NATURAL RESOURCES

LANDSLIDE INVENTORY OF PORTIONS OF SNOHOMISH COUNTY, WASHINGTON

by Katherine A. Mickelson, Trevor A. Contreras, Mitchell D. Allen, Kara E. Jacobacci, Emilie M. Richard, William N. Gallin, Kara Fisher, and Gabriel Legoretta Paulín

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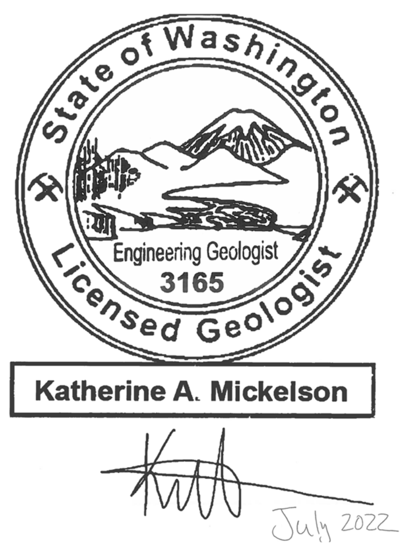

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ABSTRACT

An updated inventory of landslides was produced by interpreting 1,663 mi^2 of lidar data in western Snohomish County. Following published protocols, mapping yielded 6,171 landslides, 7,145 fans, and 1,289 rockfall deposits. Through a review of orthophotos and historical data, 396 recent landslides were identified and mapped as points. High landslide density was noted along Puget Sound bluffs, river corridors, and in upland areas of the Cascade Range. This updated landslide inventory will increase awareness of landslide hazards in western Snohomish County and provide information for planners, emergency managers, public works departments, and those who live or work where landslides could impact their daily lives.

INTRODUCTION

Landslides are among the most commonly occurring and devastating natural hazards in Washington State. In the previous 30 years, the state has experienced numerous destructive landslides, including the 2014 SR-530 "Oso" landslide that took 43 lives. The 1998 Aldercrest–Banyon and 1999 Carlyon Beach landslides damaged or destroyed 138 houses near Kelso (Wegmann, 2006) and 41 houses near Olympia (GeoEngineers Inc., 1999), respectively. Thousands of shallow landslides initiated as a result of winter storms in 1996–1997, 2007, and 2009 (Baum and others, 1998; Sarikhan and others, 2008; Sarikhan and others, 2009, respectively).

In densely populated areas, landslides are of particular interest as landowners continue to develop on or adjacent to steep slopes, despite landslide risk. As populations move to undeveloped portions of Snohomish County, hazards such as unrecognized landslides and fans pose an increased risk to lives and property. Those living on or adjacent to an existing landslide or fan are often unaware of the hazards and the potential consequences of landslide (re)activation.

Landslide inventories identify areas that have likely experienced landslides, rockfall, and flooding in the past. Areas that have experienced these hazards are more susceptible to experiencing them in the future. This inventory has been prepared by geologists trained in identifying landslide hazards, using the best available science.

This report and the accompanying GIS data available for download on the Washington Geologic Information Portal provide information about the landslides, rockfall, and fans mapped in Snohomish County.

INTENDED USE

Landslide inventory data assist planners, emergency managers, public works departments, and those who live and work where landslides could impact their daily lives by identifying areas that have likely experienced landslide hazards in the past. Some examples of uses include:

- Public works—A landslide inventory can identify areas where underground utilities or transportation networks may be impacted. Areas with a history of maintenance issues may benefit from a review of the landslide inventory, which may identify previously unrecognized landslide hazards.
- Planning—Landslide inventory mapping can identify areas where proposed land use intersects landslide hazards. These areas need additional geotechnical review to ensure that the proposed land use will not be adversely impacted by the landslide hazard(s). Improperly graded slopes and (or) disturbances of sensitive geological materials may contribute to destabilization. Poor surface-water management can reactivate old landslides, affecting not just one home or business but potentially an entire neighborhood.
- Emergency management—Access to landslide inventory mapping can help emergency managers assess the likelihood that a reported incident may be landslide related. When planning evacuation routes (such as for a tsunami or lahar), roads that cross existing landslides should be avoided due to an increased likelihood of landslide reactivation, which may block or hinder emergency response and (or) evacuation routes. During intense precipitation events, roads that cross fans may be impassable due to flooding and debris on the roadway.

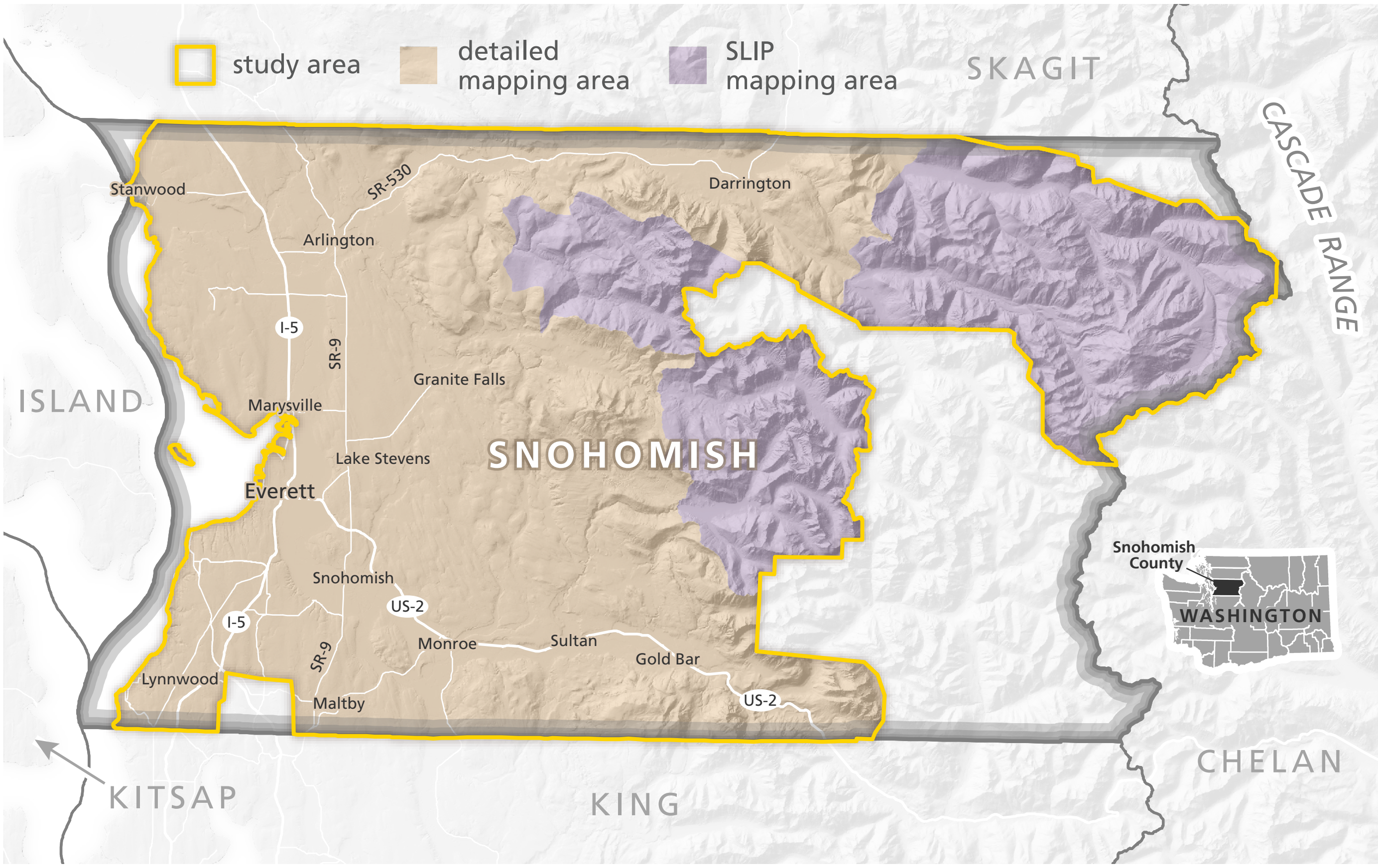

Figure 1. Study area for the Snohomish County landslide mapping project, showing areas mapped in detail and areas mapped using the Streamlined Landslide Inventory Protocol (SLIP). Managed timberlands, federally managed lands, and large areas with poor-quality lidar were excluded from the study area.

- Public—Individuals purchasing or renting property or a home, or currently living on or near a landslide, should be aware of landslide hazards. It is critical that the public manages storm water and runoff on their property and recognizes the signs of potential landslide activity. During intense or prolonged precipitation events, homes and roads on fans may be impacted by flooding and debris. Hazards on fans may also be temporarily increased downstream of areas impacted by wildfires.

In Washington, city or county governments regulate land-use planning. While the Washington Geological Survey (WGS) updates landslide inventories to ensure that city and county planners have the best data available to them, WGS does not revise building codes or evaluate development permits. Those decisions are controlled by county- and city-level governments. For more information on land-use planning, please consult your local jurisdiction's planning office.

STUDY AREA

WGS prioritizes landslide mapping in areas with high population density, dense infrastructure, and high-quality lidar coverage. The 1,663 mi^2 study area for Snohomish County covers the western 76 percent of the county (Fig. 1). Most managed timberlands, federally managed lands, and large areas with poor-quality lidar are excluded from the study area.

METHODS

Lidar

Lidar collected between 2003 and 2017 covers the study area. Table 1 summarizes the lidar datasets used and their specifications. Where datasets overlapped, data with the greatest number of pulses per square meter were used to identify and map landslides. In some cases, this may not have been the most recent dataset.

Lidar-derived Digital Elevation Models (DEMs) were processed to create slope gradient maps for each dataset. Following the protocol of Slaughter and others (2017), geologists trained in landslide identification used these layers to interpret and delineate landslides. Orthoimages taken between 1990 and 2020 also aided in interpretation of lidar data and in distinguishing man-made features from natural geomorphic features and recent landslide activity.

Landslide Mapping

Detailed landslide mapping was performed in the majority of the study area (1,163 mi^2), while Streamlined Landslide Inventory Protocol (SLIP) mapping was used primarily in U. S. Forest Service (USFS) and Washington Department of Natural Resources (DNR) lands (500 mi^2). The differences between detailed and SLIP landslide mapping are discussed in the following sections.

DETAILED LANDSLIDE INVENTORY MAPPING

We followed the landslide inventory mapping protocol of Slaughter and others (2017), a slight modification of Burns and Madin (2009). The detailed mapping area covers approximately 1,669 mi^2, focusing on areas with population and infrastructure (Fig. 1). Geologists digitized landslides from lidar derivatives and mapped the deposit, scarp(s), and flank(s) (Fig. 2). If present, one or more internal scarps were digitized. The landslide deposits were assigned unique identification numbers along with 16 attributes, including material, movement type, identification confidence, age, year of movement (if known), field verification, slope degrees, headscarp height, failure depth, movement azimuth, and average scarp distance. For more details about these attributes, refer to Slaughter and others (2017).

Alluvial and (or) debris-flow fans were mapped where cone-shaped deposits were visible on the lidar at the mouth of a drainage (Fig. 3). Sediment on the fan is deposited by streams, floods, and (or) debris flows and is typically sourced from a single channel. Mapped fan deposits were assigned unique identification numbers along with attributes, including identification confidence, age, year of movement (if known), field verification, slope degrees, fan height, area, and volume.

Rockfall deposits are generally found below steep slopes or cliffs where weathered bedrock falls onto an area of deposition. The rockfall deposit polygon is created by outlining this area of deposition and adding a scarp line that depicts the uphill edge of the area from which the rock is falling (Fig. 4). Geologists use a combination of orthoimagery and lidar to digitize rockfall deposits and scarps. Mapped rockfall deposits were assigned unique identification numbers along with attributes, including identification confidence, age, year of movement (if known), field verification, slope degrees, area, and volume.

Field verification, performed on approximately five percent of mapped landslides and fans, was focused on landforms that were difficult to interpret from lidar and were in, or around, populated areas and (or) infrastructure. In the field, any visible landslide indicators (such as headscarps, sag ponds, internal cracks, springs or seeps, and pistol-butted trees) were noted. Recorded observations are considered in the final determination of landslide confidence. Mapped rockfall hazards were not field verified during this mapping effort.

Recent landslides were also identified in the detailed mapping area using the established protocol (Slaughter and others, 2017). Geologists reviewed and compared orthoimagery from various years, along with historical data, to compile recent landslide points. These points record landslides that may not be visible in lidar but are visible in orthoimagery. Alternately, some landslides are reported from field observations alone.

After the completion of mapping, a licensed engineering geologist provided quality control by reviewing the entire landslide inventory and associated attributes. External review was also performed on this landslide inventory. This process was conducted for both the detailed and SLIP mapping.

STREAMLINED LANDSLIDE INVENTORY PROTOCOL (SLIP) MAPPING

The SLIP method of Slaughter and others (2017) differs from detailed landslide mapping protocols by including only a landslide or fan identification number and the geologist's confidence of the landform's presence. Landslides are delineated by a polygon that encompasses the entire landslide (a combination of headscarp, internal scarps, flanks, and body). This protocol is an effective method to quickly and accurately map landslides in areas that are generally unpopulated but may contain significant infrastructure. SLIP mapping for this project focused on a 500 mi^2 area (Fig. 1) that includes USFS and DNR lands.

Table 1. Lidar projects used in landslide interpretation. All lidar data were obtained from the WGS Lidar Program repository (https://lidarportal.dnr.wa.gov/). More details about each dataset are provided in the References.

Lidar Project	Year Collected	Lidar Ground Returns (Pulses/m^2)	Raster Grid Size (ft)
Darrington	2003	unknown	6
King County	2003	unknown	6
Snohoco Northwest	2003	unknown	6
Snohoco Southwest	2003	unknown	6
Snohoco Skykomish	2003	unknown	6
Snohoco Snoqualmie	2004	unknown	6
Snohoco Sauk River	2005	unknown	6
Snohomish	2005	unknown	6
North Puget USGS	2006	unknown	3
Snohoco East	2006	unknown	6
Snohoco West	2006	unknown	6
Snohoco Hat Island	2006	unknown	6
Snohoco Hazel	2006	unknown	6
Snohoco Index Galena	2007	unknown	3
Snohomish River	2009	6.97	3
Glacier Peak	2010	9.31	3
Tulalip	2013	11.43	3
Snohoco Railway	2013	9.54	3
Stillaguamish	2014	13.8	3
Cedar River A	2014	12.41	3
Snohoco Oso A	2014	12.57	3
Snohoco Oso B	2014	unknown	3
Snohoco Oso C	2014	unknown	3
Glacier Peak	2015	27.05	3
North Puget	2017	12.29	3

RESULTS AND CONCLUSIONS

The new landslide inventory includes both detailed and SLIP landslide and fan mapping. Rockfall was only mapped in the detailed area. SLIP mapping focused on USFS and DNR land

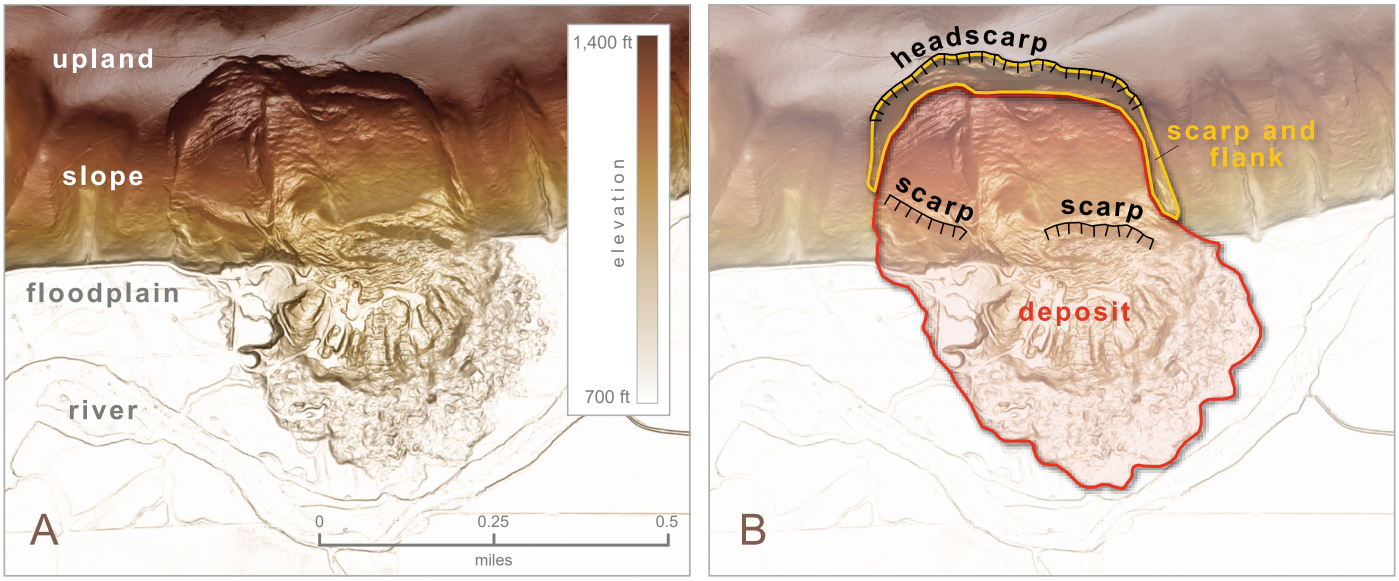

Figure 2. **A.** An example of the geomorphic expression of a landslide using lidar. **B.** Digitized components of the landslide. See Appendix A for information about landslide data in GIS format.

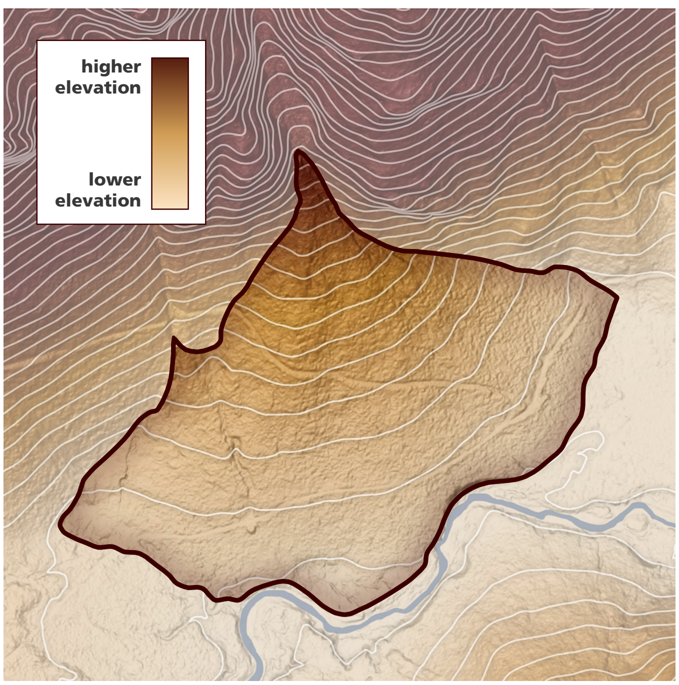

Figure 3. An example of a mapped fan deposit (dark brown line) with 40-ft contours to better distinguish the depositional surface from the valley bottom.

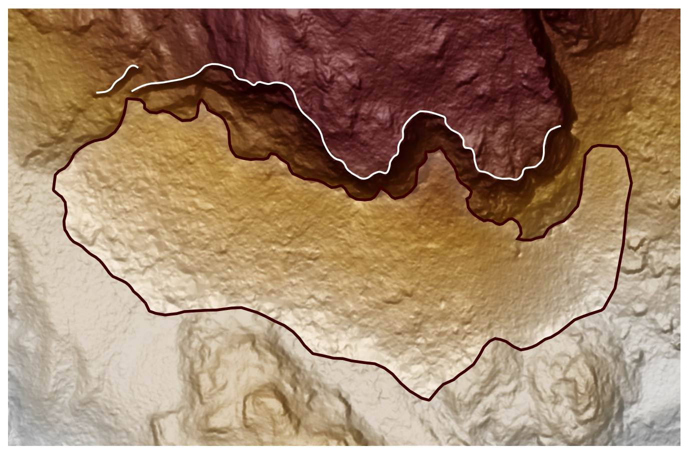

Figure 4. An example of a mapped rockfall deposit (dark brown line). White lines indicate rockfall source areas (scarps).

where landslide reactivation has the potential to degrade water quality and critical salmon habitat, compromise public and private infrastructure, and pose a downstream threat to life and safety.

The inventory contains 15,001 landslide, fan, and rockfall deposits. The number of individual landforms mapped is displayed in Table 2. In the detailed mapping area, 458 landslides (11%) and 580 fans (13%) are historical, meaning that all or portions of these landforms slid or reactivated in the past 150 years.

High landslide density was noted along Puget Sound bluffs, river corridors, and in upland areas of the Cascade Range. Debris flows and floods occur episodically in western Snohomish County and pose a significant hazard to people and infrastructure on fans during intense and prolonged rainfall, especially when this rain melts snow in the uplands.

The mapped landslide, fan, and rockfall hazards were incorporated into the Washington State Landslide Inventory Database (WASLID) (see Appendix A). This dataset is displayed and available for download on the Washington Geologic Information Portal (http://www.dnr.wa.gov/geologyportal).

High-quality hazard maps and dissemination of information about landslide hazards are essential to the establishment of a landslide hazard reduction program. This updated landslide inventory will help inform communities in Snohomish County about landslide hazards so that they may become more resilient to these events. People living on landslides may recognize the potential hazard and take appropriate actions to reduce the likelihood of reactivation or impacts of landslide activity. Planners can use the new data to guide land-use decisions when updating hazard ordinances and local building codes. By identifying areas that may need further site-specific investigations and mitigation, planners can also use these hazard maps to evaluate the risk to people and property when considering future development.

Table 2. Landslide inventory results for Snohomish County, showing how many of each feature type were mapped.

Feature	Total Number of Features Mapped
Landslides	4,207
Fans	4,536
Rockfall	1,289
Recent landslide points	396
SLIP landslides	1,964
SLIP fans	2,609

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Appendix A. Landslide Inventory Data

An Esri file geodatabase containing the mapped landslides, fans, and rock fall areas is available for download from the Washington Geological Survey website (https://www.dnr.wa.gov/programs-and-services/geology/publications-and-data/gis-data-and-databases). It is also viewable on the interactive Washington Geologic Information Portal (https://geologyportal.dnr.wa.gov). Note that this geodatabase is a combined dataset. It contains landslide data for all the counties in Washington that have already been inventoried. The combined inventory is known as the Washington State Landslide Inventory Database (WASLID). WASLID contains both detailed mapping (conducted using the protocol referred to in this publication), and a compilation of other landslides mapped by various groups and for various purposes over the past few decades. These compiled landslides were not mapped using the protocol of Slaughter and others (2017).