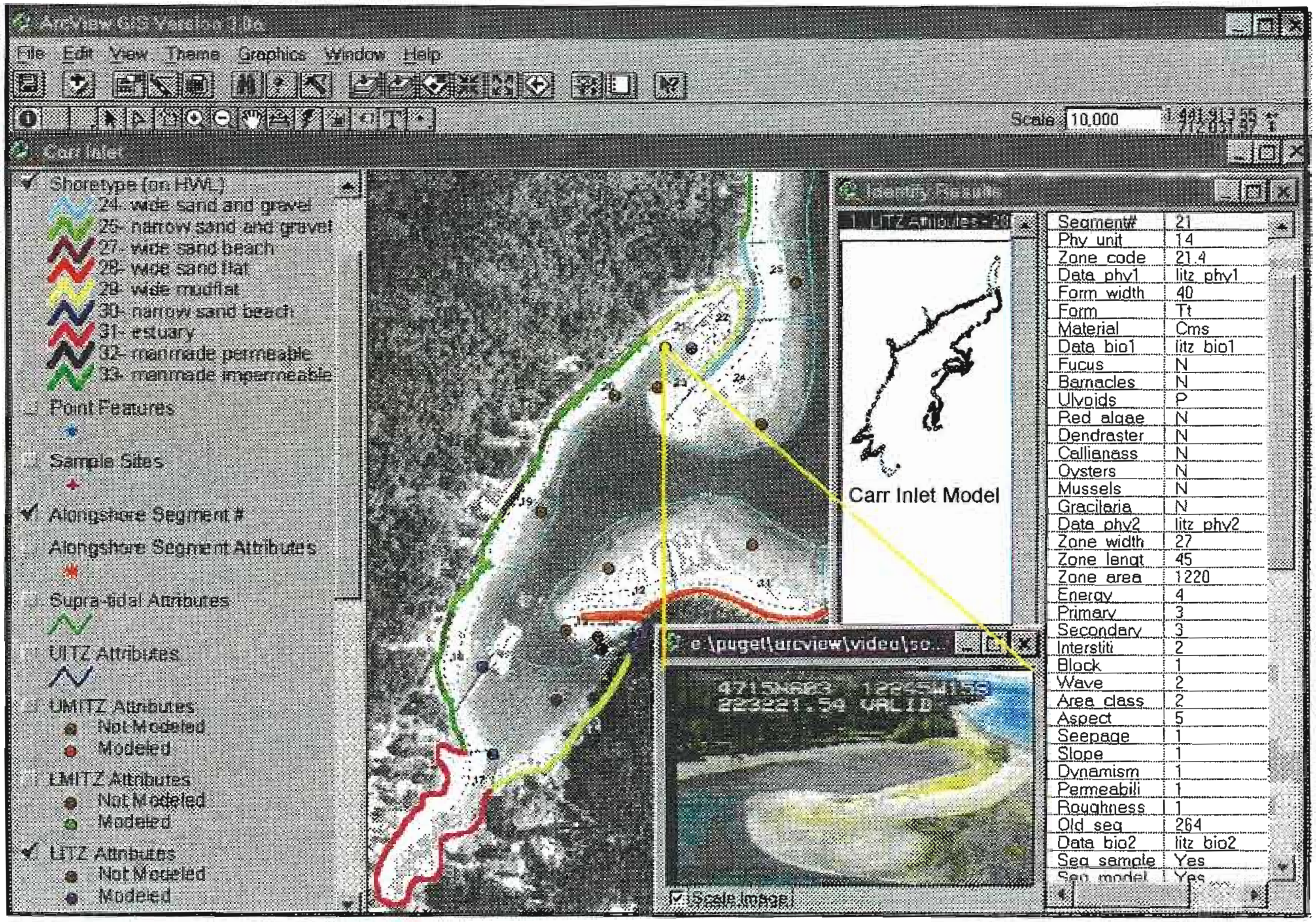
Callianassa burrows are difficult to see from the air, it is not surprising that they are under represented by the aerial survey data. The oysters in Carr Inlet are mostly (if not entirely) cultured, so the spatial distribution will be more a function of which owners decide to seed beaches rather that on the physical attributes of the segments. We can speculate (in the absence of validation data) that in this case the SCALE model fails to accurately predict the occurrence of oysters and that direct observation from an aerial survey is a better indicator of the actual distribution.

GIS Data Structure

Effective management of the coastal zone is dependent on the availability of accurate information about the distribution of natural resources in both space and time. Access to current and accurate resource inventories can benefit resource managers in monitoring trends in response to natural and anthropogenic disturbances. The goal of this component of the project was to develop and assemble a series of coverages representing the important features of the nearshore environment pertinent to the needs of coastal scientists. The database was designed to be compatible with GIS software such as ArcView (ESRI, 1996). The large amount of data resulting from the classification and modeling work described above needs an organized structure in order to be usable. The GIS format provides an interface to the data that allows for rapid viewing and sophisticated queries. Possible applications of this database include identifying critical habitats for coastal-dependent species, selection of monitoring sites and marine preserves, natural resource damage assessments, and habitat sensitivity analyses.

An example window from the designed ArcView data model is shown on Figure 19. The data are represented by a series of points, lines, and polygons. Table 9 shows the data attributes and structure for eight of the 14 coverages included in the database. The SZMS shore type classification is represented by a line coverage with two database files (dbf) joined by the "Physical Unit" field. The first is the "Shoretype" file which includes information on the general geomorphology of the physical unit, and the second join is the "Bulkhead" file with information about the shore protection structures there. Other line coverages represent supra-tidal data on the digitized high water line, upper intertidal data also on the high water line, and sub-tidal data on the digitized low water line. The line coverage attributes are joined to the data listed on Table 9 by the "Physical Unit" or the "Segment" relational link fields.

Two polygon coverages represent the intertidal zone. Alongshore segments are delineated by solid lines along the interpreted high and low water extents and horizontal boundaries. Across-shore sub-zone approximations are represented by dashed lines as shown in Figure 19. Separate point coverages were created to represent the polygon centers for each sub-zone. The polygon attributes were added to these files, then they were joined to the component attribute file (derived from the SZMS classification data), the aerial biota inventory, the SCALE attribute file, and the model results file as shown in Table 9. Another point coverage shows the general segment data and links to aerial video frames captured for each alongshore segment as shown in Figure 19. The inset of Carr



Segment#	21
Phy_unit	14
Zone_code	21.4
Data_phy1	litz_phy1
Form_width	40
Form	Tt
Material	Cms
Data_bio1	litz_bio1
Fucus	N
Barnacles	N
Ulvoids	P
Red_algae	N
Dendraster	N
Callianass	N
Oysters	N
Mussels	N
Gracilaria	N
Data_phy2	litz_phy2
Zone_width	27
Zone_lengt	45
Zone_area	1220
Energy	4
Primary	3
Secondary	3
Interstiti	2
Block	1
Wave	2
Area_class	2
Aspect	5
Seepage	1
Slope	1
Dynamism	1
Permeabili	1
Roughness	1
Old_seg	264
Data_bio2	litz_bio2
Seg_sample	Yes
Seg_model	Yes

Figure 19. The GIS data structure in ArcView. Shown are the coverage legend, orthophoto basemap, alongshore segments, across-shore zones, lower sub-zone data attribute table and photo hotlink for Segment 21.

Table 9. GIS data structure and attribute tables. Horizontal lines indicate where data tables are joined.

Coverage Name	SHORETYPE	SUPRA-TIDAL	LONGSHORE SEGMEN	UITZ	UMITZ	LITZ	SUB-TIDAL
Feature Type	LINE	LINE	POINT	LINE	POINT	POINT	LINE
Data Source	SZMS Aerial Classification	SZMS		SZMS	SZMS	SZMS	
Table Name	Shoretype	Sup_p1		uiyz_p1	umitz_p1	litz_p1	
Table Contents	Physical Unit	Physical Unit		Physical Unit	Physical Unit	Physical Unit	
	Shore Name	Zone Code		Zone Code	Zone Code	Zone Code	
	Shore Type	Data Type		Data Type	Data Type	Data Type	
	Shore Length (m)	Form		Form	Form	Form	
	Exposure	Form Width		Form Width	Form Width	Form Width	
	Sediment Source	Material		Material	Material	Material	
	Sediment Abundance						
	Transport Direction						
	Rate of Change						
Data Source	SZMS						
Table Name	Bulkhead						
Table Contents	Physical Unit						
	Data Type						
	Shore Protection Structures						
	Percent of Physical Unit						
	Total Meters						
Data Source		SZMS		SZMS	SZMS	SZMS	SZMS
Table Name		Sup_b1		uitz_b1	umitz_b1	litz_b1	sub_b1
Table Contents		Physical Unit		Physical Unit	Physical Unit	Physical Unit	Physical Unit
		Segment #		Segment #	Segment #	Segment #	Segment #
		Zone Code		Zone Code	Zone Code	Zone Code	Zone Code
		Data Type		Data Type	Data Type	Data Type	Data Type
		Biota		Biota	Biota	Biota	Biota
Data Source			SCALE	SCALE	SCALE	SCALE	
Table Name			along_p2	uitz_p2	umitz_p2	litz_p2	
Table Contents			Physical Unit	Segment #	Segment #	Segment #	
			Segment #	Zone Code	Zone Code	Zone Code	
			Nearshore Cell	Data Type	Data Type	Data Type	
			Latitude	Zone Width	Zone Width	Zone Width	
			Longitude	Zone Length	Zone Length	Zone Length	
			Area	Zone Area	Zone Area	Zone Area	
			Fetch Length	Primary Size	Primary Size	Primary Size	
			Fetch Class	Secondary Size	Secondary Size	Secondary Size	
			Wave Aspect	Interstitial Size	Interstitial Size	Interstitial Size	
			Wave Power	Energy Dissipation	Energy Dissipation	Energy Dissipation	
			Wave Height	Area Class	Area Class	Area Class	
			Wave Period	Orientation	Orientation	Orientation	
			Wave Length	Seepage	Seepage	Seepage	
			Drift	Slope	Slope	Slope	
			Photo (hotlink)	Dynamism	Dynamism	Dynamism	
				Permeability	Permeability	Permeability	
				Roughness	Roughness	Roughness	
Data Source					SCALE	SCALE	
Table Name					umitz_b2	litz_b2	
Table Contents					Zone Code	Zone Code	
					Data Type	Data Type	
					Segment Sampled	Segment Sampled	
					Segment Modeled	Segment Modeled	
					Segment Group	Segment Group	
					Segment Score	Segment Score	
					Indicator Organisms	Indicator Organisms	
Data Source					SCALE	SCALE	
Table Name					umitz_b3	litz_b3	
Table Contents					Segment #	Segment #	
					Data Type	Data Type	
					More Indicator Organisms	More Indicator Organisms	

Inlet in Figure 19 shows the results of a spatial query which is described earlier and illustrated in Figures 13 through 18.

Features such as marinas and large dock structures are represented by the 'Point Feature" coverage. This data layer has not been fully utilized but future improvements of the database will include more information on public access points such as parks and boat ramps. Also, aquaculture operations and river mouths will be located.

Documentation was generated for each data layer. The source, the projection and resolution, and the types of analysis and reformatting are contained in a metadata file (included on the data CD-ROM). This will allow the end-user to make informed decisions concerning the usefulness of a particular data layer on a map.

6. Conclusions

This study describes a model for determining landscape scale patterns in nearshore biota based on physical characteristics of a shoreline. The comparison of the SZMS classification and the SCALE model described in this report highlights some incompatibilities, but more importantly shows how the two systems can work in tandem to provide a very powerful database. By nesting the SCALE model into the SZMS classification system at the hierarchical level of the SZMS zone component, two scales of resolution are created that combine the power of full spatial coverage with the physical and biological resolution required for studies of environmental change. The proposed modular design for the nested hierarchical model first generates a spatially comprehensive physical classification and superficial biological inventory, followed by a high resolution quantification of physical attributes for all or part of the area covered by the first data set.

The SZMS system can be used to select areas for SCALE modeling. The aerial video imagery can be analyzed to isolate areas of ecological interest. The linear and point features can be queried for spatial distributions and extents of shoretype and associated biota, and proximity to potential sources of perturbations. Examples of how the SCALE model can be applied include higher resolution characterization of predominant shore habitats, for baseline monitoring near sewage outfalls of industrial sites, and for landscape scale ecological monitoring for local or global change detection. Additional applications can be explored in hindcasting the ecological functions of disturbed habitats for mitigation and restoration projects, forecasting impacts based on trends in human or natural perturbation patterns, and selecting sites for monitoring or for experiments in community ecology.

Predicting the spatial distribution of nearshore biota has important implications for resource managers in assessing the vulnerability and sensitivity to anthropogenic perturbations of aesthetically, economically or scientifically important resources. These data should enable managers to establish protective measures through policy directives. This work is a significant contribution to science and to resource management in coastal areas where the change in spatial distributions of habitats over time is a concern.

7. Acknowledgements

We are grateful for the funding and support provided by Tom Mumford and Helen Berry of the Washington State Department of Natural Resources in Olympia. Office space and computer time were provided to G.C.S by Mark Abbott at Oregon State University. We thank Dan Schafer for advice on statistical designs, and Paul Komar for reviewing this manuscript.

8. References

Allen, T.F.H. & T.B. Starr, 1982. Hierarchy: Perspectives for Ecological Complexity. The University of Chicago Press, Chicago, IL, 311 pp.

Alexander, S.E., and J. Roughgarden, 1996. Larval transport and population dynamics of intertidal barnacles: a coupled benthic/oceanic model. Ecol. Monogr., 66:259-275.

Bailey, A., H. Berry, B. Bookheim, and D. Stevens. 1998. Probability-based estimation of nearshore habitat characteristics. In: Proceedings of Puget Sound Research '98 Conference, march 12-13. Puget Sound Water Quality Action Team, Olympia, WA.

Battjes, J. A., 1974. Computation of set-up, logshore currents, run-up and overtopping due to wind-generated waves. Report 74-2, Committee on Hydraulics, Dept. of Civil Engineering, Delft University of Technology, Delft, Netherlands.

Beatley, T., 1991. Protecting biodiversity in coastal environments: Introduction and overview. Coastal Management, vol. 19, pp. 1-19.

Brown, A.C., and A. McLachlan, 1990. Ecology of Sandy Shores. Elsevier, Amsterdam, 328 pp.

Bustamente, R. H., G. M. Branch, S. Eekhout, B. Robertson, P. Zoutendyk, M. Schleyer, A. Dye, N. Hanekom, D. Keats, M. Jurd, and C. McQuaid. 1985. Gradients of intertidal primary productivity around the coast of South Africa and their relationships with consumer biomass. Oecologia, 102:189-201.

Carefoot, T., 1977. Pacific Seashores. University of Washington Press, Seattle, Washington, 208 pp.

Carter, R.W.G., 1988. Coastal environments, An introduction to the physical, ecological and cultural systems of coastlines. Academic Press, London, 617 pp.

Coastal Engineering Research Center, 1984. Shore Protection Manual. U.S. Army Corps of Engineers, Vicksburg, Misissippi, 3 vol.

Connell, J.H., 1961. The influence of interspecific competition and other factors on the distribution of the barnacle Chthamalus stellatus. Ecology, vol. 42, pp710-723.

Connell, J.H., 1972. Community interactions on marine rocky intertidal shores. Ann. Rev. Ecol. Syst., vol. 3, pp. 169-192.

Cowardin, L.M., V. Carter, F.C. Golet, & E.T. LaRoe, 1979. Classification of wetlands and deepwater habitats of the United States. U.S. Fish and Wildlife Service. FWS/OBS-79/31.

Daly, M.A. & A.C. Mathieson, 1977. The effects of sand movements on intertidal seaweeds and selected invertebrates at Bound Rock, New Hampshire, USA. Mar. Biol., vol. 43, pp. 45-55.

Davis, J.A., & L.A. Barmuta, 1989. An ecologically useful classification of mean and near-bed flows in streams and rivers, Freshwater Biol., vol. 21, pp.271-282.

Davies, J.L., 1980. Geographical Variation in Coastal Development. Edinburgh: Oliver and Boyd, 212p.

Dayton, P.K., V. Currie, T. Gerrodette, B.D. Keller, R. Rosenthal, & D. VenTresca, 1984. Patch dynamics and stability of some California kelp communities. Ecol. Monogr., vol. 54, pp. 253-289.

Denny, M.W., T.L. Daniel, M.A.R. Koehl, 1985. Mechanical limits to size in wave-swept organisms. Ecol. Monogr, vol. 55, no. 1, pp. 69-102.

Denny, M.W., 1988. Biology and the mechanics of the wave-swept environment. Princeton University Press, Princeton, New Jersey, 329 pp.

Denny, M.W., 1995. Predicting physical disturbance: mechanistic approaches to th study of survivorship on wave-swept shores. Ecological Monographs 65:371-418.

Dethier, M.N., 1990. A marine and estuarine habitat classification system for Washington State. Washington Natural Heritage Program, Dept. Natural Resources, Olympia, WA., 56 pp.

Domeracki, D.D., L.C. Thebeau, C.D. Getter, J.L. Saad, & C.H. Ruby, 1981. Sensitivity of Coastal Environments and Wildlife to Oil, Shelikof Strait Region, Alaska. Final report to OCSEAP, RPI report 81/2/10-4, Minerals Management Service, 132 pp.

Dufrene, M., and P. Legendre 1997. Species assemblages and indicator species: the need for a flexible asymmetrical approach. Ecological Monographs 67:345-366.

Duggins, D. & M.N. Dethier, 1985. Experimental studies of herbivory and algal competition in a low intertidal habitat. Oecologia, Vol. 67, pp 183-191.

Eckman, J. E., D. O. Duggins, and A. T. Sewell. 1989. Ecology of understory kelp environments. I. Effects of kelps on flow and particle transport near the bottom. J. Exp. Mar. Biol. Ecol., 129:173-187.

Environmental Systems research Institute, Inc., 1996. Using ArcView GIS. ESRI, Redlands CA, 350 pp.

Foster, M.S., 1990. Organization of macroalgal assemblages in the Northeast Pacific: the assumption of homogeneity and the illusion of generality. Hydrobiologia, vol. 192, pp. 21-33.

Foster, M.S., A.P. De Vogelaere, C. Harrold, J.S. Pearse, & A.B. Thum, 1988. Causes of spatial and temporal patterns in rocky intertidal communites of central and northern California. California Academy of Sciences, San Francisco, California, 45 pp.

Fox, D., A. Merems, B. Miller, M. Long, J. McCrae, & J. Mohler, 1994. Oregon rocky shores natural resource inventory. A report for the Oregon Department of Fish and Wildlife, Newport, OR, 168 p.

Frechette, M., and E. Bourget, 1985. Energy flow between the pelagic and benthic zones: factors controlling particulate organic matter available to an intertidal mussel bed. Canadian Journal of Fisheries and Aquatic Sciences, 42:1158-1165.

French, D.P., 1991. Quantitative mapping of coastal habitats and natural resource distributions: Application to Narragansett Bay, Rhode Island. Coastal Zone '91. p. 407-415.

Gordon, N.D., T.A. McMahon, & B.L. Finlayson, 1992. Stream hydrology: An introduction for ecologists. John Wiley & Sons, New York, 526 p.

Guza, R.T., 1988. Comment on "Kinematic and dynamic estimates from electromagnetic curent meter data" by D.G. Aubrey and J.H. Trowbridge. Journal of Geophysical Rsearch, Vol. 93, No. C2, pp. 1337-1343.

Harper, J.R., D.E. Howes, & P.D. Reimer, 1991. Shore-zone mapping system for use in sensitivity mapping and shoreline countermeasures. Proceedings of the 14th Arctic and Marine Oilspill Program (AMOP), Environment Canada, p. 509-523.

Hayes, M., 1980. Oil spill vulnerability and coastal morphology. Final report for Outer Continental Shelf Environmental Assessment Program, Minerals Management Service, pp. 431-538.

Holland, K.T., B. Raubenheimer, R.T. Guza, & R.A. Holman, 1995. Runup kinematics on a natural beach, Journal of Geophysical research, Vol. 100, No. C3, pp. 4985-4993.

Holman, R.A., 1986. Extreme value statistics for wave runup on a natural beach. Coastal Engineering, vol. 9, pp 527-544.

Holman, R.A., A.H. Sallenger Jr., T.C. Lippman, & J.W. Haines, 1993. The appliction of video imaage processing to the study of nearshore processes. Oceanography, Vol. 6, No. 3, pp. 78-85.

Howes, D., J. Harper, & E. Owens, 1994. British Columbia physical shore-zone mapping system. British Columbia Ministry of the Environment, 71 pp.

Hurlbert, S.H., 1984. Pseudoreplication and the design of ecological field experiments. Ecol. Monogr., vol. 54, no. 2, pp. 187-211.

Inman, D.L., & C.E. Nordstrom, 1971. On the tectonic and morphological classification of coasts. Journal of Geology, vol. 70, pp. 1-21.

Johansen, H.W., 1972. Effects of elevation changes on benthic algae in Prince William Sound. Pp 35-68 in The great Alaska earthquake of 1964. K.B. Krauskopf, chairman. Biology. Natl. Acad. Sci., Pub. 1604, Washington, D.C.

Komar, P.D, 1997. Beach processes and sedimentation 2nd ed. Prentice-Hall, Upper Saddle River, NJ, 544 pp.

Kozloff, E.N., 1993. Seashore life of the Northern Pacific coast. University of Washington pPess. Seattle, WA., 359p.

Legendre, P., M. Troussellier, V. Jarry, & M. Fortin, 1989. Design for simultaneous sampling of ecological variables: from concepts to numerical solutions. Oikos, vol. 55, pp. 30-42.

Lesser, M. P., J. D. Witman, and K. P. Sebens, 1994. Effects of flow and seston availability on scope for growth of benthic suspension-feeding invertebrates from the Gulf of Maine. Biological Bulletin, 187:319-335.

Lewis, J.R. 1964. The ecology of rocky shores. Engl. Univ. Press Ltd, London.

Littler, M.M., D.R. Martz & D.S. Littler, 1983. Effects of recurrent sand deposition on rocky intertidal organisms: importance of substrate heterogeneity in a fluctuating environment. Mar. Ecol. Prog. Ser., vol. 11, pp. 129-139.

Lobban, C.S., & P.J. Harrison, 1994. Seaweed ecology and Physiology. Cambridge University Press, New York, 365 pp.

McLachlan, A. 1990. Dissipative beaches and macrofauna communities on exposed intertidal sands. Journal of Coastal Research, 6:57-71.

Menge, B.A. 1991. Relative importance of recruitment and other causes of variation in rocky intertidal community structure. J. Exp. Mar. Biol. Ecol., vol. 146, pp. 69-100.

Menge, B.A., L.R. Ashkenas & A. Matson, 1983. Use of artificial holes in studying community development in cryptic marine habitats in a tropical intertidal region. Mar. Biol., vol. 77, pp. 129-142.

Menge, B.A. & T.M. Farrell, 1989. Community structure and interaction webs in shallow marine hard-bottom communities: tests of an environmental stress model. Adv. Ecol. Res., vol. 19, pp. 189-262.

Menge, B.A. & A.M. Olson, 1990. Role of scale and environmental factors in regulation of community structure. Tree, vol. 5, pp. 52-57.

Menge, B.A., B. Daley, P.A. Wheeler, and P.T. Strub, 1997. Rocky intertidal oceanography: An association between community structure and nearshore phytoplankton concentration. Limnol. Oceanogr., 42:57-66.

Michel, J., M.O. Hayes and P.J. Brown, 1978. Application of an oil spill vulnerability index to the shoreline of Lower Cook Inlet, Alaska. Environmental Geology, pp. 107-117.

Michel, J. & M.O. Hayes, 1991. Geomorphological controls on the persistence of shoreline contamination from the Exxon Valdez oil spill. A report prepared for the Hazardous Materials Response Branch, National Oceanic and Atmospheric Administration, Seattle, WA. 346 pp.

Morris, M., J.R. Harper, P.D. Reimer, H.R. Frith and D.E. Howes, 1995. Coastal biotic mapping system using aerial video imagery. In Proceedings of the Third Thematic Conference on Remote Sensing for Marine and Coastal Environments, Seattle, WA, pp. 200-210.

Mumford, T.F., D.J. Saul, J.A. Shaffer, A Bailey, E. Calvert, E. Lanzer, T. Manning, and R.M. Thom, 1992. Implementation plan for the characterization of Puget Sound nearshore habitats. A report for U.S. Environmental Protection Agency and the Puget Sound Water Quality Authority, Olympia, WA 41 p.

National Research Council, 1995. Understanding marine biodiversity. National Academy Press, Washington, D.C., 119 pp.

Ormond, R. F. G., and S. A. Banaimoon. 1994. Ecology of intertidal macroalgal assemblages on the Hadromout coast of southern Yemen, an area of seasonal upwelling. Marine Ecology Progress Series, 105:105-120.

Owens, E. H., 1982. Mapping of coastal characteristics: in Schwartz, M. L., 1982. The encyclopedia of beaches and coastal environments. Hutchinson Ross, New York. 940 pp.

Paine, R.T., 1974. Intertidal community structure: experimental studies on the relationship between a dominant competitor and its principal predator. Oecologia, vol. 15, pp. 93-120.

Paine, R.T., 1980. Food webs: Linkage, interaction strength and community infrastructure. J. Anim. Ecol., vol. 49, pp. 667-685.

Paine, R.T. & S.A. Levin, 1981. Intertidal landscapes: disturbance and the dynamics of pattern. Ecol. Monogr., vol. 51, pp. 145-178.

Pethnick, J., 1984. An introduction to coastal geomorphology. E. Arnold Publishers, London, 260 pp.

Pettijohn, F.J., 1949. Sedimentary rocks. Harper, New York, 526 pp.

Raimondi, P.T., 1988. Rock type affects settlement, recruitment, and zonation of the barnacle Chthamalus anispoma Pilsbury. J. Exp. Mar. Biol. Ecol., vol. 123, pp. 253-267.

Roughgarden, J., S. Gaines, & H. Possingham, 1988. Recuitment dynamics in complex life cycles. Science, vol. 241, pp. 1460-1466.

Sallenger, A.H., P.C. Howard, C.H. Fletcher, & P.A. Howd, 1983. A system for measuring bottom profile, waves and currents in the high energy nearshore environment, Marine Geology, Vol. 51, no. 183, pp. 63-76.

Sanford, E., D. Bermudez, M. D. Bertness, and S. D. Gaines. 1994. Flow, food supply and acorn barnacle population dynamics. Marine Ecology Progress Series, 104:49-62.

Santelices, B. 1990. Patterns of reproduction, dispersal and recruitment in seaweeds. Oceanogr. Mar. Biol. Ann. Rev., Vol. 28, pp. 177-276.

Schoch, G.C., 1994. Geomorphological shoreline classification and habitat sensitivity analysis for Katmai National Park and Preserve, Alaska. 1994 Proceedings, The Coastal Society, The Fourteenth International Conference, Charleston, SC, 4 pp.

Schoch, G.C., & M.N. Dethier, 1996. Scaling up: the statistical linkage between organismal abundance and geomorphology on rocky intertidal shorelines. J. Exp. Mar. Biol. Ecol.

Schoch, G. C., & M. N. Dethier, 1997. Biophysical coupling in marine ecosystems: examining issues of intertidal community variability and scaling. A report to the Washington Department of Natural Resources, Olympia, WA, 64 pp.

Seapy, R.R., & M.M. Littler, 1978. The distribution, abundance, community structure, and primary productivity of macroorganisms from two central California rocky intertidal habitats. Pacific Science, vol. 32, no. 3, pp. 293-314.

Searing, G.F. and H.R. Frith, 1995. British Columbia Biological Shore-Zone Mapping System. Contract Report by LGL Ltd., Sidney, B.C. to the Land-Use Coordination Office, Victoria, B.C., 46 pp.

Shepard, F.P. 1976. Coastal classification and changing coastlines. Geoscience and Man, vol. 14, pp. 53-64.

Shih, S.M., P.D. Komar, K.J. Tillotson, W.G. McDougal, & P. Ruggiero, 1994. Wave runup and sea cliff erosion. Coastal Engineering 1994 Proceedings, 24th International Conference, Kobe, Japan, pp 2170-2184.

Sindeman, C.J., 1988. Biological indicators and biological effects of estuarine/coastal pollution. Water Resources Bulletin, vol. 24, No. 5, pp. 931-939.

Snead, R.E., 1982. Coastal landforms and surface features, a photographic atlas and glossary. Hutchinson Ross, 235 pp.

Steneck, R.S. and M.N. Dethier 1994. A functional group approach to the structure of algal dominated communities. Oikos 69:476-498.

Strickland, J.D.H. & T.R. Parsons, 1972. A practical handbook of seawater analysis, 2nd ed.. Fish Res. Bd. Canada Bull. Vol. 176, 310 p.

Tillotson, K.J., 1995. Wave climate and storm systems on the Pacific Northwest Coast: M.S. Thesis, Oceanography, Oregon State University, Corvallis, OR. 138 pp.

Underwood, A.J., & P. Jernakoff, 1984. The effects of tidal height, wave exposure, seasonality and rock-pools on grazing and the distribution of intertidal macroalgae in New South Wales. J. Exp. Mar. Biol. Ecol., vol. 75, pp. 71-96.

Van Der Meer, J.W., & C.J.M. Stam, 1992. Wave runup on smooth and rock slopes of coastal structures. Journal of waterway, port, coastal and ocean engineering. vol. 118, pp. 534-550.

Vitousek, P.M., H.A. Mooney, J. Lubchenko, & J.M. Melille, 1997. Human Domination of Earth's Ecosystems. Science, vol. 277, pp 494-500.

Wethey, D.S. 1985. Catastrophe, extinction, and species diversity: a rocky intertidal example. Ecology, vol. 66, pp. 445-456.

Wright, L.D., A.D. Short, 1983. Morphodynamics of beaches and surf zones in Australia: in CRC Handbook of coastal processes and erosion, P.D. Komar ed.,CRC Press, Boca Ratin, Florida, pp. 35-64.