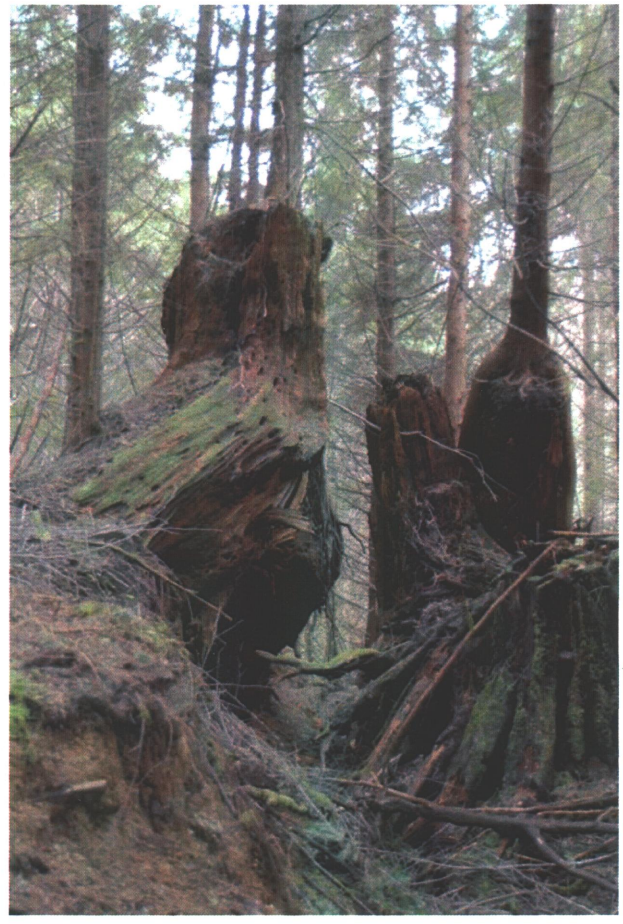
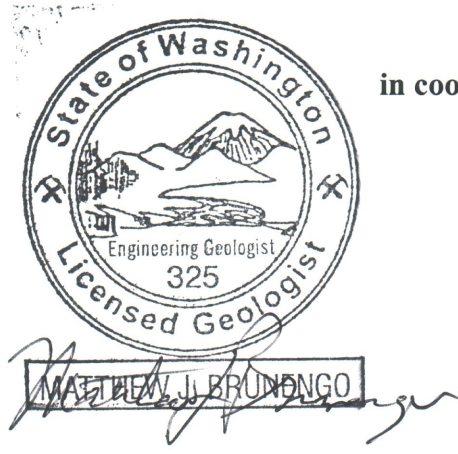
# Skamokawa
## LANDSLIDE HAZARD ZONATION PROJECT
## Wahkiakum County, Washington

**Prepared By**
**Eric L. Bilderback and Matthew J. Brunengo**






**Forest Practices Division,**
**Adaptive Management Program**
**in coordination with the Washington Division**
**of Geology and Earth Resources**

**Priority 3**
**Mass Wasting Assessment**
**January 2007**

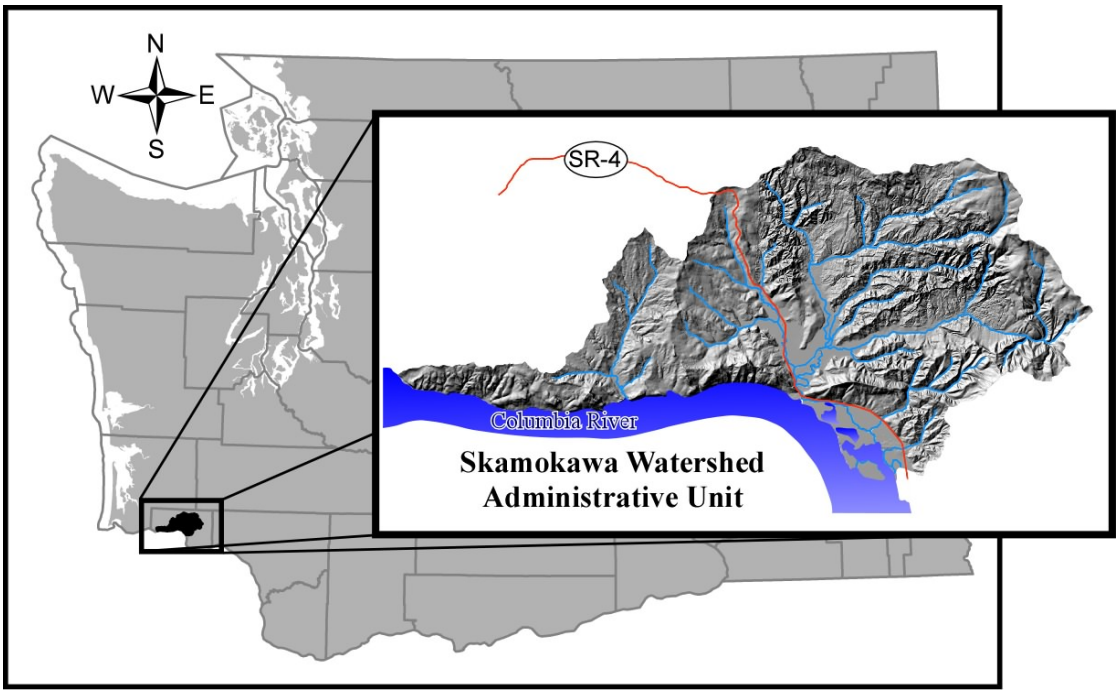
WASHINGTON STATE DEPARTMENT OF
**Natural Resources**
Doug Sutherland - Commissioner of Public Lands

# Washington State Department of Natural Resources

**Forest Practices Division**
PO Box 47012
Olympia, WA 98504-7012
*Phone:* 360-902-1400
*Fax:* 360-902-1428

**Division of Geology and Earth Resources**
PO Box 47007
Olympia, WA 98504-7007
360-902-1450
360-902-1785

*Web sites:* http://www.dnr.wa.gov/forestpractices/lhzproject
http://www.dnr.wa.gov/forestpractices/adaptivemanagement
http://www.dnr.wa.gov/geology/




**DISCLAIMER**
Neither the State of Washington, nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the State of Washington or any agency thereof. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the State of Washington or any agency thereof.

## CONTENTS

**1.0 Project Summary** ..... 1

**2.0 Introduction and Summary of Methods** ..... 3

**3.0 Study Area** ..... 5

**4.0 Summary of Landslide Inventory** ..... 11

**5.0 Landforms** ..... 12

**6.0 Hazard Ratings**…..... 13

**7.0 Confidence in Work Products** ..... 14

**8.0 Acknowledgments** ..... 15

**9.0 References** ..... 16

**Appendix A – Landslide Inventory: Form A-1** ..... 18

**Appendix B – Landform Descriptions: Form A-2** ..... 42

**Appendix C – Mass Wasting Descriptions: Form A-3** ..... 52

**Appendix D – Landform Hazard Rating Table: Form A-4** ..... 57

**Appendix E – Geology of the Skamokawa Area** ..... 58

**Appendix F – Vegetation, Land-Use and Historic Considerations** ..... 61

**Appendix G – Detailed Air Photo List** ..... 64

## 1.0 Project Summary

The ***Skamokawa watershed administrative unit*** (WAU) is located in the southwest corner of the Willapa Hills along the north bank of the Columbia River. The WAU covers 48,142 acres (about 75 $mi^2$), including the entire catchments of Skamokawa and Jim Crow creeks plus the basins of several small streams that drain into the Columbia along the bluffs separating the Skamokawa catchment from the Columbia.

The wet temperate maritime climate of the WAU is typical of the Pacific Northwest coast. Average annual precipitation ranges from about 70–90 in. at the coast and along the Columbia, to about 120–140 in. on the uplands. Most of the precipitation falls between October and April; rain is dominant in this region, although some snow falls during about half the winters even in the lowlands. The region is also susceptible to hurricane-force windstorms that can cause significant blowdown of forest trees, most notably the Columbus Day Storm of 1962.

The Willapa Hills are part of the Coast Ranges physiographic province, built on a basement of ocean floor volcanics overlain by volcanic and marine sedimentary rocks. Tectonic uplift created relief and has exposed the region to fluvial and mass-wasting processes in a wet climate for several million years, resulting in high erosion rates and deep subaerial weathering. Mass movement in the Willapa region includes small shallow landslides and debris flows as well as large deep-seated landslides.

Bedrock of the Skamokawa WAU falls into three broad categories which affect the geomorphology and the pattern of observed landslides; the rocks can be placed on a strength or resistance scale, inferred from the ways they affect landforms. The weakest sedimentary units, ***marine siltstones***, tend to form lower and gentler hills, except where they are deeply incised by streams. Bedrock hollows and inner gorges are only occasionally found in areas dominated by fine-grained siltstones. The main mass-wasting features of these weak rocks are large translational and combination translational-rotational deep-seated landslides, especially earthflows. The ***marine sandstones*** form comparatively high-relief uplands in the WAU that are characterized by large areas of deeply incised drainages separated by steep ridges. The ridge tops in marine sandstones tend to be deeply weathered to form convergent headwalls, bedrock hollows, and inner gorges that are the initiation points for many debris slides and flows. ***Basaltic volcanic rocks*** are strong enough to support the highest and most rugged mountains of the Willapa Hills province. Located between the Columbia River and the Skamokawa Creek basin and along the high ridges surrounding the WAU, they tend to form bedrock-capped ridges with deep weathering profiles. Many debris slides and debris flows originate on these high-relief ridges, occurring mostly within the weathered basalt. Bedrock hollows and associated inner gorges are also common in this unit.

Landslides in the Skamokawa WAU were observed on two sets of 1:12,000 aerial photographs from 1967 and 1999, and one set of 1:24,000 photos from 1978. Slope failures were classified and cataloged according to the mass-wasting processes that caused them. During this study a representative sample of 1222 landslides were inventoried from air photos, lidar, and field investigation. Of the landslides identified, 39% were mapped as shallow-undifferentiated failures, 18% as debris flows, 26% as debris slides and debris avalanches, and 17% as deep-seated landslides. (See Map A-1 and Appendix A.)

The air-photo survey and landslide inventory were also used to determine land use and to map ***rule-identified and analyst-described landforms***. USGS digital elevation models, lidar and other GIS products were used to map low-hazard flat and low gradient areas according to the LHZ protocol. The remaining land in the WAU was divided into analyst-described landforms. These land-

forms were delineated to identify areas that have similar mass wasting potential, potential to deliver wood, water and sediment to public resources, and potential to adversely affect public safety. They were developed from a series of iterative statistical analyses of landslide attributes including gradient, elevation, lithology, and slope shape at locations of landslide initiation. Each landform was assigned a landslide frequency rate (LFR), a landslide area rate for delivery (LAR), and an overall hazard rating as called for by the LHZ Protocol (Appendix D).

The distributions of the landforms identified during the Skamokawa LHZ study are shown on Map A-2 and are described in Forms A-2 (Appendix B). Rule-identified landforms present in the Skamokawa WAU, which were mapped independently of other high hazard landforms, include ***inner gorges, bedrock hollows, and toes of deep-seated landslides***. Analyst-described landforms in the study area include three landform units rated as very high hazard, described below:

***Highly incised terrain*** consists of high-relief uplands characterized by deeply incised drainages separated by steep ridges. Slopes in this large landform unit are steep; over half of the slopes are steeper than 50% and about a quarter are steeper than 70% (~2000 acres). Ridge tops in this unit tend to be deeply weathered, and the steep slopes are mantled by thin, poorly developed soils. This landform contains many convergent headwalls, bedrock hollows, and inner gorges that are the initiation points for many debris slides and debris flows. Almost 75% of the 467 landslides observed in this landform began in landforms that are rule-identified, based on air photos and GIS data. Many of the remaining landslides also probably start in rule-identified landforms that were obscured by canopy or fell below the resolution of the DEM. Because rule-identified convergent headwalls, bedrock hollows and inner gorges in this landform were too numerous to map individually in a reasonable time frame, they were grouped together into this landform. Thin soils that are not strongly anchored to incompetent, poorly consolidated, and weathered bedrock, along with abundant rainfall, make highly incised terrain susceptible to debris slides, debris flows, and other shallow landslides. While landslides occur on all slope forms in this landform, areas where surface or groundwater is concentrated, contributing to increased pore-water pressure in the soil are particularly susceptible to failure. Roots from trees that stand on steep slopes play a significant role in stabilizing the soils mantling bedrock in this landform.

***Steep bedrock-capped ridges*** are located between the Columbia River and the interior of the Skamokawa WAU and are mostly composed of (capped by) resistant volcanic flows and dikes that stand in high relief above underlying weaker bedrock units. Slopes in this landform are steep; more than two thirds of all the slopes are steeper than 50% and over one third are steeper than 70%. These bedrock ridges exhibit a deep weathering profile and tend to weather into low-cohesion soils with little internal strength. Many debris slides and flows originate on these high relief ridges with the slides occurring mostly within the weathering profile of the basalt. Bedrock hollows and associated inner gorges are common in this unit and were not mapped individually.

***Scarps of land-shaping deep-seated landslides*** are the head and lateral scarps of large relict deep-seated landslides that have shaped the topography and overall character of large sections of the Skamokawa WAU. These areas have been oversteepened due to past landslide motion, and are also the site of fractured and weakened bedrock at the exposed slip planes. These slopes are mantled by thin soils that are not strongly anchored to incompetent and weathered bedrock. Abundant rainfall makes scarps of land-shaping deep-seated landslides susceptible to debris slides, debris flows, and other shallow landslides. While landslides start on all slope forms in this landform, areas where surface or groundwater is concentrated, contributing to increased soil pore-water pressure, are particularly susceptible to failure. Roots from trees growing on these steep slopes play a significant role in stabilizing the soils mantling bedrock in this landform. Bedrock hollows and associated inner gorges can form in this unit, but were not mapped individually.

## 2.0 Introduction and Summary of Methods

### 2.1 Use of this report

The purpose of this mass wasting assessment is to identify areas within the Skamokawa watershed administrative unit (WAU) that have moderate to high risk of landsliding due to both natural phenomena and the effects of forest practices (logging, roading, yarding, etc.). All lands within the WAU have been divided into designated mass-wasting hazard landforms[1]. Maps of these landforms are designed for use by landowners in determining the areas likely to be susceptible to or experience landslide hazard, and by the Department of Natural Resources regional staff to identify sites where future forest-practice applications may require detailed investigation prior to classification (Chapters 222-20 and 222-16-050 WAC).

This assessment is a reconnaissance survey, and its relatively broad resolution must be considered when using this document and its accompanying maps. Moreover, the survey was conducted within a constrained timeline that was budgeted to produce a statewide unstable-slopes screening tool as quickly as possible. For this reason, it is likely that some landslides and unstable landforms have been overlooked, some benign features have been mistakenly mapped as landslides, and some landslides have been classified improperly. Thus, the landslide inventory presented in this report (Map A-1, Form A-1) is intended to be a representative but not necessarily complete inventory.

This analysis was largely conducted remotely using the best map and image-based resources available, supplemented by field visits to verify mapping results. However, we note that landslide inventories that are conducted primarily using air photos have been demonstrated to omit up to 85% of the landslides that actually exist on the ground in heavily forested terrain; furthermore, they tend to skew the majority of landslide occurrences toward clear-cuts because they are easier to spot in these areas than under canopy on air photos (Brardinoni and others, 2003).

Information was collected and compiled in a manner that was designed to respond to the critical questions that are outlined in Section II of the Landslide Hazard Zonation (LHZ) protocol, and to direct attention to areas where more detailed analysis is necessary. The chief objective of the data collection was to generate information sufficient to establish:

- A generalized characterization of mass-wasting processes that are active in the WAU;
- Areas of landscape that share similar physical characteristics related to mass-wasting behavior;
- The relative potential for mass wasting to occur among the various landform units.

No comprehensive analysis of slope stability had been conducted in the Skamokawa watershed prior to this investigation[2].

---

[1] *Landforms* as defined herein can be more inclusive than the small-scale unstable landforms defined in rule (WAC 222-16-050(i)), referred to as "rule-identified landforms". Mapped rule-identified landforms in the Skamokawa WAU include inner gorges, bedrock hollows, and toes of deep-seated landslides.

[2] Landslides in this basin were identified during geologic mapping (see Appendix E) and general slope-stability studies (e.g., Fiksdal and Brunengo, 1980, 1981). Landslides were inventoried and landforms were mapped for the watershed analysis of the North Elochoman WAU bordering the Skamokawa WAU to the east (Washington Department of Natural Resources, 1996). In addition, the Grays Bay WAU, bordering Skamokawa to the west, has been examined under this Landslide Hazard Zonation Project.

## 2.2 Methods

The procedures described below follow the Landslide Hazard Zonation Protocol version 2.0 (http://www.dnr.wa.gov/forestpractices/lhzproject/lhz_protocol_v2_final.pdf), with minor modification. Two sets of 1:12,000 aerial photographs (1967 and 1999), and one set of 1:24,000 (1978) photos were analyzed with a mirror stereoscope at 3x magnification (Table 1 and Appendix G). Other photo flight years were available from DNR's collection in Olympia, but these three photo sets were the most complete, spanned a large time frame, and were sufficient to develop a large landslide inventory. Most shallow landslides were mapped from air photos; however several were identified in the field that were not evident on the photos because they are either in areas of heavy canopy or are landslides that postdate the most recent photo set. Deep-seated landslides were mapped either from air photos or from the available lidar, and a small number were mapped from the USGS 10-meter digital elevation model (DEM).

**Table 1.** Aerial photographs used in this study.

| Year | Project ID | Scale | Image Type | Coverage of WAU |
|---|---|---|---|---|
| 1967 | WC-67 | 1:12,000 | black and white stereo | nearly complete |
| 1978 | SW-C-78 | 1:24,000 | color stereo | nearly complete |
| 1999 | SW-C-99 | 1:12,000 | color stereo | nearly complete |

Landslides observed on the photos were classified and catalogued according to the mass-wasting processes that caused them. For the purposes of this analysis, landslides that failed below rooting depth are categorized as deep-seated landslides (per the Forest Practices Board Manual); all remaining slides are classified as shallow landslides. Mass-wasting process types include shallow-undifferentiated landslides, debris flows, debris slides and avalanches, rock topples and falls, deep-seated landslides (including earthflows), and snow avalanches.

The mapped landslides were categorized according to their relative level of certainty as questionable, probable, or definite. Some combination of distinct headscarps, lateral margins, scoured runouts, oversteepened toes, obvious deposits with hummocky topography, or vegetation patterns indicating disturbance by movement were considered to be definite landslides. Features that were more subdued or concealed by vegetation made identification of them as landslides less than certain, and were thus considered to be probable landslides. Features that resemble degraded landslides but could also have been formed by processes other than mass movement were considered to be questionable (following Wieczorek, 1984 and Turner and Schuster, 1996).

Following stereo air-photo analysis, all observed landslides were mapped directly into GIS. Transfer of mapped features to a digital database was accomplished by "heads-up" digitization of landslides into a GIS map with layers that include streams, roads, townships, geology, limited high-resolution lidar coverage, and a USGS 10-m digital elevation model with DEM-derived contours, slope gradients, and hillshades. The landslides mapped in the Skamokawa WAU are presented on Map A-1 and tabulated in Appendix A.

Slope gradients for shallow landslides were determined by calculating the maximum DEM-derived slope angle within each landslide initiation polygon. For deep-seated landslides, the average slope angle over the entire landslide polygon was calculated. We found that using the average slope gradient for deep-seated landslides provides the quickest and most reasonable representation of the pre-failure slope surface, compared to other GIS slope measurement methods (Bilderback, 2006).

At the time of this survey, lidar was available for only about 31% of the study area. In these areas, the topographic resolution is about 1.8 m (6 ft). The remaining area of the map base has a maximum resolution of about 10 m (33 ft). Because lidar data are more accurate even at the same precision as the USGS 10-m DEM, the lidar was downsampled to equal the cell size of the USGS 10-m DEM and merged with that DEM to provide for a single combined elevation layer from which contours and slope gradients could be calculated. Slope gradients and elevations of small failures that were identified on high-resolution air photos are not accurately estimated by the 10-m DEM due to raster data smoothing. Typically, DEM-derived slope gradients are underestimated by at least 10% relative to field-measured gradients (Dragovich and others, 1993), and more so on smaller features that are smoothed over by the DEM's coarse resolution. Despite these limitations, the 10-m DEM was used in place of field measurements for the sake of expeditiousness to estimate the gradients of landslides. It should be emphasized that all slope gradient estimates presented in this report are likely to be minimal approximations.

The air-photo survey was also used to determine land-use and to map rule-identified landforms (inner gorges, bedrock hollows, etc.). Where possible, lidar was used in combination with air photos to map rule-identified landforms. The 10-m DEM and other GIS products were used to map low-hazard flat areas, ridgetops, and low-gradient hillslopes as prescribed by the LHZ Protocol. The remaining land in the WAU was divided into analyst-described landforms. These landforms were identified from primary driving forces of mass wasting based on physical attributes of the landscape such as slope gradient, elevation, annual precipitation, lithology, and slope convergence. We used a combination of data types in the designation of the analyst-described landform units, including: slope gradient and elevation (derived from the combined USGS and lidar 10-m DEM); slope convergence (from the DNR SLPSTAB model; Shaw and Johnson, 1995); geologic information (from digital versions of DGER 1:100,000 mapping); and precipitation and rain-on-snow magnitudes (from DNR GIS coverages). These landforms are intended to predict areas within the WAU that are at particularly high hazard of mass wasting. The landforms mapped in the Skamokawa WAU are presented on Map A-2 and described in Appendix B. Each landform was assigned a landslide frequency rate (LFR), a landslide area rate for delivery (LAR), and an overall hazard rating as called for by the LHZ Protocol (Appendix D).

## 3.0 Study Area

### 3.1 Location, Physiography, Climate

The Skamokawa[3] WAU is located in the southwest corner of the Willapa Hills along the northern bank of the Columbia River (Figure 1). The WAU covers 48,142 acres (about 75 $mi^2$), comprising the entire catchments of Skamokawa and Jim Crow creeks plus the basins of several small streams draining into the Columbia along the bluffs separating the Skamokawa catchment from the Columbia.

The Willapa Hills are part of the Coast Ranges physiographic province (see Muhs and others, 1987; Galster and others, 1989). They are built on a basement of Paleogene oceanic basalts overlain by Paleogene to Neogene volcanic and marine sedimentary rocks. Although parts of the Willapas are steep and rugged, most of the topography is generally more subdued, especially compared to the Olympics. Nevertheless, uplift in the Neogene to Quaternary has exposed the region to fluvial and mass-wasting processes in a wet climate for several million years, resulting in high

[3] Skamokawa means "smoke on the waters", and refers to the fog on the river, also the name of a Wahkiakum chief (Hitchman, 1985).

erosion rates and deep subaerial weathering. Mass movement in the Willapa region includes small shallow landslides and debris flows as well as large deep-seated landslides.

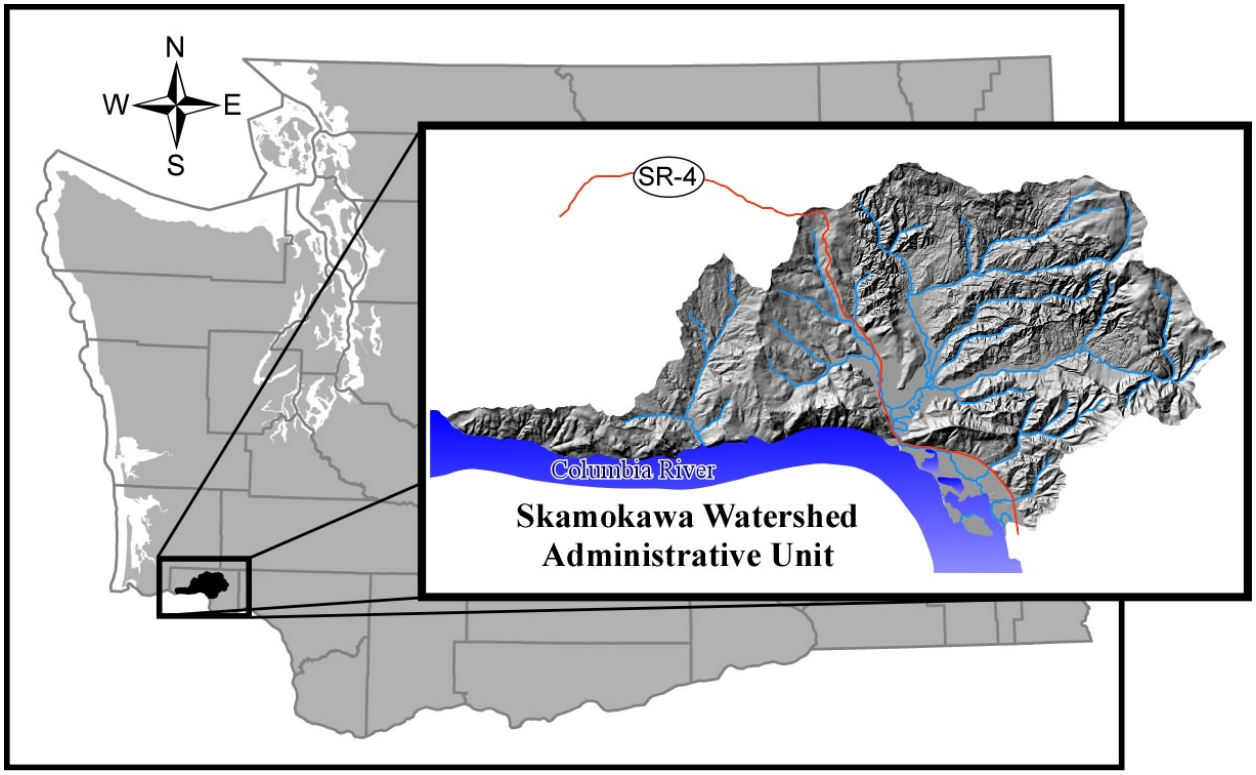



**Figure 1:** Location and terrain of the Skamokawa WAU.

The higher ridges around the basins surrounding Skamokawa are fairly accordant, at about 800–1200 ft elevation on the west side, to about 1500–2400 ft on the north and east sides. Local relief can exceed 1000 ft in the upper tributary canyons. Unconsolidated fluvial, estuarine and marsh sediments have been deposited along the larger river valleys, particularly along the Columbia River and in the lowlands around Skamokawa.

The wet temperate maritime climate of the WAU is typical of the Northwest coast.[4] Figure 2 shows time series of water-year precipitation at four weather stations in the region. Average annual precipitation ranges from about 70–90 in. at the coast and along the Columbia, to about 120–140 in. on the uplands. Most of the precipitation falls between October and April; rainfall is dominant in this region, although some snow falls in about half the winters even in the lowlands. The region is also susceptible to hurricane-force wind storms that can cause significant blowdown of forest trees, most notably the Columbus Day Storm of 12 October 1962.

Heavy and/or intense precipitation is significant in triggering landslides. The graph in Figure 2 shows that some years, and some periods, can be much wetter than average (e.g., 1965–76, 1981–84, the late 1990s), and others are relatively dry (1977, 1985–94, 2001). More than 30 in. can fall during a single month; individual storms can deliver >10 inches in 24 hr, which can be enhanced by snowmelt at higher elevations during rain-on-snow events.

[4] Data from Western Regional Climate Center, http://www.wrcc.dri.edu; and OSU Spatial Climate Analysis Service, PRISM precipitation maps, http://mistral.oce.orst.edu/www/mapserv.

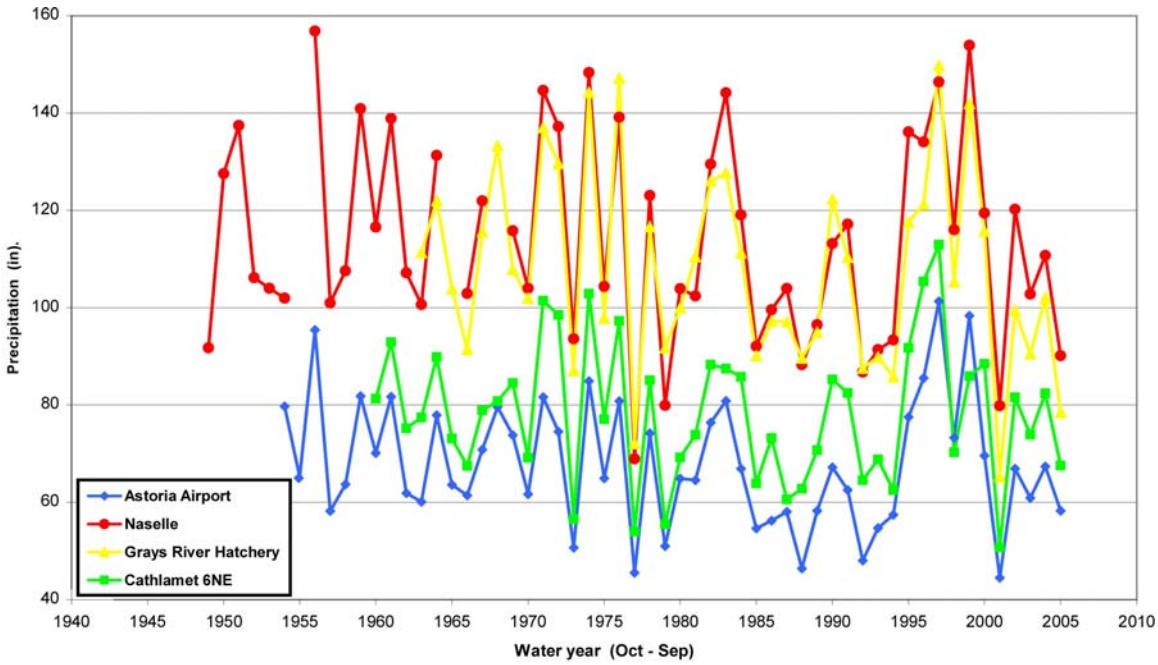



**Figure 2:** Record of precipitation from representative weather stations near Skamokawa WAU, from water years 1949 to 2005.

3.2 Geologic Effects on Slope Processes

Rock types, structure, and geologic history have great influence on slope processes in the Skamokawa WAU (see Appendix E). While uplift created relief, long-term weathering and erosion have carved it into prominent ridges and slopes. Intrinsic material strength, as well as the stratigraphic and structural juxtaposition of differing materials influence the patterns of resistance to erosion and thus the shape of many landforms, from large-scale ridge and valley trends to site-scale slope gradients.

Most of the rocks exposed in the Skamokawa WAU are not particularly strong (compared to all rock types). The sedimentary rocks were never deeply buried and so have not been strongly lithified[5]; most of the volcanic rocks underwent aqueous alteration early in their histories, either on the sea floor or within wet marine sediments. Folding and faulting has further disrupted rocks throughout the region. The near-surface materials have experienced humid, subtropical to temperate climates throughout their history, fostering deep and intense weathering. The region was beyond the Pleistocene ice limit, so the deeply weathered, weak rock material at the surface, which was largely stripped away in the higher Olympics and North Cascades, remains in the Willapa Hills.

The bedrock of the Skamokawa WAU falls into three broad categories, which affect the geomorphic processes and landforms of the area, and consequently the pattern of observed landslides (see Figure 3). These major rock types can be placed on a strength or resistance scale, inferred from the ways they affect landforms.

- The weakest sedimentary units, marine siltstones (Eocene to Miocene in age), tend to form lower and gentler hills, except where they are deeply incised by streams. Bedrock hollows and inner gorges are only occasionally found in areas dominated by these fine-grained silt-

[5] The conversion of newly deposited, unconsolidated sediment into coherent, solid rock.

stones. The main mass-wasting features of these weak rocks are large translational and combination translational-rotational deep-seated landslides, especially earthflows.

- The marine sandstones (Eocene to Miocene) form comparatively high relief uplands that are characterized by large tracts of deeply incised drainages separated by steep ridges. The ridge tops of this marine sandstone tend to be deeply weathered. The sandstones are also characterized by convergent headwalls, bedrock hollows, and inner gorges that are the initiation points for many debris slides and flows.
- The basaltic volcanic rocks (either Eocene or Miocene) are generally strong enough to support the highest and most rugged mountains of the Willapa Hills province. In the Skamokawa area, they tend to form high-relief bedrock capped ridges with deep weathering profiles, located along the Columbia River and in the highlands surrounding the WAU. Many debris slides and flows originate on these ridges, with the slides occurring mostly within the weathering profile of the basalt. Bedrock hollows and associated inner gorges are common in this unit.

These generalities are clouded by local variations in materials, processes, and history. Some landform shapes are affected by the juxtaposition of weaker and stronger strata, such as where volcanics overlie sedimentary layers, or where faults have placed harder against softer rocks. Fault lines themselves are zones of weakness, and are commonly preferred paths of weathering and stream erosion. Further complications arise from the irregular shapes and thicknesses of various units, grain size variations within formations, and the disturbances caused by folding, ground-water-induced weathering, large-scale landsliding, etc. through geologic history.

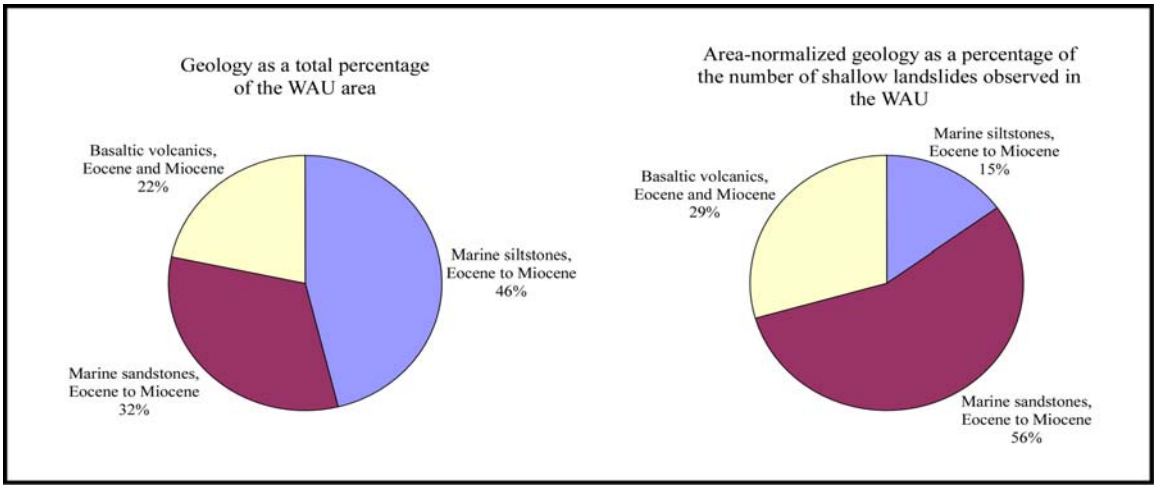



**Figure 3:** Of three major bedrock groups exposed in the Skamokawa WAU (excluding unconsolidated deposits): proportion of bedrock acreage in each type; and proportion of shallow landslides that would have occurred on each type if they all occupied the same area (i.e., areally normalized; see Table 2 for landslide types and numbers).

**Figure 4:** The basalt exhibits a deep weathering profile (orange material) on many of the bedrock-capped ridges.

3.3 Slope Processes

The rocks of the Willapa Hills have been eroding almost as long as they have been forming. With a more-or-less continually humid climate for tens of millions of years, water has been the dominant actor: as weathering agent, as trigger for mass wasting, and as transporter of debris out of the area. Streams flowing off uplands attempt to remove the debris produced by weathering and mass wasting. Judging from the prevalence of deep soils in most areas, and the persistence of mass-wasting deposits in the landscape, the streams are not able to remove enough material to keep up with weathering and mass wasting in the area. This transport-limited environment (i.e., more debris is produced than can be removed, at long time scales) is probably at least partly due to the reinforcing effects of the lush vegetation, on the hillslopes and in the streams.

The combination of weak rocks, topographic relief, and abundant water has contributed to high rates of mass wasting. This terrain is susceptible to many movement processes, from creep to shallow soil slips and debris flows to deep landslides (see Turner and Schuster, 1996). Most of the region has experienced deep-seated landsliding at one time or another, and smaller landslides occur quite frequently in some areas. The various mass-wasting processes are influenced by different combinations of rock and soil resistance (strength), and acted upon by gravitational stress and triggering events such as large storms and earthquakes. Structures that influence downslope movement include geologic contacts, bedding planes, and the soil/bedrock interface; the strength available to resist downslope stress varies depends on the orientations of the discontinuities. Fiksdal and Brunengo (1981) identified bedding-controlled landforms in the upper Grays River basin

to the north, with landslide processes differing on dip- and scarp-slopes, and such features are also found in the Skamokawa basin.

Shallow-rapid slides occur mostly in steeper terrain underlain by the harder marine sandstones and volcanic rocks, within the mantle of soil or regolith. The sandstone and the volcanics weather into lower-cohesion (though with some clay) soils with little internal strength. The combination of high relief, low cohesion, and abrupt strength and groundwater boundaries at the soil-rock interface makes these slopes more susceptible to debris slides and flows. Harvesting of trees can cause loss of the component of strength contributed by tree roots, which can be critical on marginally stable slopes.

The marine siltstones tend to form gentler terrain with deeper, finer-textured soils having more cohesion. In many areas, these materials lack the erosional resistance required to create high, steep slopes, and so are less susceptible to shallow-rapid slides, usually eroding by creep instead. Exceptions occur where slopes have been oversteepened by stream erosion or other processes.

The bedded sedimentary and volcanic units in and around the Skamokawa WAU are also susceptible to deep-seated landslides. Many of these large relict land-shaping slumps and rock-based slides are very large (tens of square miles), and collectively they occupy a major proportion of the landscape, about 23% of this WAU (Figure 5). Fiksdal and Brunengo (1980, 1981) mapped many such features within the region, along with areas of “flow topography” with less distinct boundaries. Over half of the area of the North Elochoman WAU, which borders the Skamokawa WAU to the east, was found to be involved in relict deep-seated landslide complexes (Goetz, 1996), further showing that these features have greatly affected the Willapa Hills. Historically, the K M Mountain slide in February 1990 disrupted traffic along S.R. 4 just east of the Skamokawa–Grays divide for many months (Lowell, 1990). Large landslides help shape the land, notably by disrupting drainage patterns by forming hummocky terrain or internal benches. These can host upland ponds and lakes (otherwise rare in this nonglaciated region), and can cause landslide damming and stream piracy.

Long-term weathering, uplift, and incision can alter the balance of stress and strength toward slope movement, but there is usually some triggering event that provides the final push to start it. With small debris slides, it is typically a big storm that saturates the soil mantle and increases pore-water pressures, reducing the effective strength of the mass. For larger landslides, increased water input due to several months or years of above-normal precipitation (or significant land-use changes) can be enough to initiate, accelerate, or reactivate deep-seated movement. Recently, the wet winter of 2005–06 reactivated at least two old earthflow type deep-seated landslides in the marine siltstones close to the Skamokawa–Grays divide.

For the largest slides, though, more energetic triggers would seem to be required, if only because they don’t occur after every big storm or run of wet winters. Earthquakes can be important triggering events for large landslides in the Willapa Hills: in particular, the nearby Cascadia subduction zone generates megathrust earthquakes. These earthquakes (up to magnitude 9+) occur at average recurrence intervals of several centuries, most recently on 26 January 1700 (Atwater and Hemphill-Haley, 1997). During these earthquakes, long, intense shaking could activate movement in marginally stable slopes.

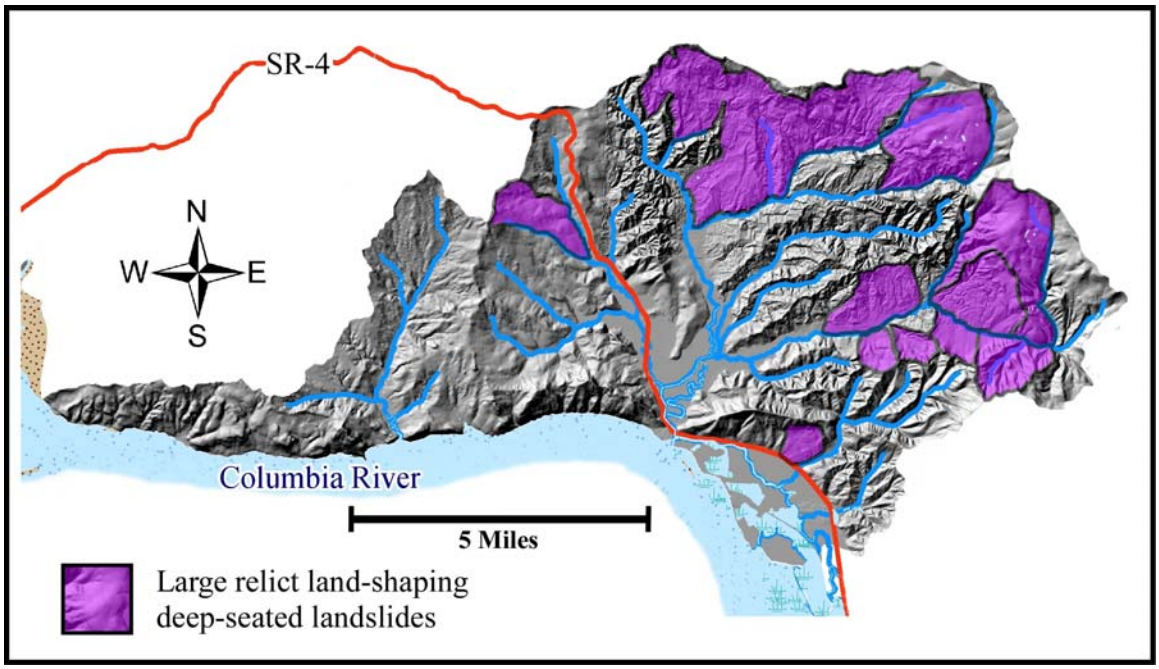



**Figure 5:** Map of the Skamokawa WAU showing the large relict land-shaping deep-seated landslides, which occupy about 23% of the WAU.

## 4.0 Summary of Landslide Inventory

During this review, we inventoried a representative sample of 1222 mass-wasting features from air photos, lidar, and field investigation. These are shown on Map A-1; pertinent attributes of individual features are compiled in Form A-1 (Appendix A); types and numbers are summarized in Table 2. Of the landslides identified, 39% were mapped as shallow-undifferentiated failures, 18% were debris flows, 26% were debris slides and debris avalanches, and 17% were deep-seated landslides. Small rock failures and snow avalanches are absent in this region of weak rocks and low elevations. Note that the deep-seated landslides cover about 17,691 acres, or about 98% of the area affected by mass movement (and about 37% of the WAU).

**Table 2:** Summary of the type and number of LHZ protocol-specified mass-wasting features mapped in the Skamokawa WAU.

| Mass Wasting Feature Type | Number of Mass Wasting Features Mapped | Area of Mass Wasting Features (ac) |
|---|---|---|
| Shallow undifferentiated landslides | 475 | 36.5 |
| Debris flows | 220 | 142.3 |
| Debris slide/avalanche | 313 | 76.9 |
| Rock topple/fall | 0 | 0.0 |
| Snow avalanche | 0 | 0.0 |
| Deep-seated landslides | 214 | 17,690.9 |
| **Totals** | **1,222** | **17,946.6** |

Land use was determined for each landslide inventoried and is recorded in the inventory spreadsheet (Form A-1). The watershed was sporadically harvested during the early 20th century, but more intense harvest and road building didn't occur in the highlands until the early 1950s (see Ap-

pendix F). Of the mapped shallow landslides, 22% were identified as road-associated failures that occurred within the past 35 years, 19% were located in newer clear-cuts (<5 yr old), and 27% were located in young stands (harvested 5-15 yr previously).

## 5.0 Landforms

We identified ten landform units during the Skamokawa study. Their locations are shown on Map A-2; they are described in Forms A-2 (Appendix B) and summarized in Table 3.

Six of the map units are specified by the LHZ protocol. Low-hazard landforms include flat areas (slopes 0–10%, LF # 19) and low-gradient hillslopes (10–40%, LF # 18), covering 62% of the land area of the WAU. Rule-identified landforms (as described in the protocol and WAC 222-16-050(i)) that were mapped in Skamokawa include inner gorges (LF # 1), bedrock hollows (LF # 2), and toes of deep-seated landslides (steeper than 65%, LF # 9); together, these landforms cover about 5% of the WAU. There are rule-identified convergent headwalls in the Skamokawa basin, but these landforms are not mapped individually and are included in the larger very high hazard analyst-described *highly incised terrain* (see below). The total number and relative prevalence of the rule-identified inner gorges, bedrock hollows, and convergent headwalls mapped in the WAU belies the much larger presence of these landforms. Many (perhaps hundreds) of these rule-identified features were left unmapped in areas covered by other analyst-described very high hazard landforms such as *highly incised terrain*, *steep bedrock capped ridges*, and *scarps of land-shaping deep-seated landslides*. Active deep-seated landslides mapped as unique landforms (LF # 8) involve only about 2% of the land area, but it is important to remember that dormant and relict deep-seated landslides are extremely prevalent in the Skamokawa WAU (another 35% of the WAU, mapped within other landform units).

Analyst-described landforms cover the remaining 31% of the study area, including: highly incised terrain (LF # 10), steep bedrock capped ridges (LF # 11), scarps of land-shaping deep-seated landslides (LF # 12), and other slopes steeper than 40% (LF # 13). These units have been delineated to identify areas that have similar potential for mass wasting, delivery of sediment/debris to public resources, and possible threat to public safety. As noted previously, they have been developed from a series of iterative statistical analyses of landslide attributes, including topographic, geologic, and climatic/precipitation characteristics at locations of landslide initiation.

**Table 3:** Summary of landforms mapped in the Skamokawa WAU.

| LF # | Landform Description | Slope Threshold or Range | Area (acres) | Hazard Rating |
|---|---|---|---|---|
| 1 | Probable inner gorges | > 60-70% | 1588.2 | very high |
| 2 | Probable bedrock hollows | > 60-70% | 208.0 | very high |
| 8 | Active deep-seated landslides | NA | 799.7 | very high |
| 9 | Toes of deep-seated landslides | > 65% | 733.3 | very high |
| 10 | Highly incised terrain | NA | 8376.3 | very high |
| 11 | Steep bedrock capped ridges | NA | 511.3 | very high |
| 12 | Scarps of land-shaping deep-seated landslides | NA | 1770.3 | very high |
| 13 | Slopes steeper than 40% | >40% | 4219.9 | moderate |
| 18 | Low gradient hillslopes | 10 – 40% | 23723.8 | low |
| 19 | Flat areas | 0 – 10% | 6211.1 | low |

## 6.0 Hazard Ratings

Pursuant to the LHZ protocol, hazard ratings for mass-wasting landforms were determined based on one or more of the following criteria: 1) identification by rule (WAC 222-16-050); 2) the landslide frequency rate (LFR) and landslide area rate for delivery (LAR); or 3) the professional judgment of the analysts. Form A-4 (Appendix D) shows the values of area, landslide numbers and frequency, and hazard ratings for each of the ten landform units and for the entire Skamokawa WAU.

The computations for LFR and LAR are shown on Form A-4. LFR is the number of shallow landslides in a map unit (excluding those of questionable certainty, or of probable certainty recognized on the first photo set), normalized for the period of study and the area of each landform; values are multiplied by one million for easier interpretation. The LFR index is used to quantify the landslide density in each map unit. LAR is calculated similarly, except that the area of delivering landslides is used instead of the number of all shallow landslides. The LAR index is a proxy for the volume of sediment that might be delivered to public resources.

Limited previous application suggests that terrain having LFRs and LARs in the ranges shown on Table 4 have the hazard levels indicated (Lingley, 2004), and these guideline ranges were used for landforms in Skamokawa. Note that higher LFR and LAR can be achieved by reducing the area of the landform. While this may appear to be 'data gerrymandering', it helps limit the area of high-hazard landforms to those areas that are demonstrated to have high hazard. Hazard ratings based on the LFR and LAR are combined into an overall hazard rating, as described in the LHZ Protocol (http://www.dnr.wa.gov/forestpractices/lhzproject/lhz_protocol_v2_final.pdf).

**Table 4**: Qualitative rating system for the LFR and LAR.

| **Qualitative Ratings** | **Landslide Frequency Rate (LFR)** | **Landslide Area Rate for Delivery (LAR)** |
|---|---|---|
| Low | < 100 | <76 |
| Moderate | 100 to 199 | 76 to 150 |
| High | 200 to 999 | 151 to 799 |
| Very high | >999 | >799 |

The hazard ratings for several landforms in the Skamokawa WAU were elevated because of specific concerns that we feel are not addressed by the semi-quantitative LFR and LAR hazard rating methods. The ratings for inner gorges (LF # 1) was upgraded from high to very high because not all landslides that started in inner gorges were attributed to that map unit. Many of these landslides were attributed to other more expansive very high hazard landforms as mentioned in section 5.0. The same problem affects bedrock hollows (LF # 2), but the LFR and LAR, in this case, was calculated as very high, even though the final numbers still underestimate the hazard of bedrock hollows in this WAU. The rating for active deep-seated landslides (LF # 8) was upgraded from high to very high because this landform is composed of active landslides that are inherently unstable and prone to deliver sediment and debris to streams or other public resources. Finally, the hazard rating for slopes steeper than 40% (LF # 13) was upgraded from low to moderate because its LAR was fairly close to the border between low and moderate levels.

Note that the Skamokawa WAU as a whole has a mass-wasting hazard rating of moderate, based on a high LFR and a moderate LAR. However, this does not reflect the unusual proportioning of the landscape between the four possible hazard ratings (low, moderate, high, and very high). About 62% of the area of the WAU is in the two low-hazard landforms, and the seven landform units rated very high hazard occupy another 29%. The one moderate-hazard map unit covers only 9%, and there are no units rated high. Thus, as evaluated here, landforms in the Skamokawa basin have one dominant mode that is fairly stable, and another smaller mode that is highly unstable.

**Potentially active earthflows in the Skamokawa WAU:** In addition to the relatively limited number of deep-seated landslides classified as active (LF #8) or rule-identified toes of deep-seated landslides (LF #9), the landscape of the Willapa Hills contains many large earthflows that appear to be dormant or relict (based on air photos or lidar). Although classified and mapped with other landform units, even as low-hazard hillslopes, it is important to understand that some of these features can become reactivated with even minor climatic and/or land-use perturbations, and have the potential to deliver enormous amounts of sediment to fish-bearing streams and other public resources. This was evident at landslide # 544, which heads on the Grays Bay/Skamokawa divide and toes in a tributary of Jim Crow Creek; and at landslide # 637, which toes in a tributary of Kelly Creek (see Form A-1). Both slides partially reactivated from previously dormant states during the winter of 2005-'06 and delivered sediment downstream into both main streams. Both these landslides exhibit a very subdued topographic expression, with average gradients gentler than 23%.

It is possible that road construction, widespread timber harvest, or other major forest practices may trigger reactivation of dormant or relict earthflows that are marginally stable. Earthflows that are susceptible to this process do not necessarily overlap with the mapped high-hazard landforms on Map A-2. Refer to the landslide inventory supplements (Map and Form A-1) for the complete distribution of earthflows that have been recognized in this study. Due to their subdued topographic expression, dormant and even potentially active earthflows could have been overlooked during landslide mapping, especially in areas outside of lidar coverage and under heavy forest canopy. Therefore, users should take great care to look out for classic features of earthflow activity in the field, including fresh scarps and cracks, minor slumps, jackstrawed trees, stretched roots, split old growth stumps, streams that are newly incised through soft sediments, etc.

## 7.0 Confidence in Work Products

The confidence in this mass-wasting assessment is generally high. This rating is based on the Landslide Hazard Zonation Project design to provide a watershed overview of slope stability in a timely manner with minimal field verification. As a consequence, fieldwork and the number of aerial photo sets examined are held to reasonable minimums. Omissions will be present due to the limited field verification of individual features; this is particularly problematic in forested areas with heavy canopy.

It is critical for the reader to understand that while these determinations are sufficient to characterize aspects of mass wasting as functions of forest management, <u>this assessment would be insufficient and misleading if it were used as a stand-alone document for protecting private and public resources or for land-use planning</u>. Keep in mind that this is a reconnaissance study; undoubtedly, some landslides have been accidentally omitted, and some benign features may be improperly mapped as landslides.

In addition, there are several sources of systematic error that reduce the confidence in the accuracy and/or precision of the work products of this analysis[6]. Omission occurs when mass-wasting features are not identified on air-photos or in the field due to canopy cover, gaps in the photo record, poor photo quality, or interpreter error. Misinterpretation occurs when a feature is identified but incorrectly classified, data are transposed, or unrecognized software/file instability occurs.

This mass-wasting assessment was primarily conducted with aerial photographs, so there is a high likelihood that errors of omission occurred, particularly in areas covered by mature forest canopies, or on steep north-facing slopes in shadow at any given time. The scarcity of mass wasting features identified in such areas is not necessarily an indication of the relative stability of slopes with mature vegetation or steep north aspects.

Misinterpretation of deep-seated landslides is more likely because many of them are quite large, remain heavily vegetated during movement, and may not have obvious scars visible through the canopy. A recent detailed study in Cowlitz County suggests that up to 25% of inferred deep-seated landslides identified solely from air-photo analysis are misinterpreted (Wegmann, 2006). However, our confidence in work products related to classification of deep-seated landslide processes in this watershed is high due to good visibility and completeness of the photo coverage.

Another important source of potential error is in the accuracy and precision of measurements of mass-wasting features. Because very few landslides were actually visited in the field, it is not possible to report the degree to which location and measurement error in the GIS environment compares to on-the-ground field measurements. Similarly, measurements of slope angle from digital elevation models typically misrepresent the true hillslope angles. Given these sources of error, the confidence in the precise location and accuracy of measurements of individual landslides is considered moderate.

## 8.0 Acknowledgments

Funding for this project was provided by a Federal Salmon Recovery grant, administered through the Washington Interagency Commission on Outdoor Recreation. Technical oversight of this project was provided by the Upslope Processes Science Advisory Group (UPSAG), a subcommittee of the Cooperative Monitoring, Evaluation and Research (CMER) committee. The following people have greatly contributed to this project (and special thanks given to): Tim Walsh, Ben Cashman, and Lorraine Powell of DNR Geology and Earth Resources, Bill Lingley of DNR State Lands, Jack Powell and Laura Vaugeois of DNR Forest Practices, and Lee Walkling of the DNR Geology Library.

[6] Accuracy involves the degree to which the physical parameters of a mass-wasting feature are correctly recognized and/or measured; precision describes how variability within an assessment can be controlled when making multiple measurements over varying temporal and spatial scales.

## 9.0 References


Atwater, B. F.; Hemphill-Haley, Eileen, 1997, Recurrence intervals for great earthquakes of the past 3,500 years at northeastern Willapa Bay, Washington: U.S. Geological Survey Professional Paper 1576, 108 p.

Bilderback, E. L., 2006, Evaluation of GIS methods for determining the pre-movement slope gradient of deep-seated landslides: DGER News, v. 3, no. 1, p. 1-2. [accessed 20 June 2006 at http://www.dnr.wa.gov/geology/pubs/dgernews/dgernews_v3no1.pdf]

Brardinoni, Francesco; Slaymaker, Olav; Hassan, M. A., 2003, Landslide inventory in a rugged forested watershed–A comparison between air-photo and field survey data: Geomorphology, v. 54, no. 3-4, p. 179-196.

Dragovich, J. D.; Brunengo, M. J.; Gerstel, W. J., 1993, Landslide inventory and analysis of the Tilton Creek-Mineral River area, Lewis County, Washington; Part 1–Terrain and geologic factors: Washington Geology, v. 21, no. 3, p. 9-18.

Fiksdal, A. J.; Brunengo, M. J., 1980, Forest slope stability project, Phase I: Washington Department of Ecology Technical Report 80-2a, 18 p., 7 plates.

Fiksdal, A. J.; Brunengo, M. J., 1981, Forest slope stability project, Phase II: Washington Department of Ecology Technical Report 81-14, 2 v.

Galster, R. W.; Coombs, H. A.; Waldron, H. H., 1989, Engineering geology in Washington–Introduction. *In* R.W. Galster, chairman, Engineering geology in Washington: Washington Division of Geology and Earth Resources Bulletin 78, v. I, p. 3-12.

Goetz, Venice, 1996, Appendix A: North Elochoman mass wasting assessment. *In* Washington Department of Natural Resources, North Elochoman watershed analysis: Washington Department of Natural Resources, 1 v.

Hitchman, Robert, 1985, *Place Names of Washington*: Washington State Historical Society, 340 p.

Krogstad, Finn, 1995, A physiology and ecology based model of lateral root reinforcement of unstable hillslopes: University of Washington Master of Science thesis, 44 p.

Landslide Hazard Zonation Technical Committee; Upslope Processes Science Advisory Group of the Cooperative Monitoring, Evaluation and Research Committee, 2005, Landslide Hazard Zonation Project Protocol, Version 2.0: Washington Forest Practices Division, 41 p. [accessed 20 June 2006, http://www.dnr.wa.gov/forestpractices/lhzproject/lhz_protocol_v2_final.pdf]

Lingley, William, 2004, Landslide hazard zonation project–South Prairie Creek Watershed, Pierce County, Washington: Washington Department of Natural Resources, online, 22 p., 2 plates, scale 1:24,000. [accessed March 08, 2006 at http://www.wadnr.gov:81/cgi-bin/completedwaus.cgi]

Lowell, S. M., 1990, The K M Mountain landslide near Skamokawa: Washington Geology, v 18(4)3-7

Muhs, D. R.; Thorson, R. M.; Clague, J. J.; Mathews, W. H.; McDowell, P. F.; Kelsey, H. M., 1987, Pacific coast and mountain system. *In* W.L. Graf, ed, Geomorphic systems of North America: Geological Society of America, Centennial Special Volume 2, p 517-581.

Shaw, S. C.; Johnson, D. A., 1995, Slope morphology model derived from digital elevation data, *In* Proceedings, 1995 Northwest Arc/Info Users Conference, Coeur d'Alene, Idaho, Oct. 23-25, 13 p.

Turner, A. K.; Schuster, R. L., editors, 1996, Landslides–Investigation and mitigation: National Academy Press; National Research Council, Transportation Research Board Special Report 247, 673 p.

Washington Department of Natural Resources, 1996, North Elochoman watershed analysis: Washington Department of Natural Resources, 1 v.

Washington Forest Practices Board, 1997, Washington Forest Practices Board manual – Standard methodology for conducting watershed analysis under Chapter 222-22 WAC, version 4.0: Washington Forest Practices Board, 1 v.

Wegmann, K. W., 2006, Digital landslide inventory for the Cowlitz County urban corridor, Washington: Washington Division of Geology and Earth Resources Report of Investigations 35, 1 CD-ROM.

Wieczorek, G. F., 1984, Preparing a detailed landslide-inventory map for hazard evaluation and reduction: Bulletin of the Association of Engineering Geologists, v. XXI, no. 3, p. 337-342.