Coastal Landsliding on Puget Sound:

A review of landslides occurring between 1996 and 1999

August, 2001

WASHINGTON STATE DEPARTMENT OF ECOLOGY

Report #01-06-019

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Olympia, Washington

August, 2001

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Unless otherwise noted, all photos are by the author.

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Executive Summary

During the winter of 1996-1997, severe landsliding occurred throughout the central Puget Sound region, resulting in many tens of millions of dollars of property damage and the loss of five lives. Landslides were central elements of two federal disaster declarations and landslides received frequent and prominent attention in the media, influenced primarily by the high levels of damage within the populated Seattle-Everett corridor. Two years later, during the winter of 1998-1999, landslides were again widespread, resulting in many homes lost or relocated, including the abandonment of over forty homes in a neighborhood near Olympia. Unlike the slides of 1996-1997, which were often shallow and fast-moving, these slides tended to be reactivations of very large, existing landslides. Because they occurred over an extended period of time, resulted in no casualties, and because many happened in relatively rural areas, they received much less attention than did the 1996-1997 slides.

The primary purpose of this report is to document these major episodes of landsliding and to use the resulting information to better understand how to reduce the risks from landslides in the future. The distinction between the types of events that occurred in each of the two winters sheds light not only on the different geological circumstances, but on how agencies and local governments might better plan for a realistic range of landslides scenarios. This report emphasizes mitigation of landslide risks and damages rather than disaster preparedness and emergency response.

Landsliding affects more than 600 miles of Puget Sound's shoreline, reflecting the pervasiveness of high, steep coastal bluffs and the widespread occurrence of geologic conditions that can give rise to slope failures when groundwater levels rise rapidly. The risks from landsliding, and the level of associated damages, are exacerbated by the intense development pressure along the shoreline and the relative value of property located in or adjacent to steep, unstable slopes. Landsliding is not restricted to the shoreline of Puget Sound, however, and occurs in many other settings in the region as well.

The 1996-1997 landslides were predominantly shallow landslides and debris avalanches on steep slopes, triggered by heavy rainstorms. They occurred over short time periods and occurred in conjunction with other rainstorm-related natural disasters such as urban and groundwater flooding and snow and ice damage. Notable examples include the Rolling Bay landslide on Bainbridge Island that took four lives, the widespread sliding in Seattle's steep-slope neighborhoods such as Magnolia and Alki, and the very large slump at Woodway, south of Edmonds, that carried a train into the Sound.

In contrast, the 1998-1999 landslides occurred following extended periods of wet weather, but were not specifically related to individual storms. Most were large, deep-seated landslides involving the reactivation of much older landslide features in the landscape. Although devastating to property owners and communities, these slides received little regional publicity and did not trigger federal disaster declarations. The most prominent examples were the Carlyon Beach landslide in Olympia and the large slides that closed Highway 101 for extended periods of time along Hood Canal.

Landslides during both periods occurred in predictable locations, reflecting generally known patterns of steep slopes, characteristic geology, and past evidence of movement. Almost all slides occurred in locations that had slid previously. Damages tended to be most severe to development located at the base of steep slopes or sited within a larger landslide complex. Damages due to shallow slides, such as in 1996-97, tend to be rapid and catastrophic, but are often limited to a single structure because the physical size of the slide is small. Damage due to reactivation of deep-seated landslides, as in 1998-99, tends to be progressive, occurring over several weeks or months, but sometimes affecting large areas that encompass many homes.

Landslides along the shoreline of Puget Sound cannot be completely prevented, nor should they. Landslides provide a critical function to maintaining our beaches and the geologic, biologic, and aesthetic diversity of our shoreline. The impacts of slides on humans and on the built environment can be reduced, however, by understanding where slides are likely and how to avoid or minimize their consequences.

Washington's Growth Management Act, along with other state and local regulations affecting building practices and development, provide a framework for guiding and regulating land use and construction in slide-prone areas. These measures often do not deal well with existing, older development in unstable areas, but with solid technical guidance and with strong local commitment to implementing effective policies, future losses can be reduced significantly.

The report concludes with some recommendations for improving how Washington State manages landslide hazards. Several key steps include:

- Improved identification and mapping of landslide hazards, making use of good quality geologic information, high-resolution topographic mapping, and systematic inventories of both past and future landslide activity.
- More effective regulation of land use and building in landslide-prone areas, particularly in those relatively rural jurisdictions where large unstable areas are just beginning to undergo intensive development and where careful planning now may greatly reduce future risks and damages.
- Developing initiatives at the state level aimed at collecting crucial geologic information, providing technical guidance and support to local governments, and directing resources to local jurisdictions to establish in-house geotechnical expertise, to carry out focused studies on problem areas, and to develop improved ordinances and locally-specific guidance and educational materials.
- Greater education of property owners and the development community, along with local officials, regarding both the nature and location of landslide risks and the wide variety of methods available to avoid or to mitigate those risks.

Landslide disasters will happen again on Puget Sound. Damages will escalate significantly as property values increase and more expensive development occurs in unstable areas. Much of the risk to new development and to personal safety can be mitigated through aggressive efforts to identify hazardous areas and to implement effective building regulations and design standards for unstable areas. *This can only occur through a comprehensive program that couples resources and technical capabilities at the state level with strongly supported local efforts to implement effective land use and building codes*.

Introduction

Following the landslides of the winter of early 1996, geologists with the United States Geological Survey (USGS) wrote:

> We suggest that the coastal cliffs of the Puget Sound area be inspected and accurate locations [of landslides] be documented to the extent possible. This is an area of intense development pressure, and an accurate picture of where landslides were triggered during this storm is vital in making intelligent land use planning decisions. A consideration of existent landslide susceptibilities and potential hazards will reduce the risk to people and property both now and with future development [Harp and others, 1996].

The scope of such a task, given the enormous amount of unstable shoreline surrounding Puget Sound and the difficulty in identifying and mapping landslides in steep, heavily vegetated terrain, is daunting. Even if funds were available to carry out such a survey immediately following a landslide disaster, it would be difficult to collect accurate and systematic data. What we can do, however, is attempt to learn from these events, to document as many landslides as we can, and to improve efforts to reduce losses from future disasters.

The late 1990s provided an opportunity to do this. Heavy rains, on top of already wet conditions, gave rise to three separate landslide-related federally-declared disasters in the Puget Sound region between February, 1996, and March, 1997. Then, during the La Nina winter of 1998-1999, the region witnessed the reactivation of several very large, deep-seated landslides, apparently in response to one of the wettest three-month periods on record. Landslides during the late 1990s killed six people, destroyed dozens of homes, and caused many tens of millions of dollars to public infrastructure. These events demonstrated that landslides present a major natural hazard in the region, and that the level of risk may be increasing with increasing development, despite better understanding of geology and landslide mechanics, but they also gave geologists, engineers, and government officials valuable information about the character and distribution of coastal landslides and about the success of various approaches to addressing landslide risk.

Landsliding along Puget Sound's steep coastal hillslopes has been described in numerous publications, going back as far as Kimball [1897], but more recently in the Coastal Atlas [Washington Department of Ecology, 1977-1980] and Thorsen [1987, 1989]. Mapping of landslides and slope stability has been carried out at the county level by many geologists, best summarized in Manson [1988, 1998]. Tubbs [1974, 1975] described landsliding in the Seattle area in work that has formed the foundation for most subsequent interpretations of Puget Lowland landslides. Following the 1996-1997 landsliding several additional studies were carried out, including: U.S. Army Corps of Engineers [1997], Baum and others [1997], Gerstel and others [1997] and Palmer [1998].

Our focus in this report is on those landslides that occur along the coastline of Puget Sound. Although landslides also occur along streams and rivers and are common on steep slopes throughout the Puget Basin, a large number of the slides that impact human development and that incur the largest costs are along the marine shoreline. This reflects two major factors: the particular susceptibility and widespread extent of steep marine bluffs and the high level and high value of development found along these bluffs.

The Coastal Zone Atlas of Washington [Washington Department of Ecology, 1977-1980] comprises the only comprehensive mapping of unstable slopes along the shores of Puget Sound and we believe it is the primary source for a variety of published estimates for the amount of shoreline susceptible to landsliding[1]. Thorsen [1989] reports that Puget Sound's shoreline includes approximately 660 miles of unstable bluffs. Downing [1983], citing the Coastal Atlas, reports a similar number (Table 1)[2]. Chleborad [1994] cites 149 miles of landslides on Puget Sound. The lower number probably indicates that only mapped landslides were included, whereas the larger numbers include all unstable slopes. All of these numbers likely underestimate the pervasiveness of landslide-prone shorelines [Thorsen, 1989], simply because older slides were hard to identify and map, many slides were too small to adequately represent at the map scale (1:24,000), and many larger, dormant landslides may have been easily overlooked. For example, the large Carlyon Beach landslide in Thurston County that reactivated in 1999 was identified as an area of Intermediate slope stability in the Coastal Zone Atlas, yet larger scale mapping in the field might have recognized the more serious character of the prehistoric landslide feature.

County	Miles of Shorelines	Miles Unstable	Percentage
Island	221	112	51%
Jefferson	195	81	42
King	113	66	58
Kitsap	246	50	20
Mason	218	96	44
Pierce	232	72	31
San Juan	376	13	3
Skagit	189	46	24
Snohomish	74	19	26
Thurston	111	50	45
Whatcom	118	36	30
TOTAL	**2093**	**641**	**31%**

Modified from Downing, 1983. Data from Washington Department of Ecology.

Table 1. Length of unstable marine shoreline in the Puget Lowland as mapped in the Coastal Zone Atlas [Washington Department of Ecology, 1977-1980].

The purpose of this report is to review our knowledge of coastal landslides on Puget Sound in the context of the extensive landsliding that occurred in the late 1990s. The report documents a large number of slides, some of which have not received attention in other publications. I also attempt to document the difference between the highly publicized and dramatic landslides of the winter of 1996-1997 and the more subtle, but possibly just as serious, reactivation of large landslides throughout the region during the winter of 1998-1999. The nature of landslides during these two periods was quite different, with implications both for understanding the geology of Puget Sound landslides and maybe more significantly, developing appropriate management strategies for reducing risks.

[1] Some tabular compilations of data from the Coastal Zone Atlas were carried out when the Atlas was published, but to our knowledge, these summary statistics were not formally published.
[2] The difference may reflect the inclusion of portions of Clallam County by the former author.

The report is divided into several sections. It begins by reviewing the geological conditions that dominate the Puget Lowland and that determine the occurrence and character of landsliding. The report then summarizes the meteorological conditions that led to the major episodes of landsliding in both 1996-1997 and in 1998-1999. In two subsequent chapters, I describe a number of the landslides that occurred during each of these periods, and then in the following chapter I look more broadly at the factors that establish the character and distribution of slides. Finally, I examine the variety of approaches available to address landslides in our region. The report concludes with a summary of significant observations and findings and a list of recommendations for reducing landslide risks in the future.

Geology of Landslides

The occurrence and distribution of landslides in the Puget Sound region is directly related to the geological and geomorphological characteristics of the area. The pervasive nature of landsliding along coastal slopes reflects a combination of steep slopes formed by centuries of erosion by waves and a widespread geological setting that places permeable glacial outwash sediments in contact with underlying impermeable fine-grained clays and silts, creating a zone of elevated pore water pressures and potential instability.

Geological setting

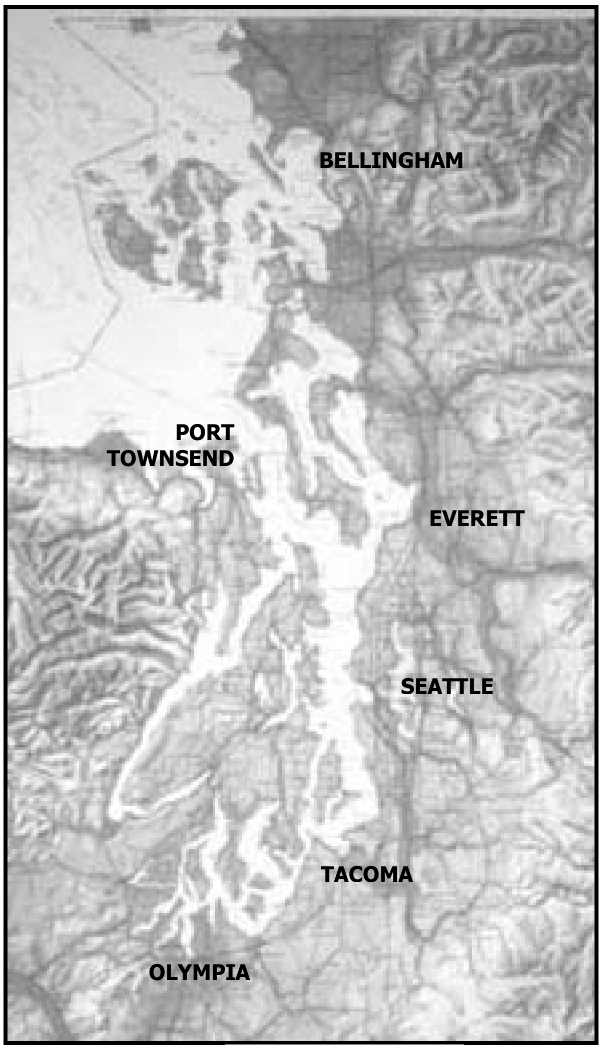


Figure 1. Map of the Puget Lowland.

The Puget Lowland contains considerable geologic variation, from extensive bedrock terrain to large Holocene river deltas (Figure 1). Most of the shoreline, however, is developed in late Pleistocene glacial and interglacial sedimentary deposits. Much of the Puget basin is blanketed with sediments deposited in association with the last advance of glaciers into the basin. At the peak of the Vashon glaciation, the Puget Lobe of the Cordilleran ice sheet extended south of

Olympia and completely filled the Puget Lowland. The resulting geological units, and in particular, the relationship between the units and their resulting hydrologic behavior, directly influences the character of landsliding on the Sound.

Significant lateral variation in these deposits exists within the region, sometimes over very short distances, but some common themes dominate. Pre-Vashon units include glacial sediments from earlier ice advances (e.g. the Double Bluff and Possession drifts) and fluvial, lacustrine, and estuarine sediments deposited during the last interglacial period (e.g. the Whidbey formation). The oldest Vashon-age sediments are fine grained silts and clays deposited in proglacial lakes (lakes formed in front of the advancing ice). In the central part of the Sound, these lakebed deposits are referred to as the Lawton Clay. The thickness of the unit varies, but it is characterized by its impermeable nature and its resulting ability to retard downward movement of groundwater.

The lakebed sediments are overlain by coarse-grained sand and gravel deposited in rivers and streams in front of the advancing ice. This advance outwash deposit is locally referred to as the Esperance sand, or more generally as Vashon Advance Outwash, and varies considerably in thickness and composition. The outwash is usually highly permeable to groundwater infiltration and movement.

In most areas, the advance outwash is overlain by a compact glacial till deposited in direct contact with the ice. The Vashon Till is poorly sorted and its composition varies, although it generally consists of everything from sand to boulders within a silty matrix. It is relatively impermeable, although joints and coarser grained units within the till can allow water movement.

Although the till is often the uppermost unit found, in many locations it is overlain by coarse and permeable recessional outwash deposited by streams as the glaciers retreated. In the northern portion of the Puget Lowland, marine waters invaded following the retreat of the ice and deposited glacial marine drift (poorly sorted sediment deposited by rafted or floating ice) that resembles a glacial till, but that generally consists of more silt and clay than till.

More recent, Holocene, deposits in the region consist largely of alluvial sediment deposited by rivers or along marine shorelines (beach and marsh deposits), but these areas generally relatively level and not prone to landsliding. Colluvial debris formed by mass-wasting and weathering on hill slopes, however, is susceptible to sliding, as is artificial fill placed on slopes to support human activities.

Landslides and geology

For much of Puget Sound's shoreline, this sequence of geologic units, and in particular, the way in which these units affect the movement of water in the soils, determines the character and likelihood of landsliding. Although sliding can occur in any of these units, particularly when slopes have been steepened by erosion, the most common scenario for sliding exists when water builds up along the boundary between porous units, such as the advance outwash, and less permeable layers beneath such as the Lawton Clay (Figure 2and Figure 3).

Kimball [1897] notes the dominant role of landslides in shaping the steep shoreline slopes surrounding Puget Sound. In particular, he recognized that the way in which the geologic units affected hydrologic conditions was critical to this instability and the different ways in which slopes developed. Kimball notes the role of landsliding in forming the benched topography of Seattle's steep slopes, the difficulties landslides posed to the engineering of the Great Northern

Railway near Edmonds, and "the great landslides of sound bluffs at Duwamish Head, West Seattle (Sept. 1894), by which several acres were lost to that village."

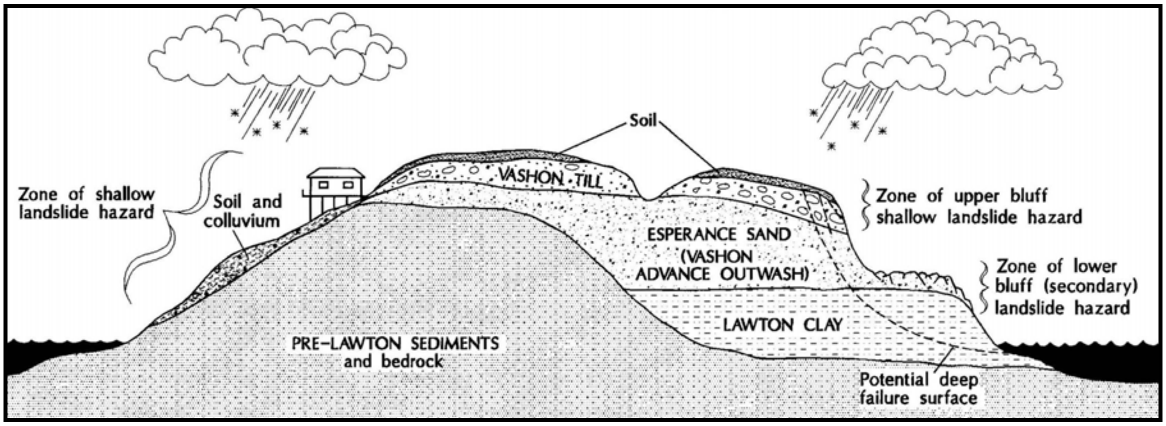


Figure 2. Typical geologic section in the Puget Lowland showing relationship between various units and likely areas of landsliding.
[Source: Gerstel and others, 1997, modified from Tubbs, 1974]

Tubbs [1974, 1975] studied this relationship in detail in an investigation of landslides that occurred in Seattle during the winter of 1971-1972, noting that a majority of the slides were located along the contact between the Vashon outwash and the underlying Lawton Clay (Figure 2). This contact follows the topographic bench noted by Kimball. This relationship is also discussed and illustrated in Dunne and Leopold [1978].

Perched water tables commonly form atop the Lawton Clay, within the lower portion of the advance outwash, since water percolating down through the more permeable outwash deposits is blocked. Seeps and springs are common at the contact between the units where it is exposed along the face of steep slopes and bluffs.

The importance of the Vashon stratigraphy to landslides on the Sound cannot be overemphasized, but neither should other landslide settings be ignored. Landslides can develop for similar reasons on slopes where permeable soils or glacial deposits overlie bedrock, where porous recessional outwash overlies glacial till or glacial marine drift, or where weathered soils and colluvium rest on less permeable unweathered glacial deposits. The latter situation is extremely common and may give rise to many of the shallow landslides observed in the area.

Landslides are not confined to settings where perched water tables develop. Glacial till can fail as fractures behind the slope face weaken. This may be aggravated by undercutting by erosion - due to wave or stream action, erosion at seeps in the underlying sands, or due to landslides lower on the slope. Such failures in till often begin as rockfalls, with large blocks of till falling to the slope below, and then continue as debris avalanches. Shannon & Wilson [2000] identified such failures as "high bluff peeloffs."

Rockfalls and slides can also occur in bedrock terrain, usually when water infiltrates fractures and joints in the bedrock weakening the rock. Such bedrock slides are serious concerns in some areas, such as in the Chuckanut formation south of Bellingham, but will no be discussed in more detail here.

Figure 3. Shallow landslide exposing characteristic sequence of Puget Sound region geological units. The darker units in the lower part of the bluff consist of Lawton Clay and underlying Whidbey formation. Much of light-colored upper bluff consists of sandy advance outwash sediments (Esperance Sand). Vashon till caps the bluff. Note seepage along contact between outwash and Lawton Clay - this zone is likely where the landslide began. *[Photo: Eglon area, Kitsap County, 1995, #95-17-7]*

Types of Landslides

The typical combination of geologic and hydrologic conditions described above for Puget Sound contribute to a broad range of slope failures, ranging from shallow landslides of colluvial debris to deep-seated landslide complexes that may have existed for millennia.

Geologists and engineers classify landslides in a variety of ways, though the most common systems consider how the landslide is initiated - for example, falls, slides, and flows [Varnes, 1978; Thorsen, 1987; Miller, 1991; and Macdonald and Witek, 1994]. Categorization can be difficult, however, as many landslides exhibit characteristics of more than one type of failure. Some slides may begin as one type of failure and end as another. A shallow landslide may be precipitated by a very small slump or a block failure in glacial till, move downhill as a debris avalanche, and become a debris flow as it incorporates water.

Terminology is complicated and often ambiguous. Deep-seated landslides might refer to failures greater than 6-10 feet deep [Shannon & Wilson, 2000] or they may be used to describe deep landslide complexes that are more than one hundred feet thick[3]. Slumps generally refer to earth movement that occurs along a curved failure surface, but may range from a few feet to many hundreds of feet in size. The terms shallow landslide, skin slide, and debris avalanche are often used interchangeably. The media often speaks of mudslides, although geologists prefer to avoid the term. Few slides on Puget Sound truly involve substantial amounts of mud, and when they do, the mud flows rather than slides.

[3] Both the large 1997 landslide at Woodway and the 1999 reactivation of a large earth movement at Carlyon Beach were deep landslides, but the two differed significantly in their geology, scale, speed, and the nature of impacts/damages.

In a recent inventory and analysis of landslides in Seattle, Shannon & Wilson [2000] chose the following categories to describe individual slides: high bluff peeloffs, groundwater blowouts, deep-seated slides, and combination slides[4]. This classification was useful in categorizing historic slides and in evaluating the type of slide failure most likely in different places.

In this report I chose to consider the following categories. I have found this system convenient and my experience suggests it works well in describing landslides to the broader public.

- Shallow landslides and debris avalanches
- Slumps and large landslides
- Deep-seated landslides and ancient landslide complexes
- Mud and debris flows

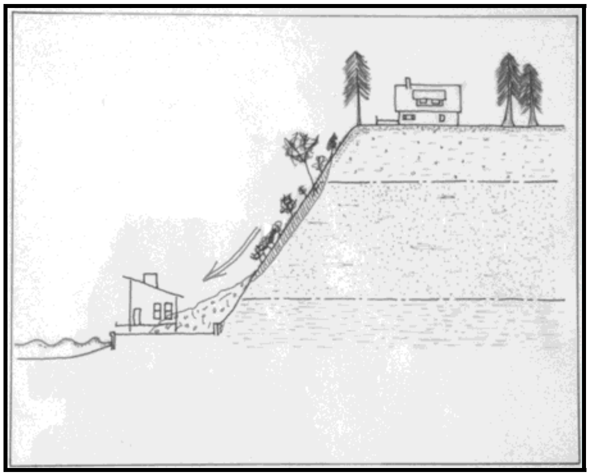
These classes overlap, however, and distinctions can be confusing. In our work, for example, we tend to view shallow slides as those that involve only weathered material and underlying units within about ten feet of the surface, whereas the large slumps, landslides, and deep-seated slides may extend many tens of feet in depth. This classification would not necessarily serve well in other geologic provinces, nor is it intended to satisfy the requirements of all geologists and engineers.

Shallow landslides and debris avalanches

Shallow failures of soils and debris are the most common landslides observed on the steep slopes around the Sound. These shallow slides typically involve a thickness of only a few feet of soil and weathered material, along with accompanying vegetation (Figure 2 and Figure 4). They are typically large relative to their depth, although their size is highly variable, from a few feet to a few hundred feet in lateral dimension. Engineers often refer to these shallow failures as "skin slides." They usually fail along a zone between the overlying weathered soils and the intact unweathered material below.

They can occur on a wide range of geological substrates, including compact, fine grained materials, sands and gravels, and artificial fill. Shallow landslides may be initiated by a small slump, the failure of the slope above, erosion of the toe of the slope, or simply the saturation of the soils.

[4] High bluff peeloffs refer to failures in glacial tills near the top of the slope. These slides may begin as falls of blocks of material, then become debris avalanches lower on the slope. Groundwater blowouts are rapid failures of sandy material due to a rapid build-up of pore pressure - Shannon & Wilson [2000] suggest these may be relatively common, although often unrecognized, causes of landslides in this area.



Note that slide involves only a thin layer of soil and vegetation. The amount of slope retreat associated with such slides is small and may not even reach the edge of the upland surface. The volume of material and the speed of the slide, however, can be sufficient to cause serious damage to structures located at the base of the slope.

Figure 4. Cartoon illustrating a typical shallow landslide.

Shallow landslides typically occur during and immediately following periods of intense rainfall or after rain-on-snow events, when rapid infiltration saturates the soils and pore pressures build along the base of the weathered materials. They are easily aggravated by drainage concentrations (associated with rapid runoff or failed drain systems, for example) and by increased seepage of shallow groundwater.

Because shallow slides do not cut far into the slope, an individual event is unlikely to pose a threat to structures located above the slope. The rapid movement of slide debris downslope, however, can damage structures that lack deep footings on the slope itself and can bury or severely impact homes or other improvements at the base of the slope. Trees and logs in the landslide debris can add to the damage. The distance the slide material travels after it reaches the toe of the slope (the runout) may depend on the velocity, the moisture content, and the volume of the slide, among other factors.

Along many steep coastal bluffs, shallow landsliding is pervasive. Although any given slope may only fail every thirty or forty years and different segments will slide at different times, all portions of the bluff can be expected to slide over the course of several decades. On much of the shoreline, shallow slides are the basic mechanism by which erosion provides sand and gravel to form beaches [Shipman, 1995].

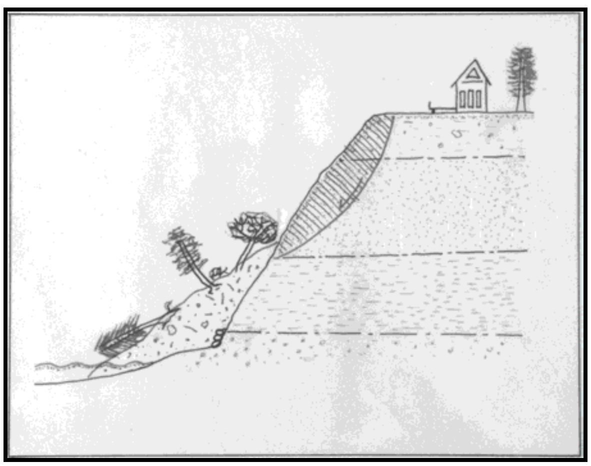
Shallow slides often occur in conjunction with larger landslides. Shallow slides may occur on the headscarp of a deep-seated slide. On mid-slope benches, shallow slides deposit sediment from the upper slope on the bench and carry sediment from the bench to the shoreline itself. Movement of deep-seated landslides can trigger shallow slides on adjoining slopes or lead to debris flows lower on the slope.

Large landslides and slumps

Slumps are generally defined as earth movements that occur along circular failure planes. They may be small, perhaps only a few feet in scale - or they can be very large, involving an acre or more. Many landslides could be technically considered slumps and many shallow slides (described in the previous section) may originate as small slumps. In this section, however, we are primarily interested in larger landslides that incorporate deeper, unweathered soils - distinguishing them from shallow landslides and debris avalanches.

In general, these larger slides are rapid events (we describe deep-seated slides subject to periodic and sometimes incremental reactivation in the following section) and may involve large areas and large volumes of material. As a consequence, they can be extremely hazardous. Examples of these larger catastrophic slides include the 1997 Woodway landslide and the 1949 Tacoma Narrows landslide [Chleborad, 1994] (the latter occurred three days after the 1949 Puget Sound earthquake).

These deeper landslides and slumps are considerably less common on Puget Sound than the shallow landslides we observe on virtually all steep coastal slopes. Geologists and engineers do not understand well the factors that contribute to their location and timing. Arndt [1999] describes the large Woodway landslide in detail, and includes a comparison to a similar 1979 landslide at Possession on South Whidbey Island (Figure 6), a large landslide north of Brownsville in 1983, and deep slides near Lone Rock north of Seabeck on Hood Canal. In deeper slides, where underlying fine grained units are involved, it appears that fractures may be important in allowing water to infiltrate units and as planes of weakness. Possibly because these slides involve relatively deep groundwater, they do not necessarily coincide with the heaviest periods of precipitation. The Woodway landslide occurred during a dry period two weeks after the 1996-97 Holiday Storm and the Possession slide occurred in the summer.



Slump has occurred in the upper portion of a coastal bluff. The landslide cuts deeply into unweathered materials and can threaten homes or roads above the bluff. Failures often involves large volumes of material and can pose a significant threat to improvements at the base of the slope.

Figure 5. Cartoon illustrating large slump.

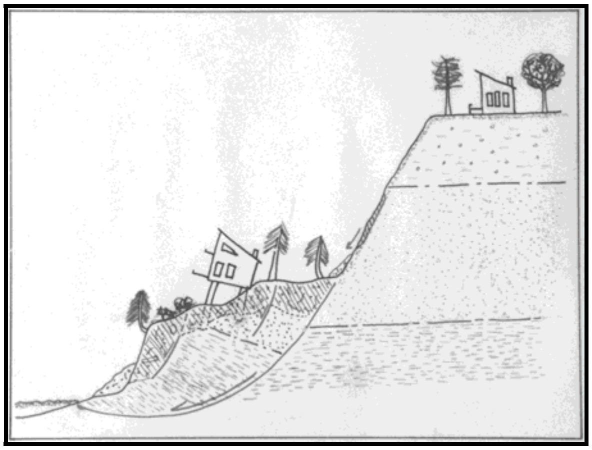
Unlike shallow slides that only affect a few feet of soil, these deep slides may cut many tens of feet into the slope (Figure 5). As a result, they pose a much more significant risk for structures built above the slope which may not be adequately set back from the bluff edge. The potentially enormous volumes of material also pose a severe threat to structures on or below the slope. The Woodway landslide buried the Burlington Northern Santa Fe railroad grade and knocked a portion of a train into the Sound. Both the Possession landslide and the Tacoma Narrows slides occurred adjacent to small communities of beach cabins built at the base of the slope - had either slide occurred a few hundred yards farther down the shore, the results would have been catastrophic.

Figure 6. Large landslide that occurred in 1979 between Possession Beach and Glendale on southeastern Whidbey Island. Note beach houses on the left for scale.
[Photo: Dave Frank, USGS, #0128_59].

Deep-seated, ancient landslides

Puget Sound's shoreline contains many large, deep-seated landslides that originally formed many hundreds or thousands of years ago, but that are periodically reactivated by unusually wet conditions. Some of these slides may have formed as glacial ice retreated. The loss of the support from the ice, combined with the abundance of meltwater, may have led to severe instability along the steep sides of the glacial troughs that became Puget Sound. Other large slides may have developed more recently as sea level reached its current position and began to cut into the shoreline, undercutting the already steep slopes. Finally, some slides may have been initially triggered by large earthquakes - for example, Karlin and others [1995] describe massive slides into Lake Washington that resulted from movement on the Seattle fault about 1100 years ago and such slides may well have occurred along Puget Sound as well.

Although these slides remain dormant during most years, movement is often observed during exceptionally wet periods. Movement is often incremental, with portions of the landslide dropping several feet during any particular cycle of reactivation. These slides often have complex internal structure and may consist of many separate landslide blocks that move somewhat independently. Most deep-seated landslides on Puget Sound exhibit rotational movement, with the toe pushing up and out as upper portions drop, and with individual blocks showing landward tilting (Figure 7).



The surface of the landslide often consists of a low bench characterized by irregular topography, backed by a distinct headscarp marking the landward limit of the slide.

Figure 7. Cartoon illustrating a deep-seated landslide.

In the Coastal Zone Atlas [Washington Department of Ecology, 1977-1980], many of these large landslides were identified as either Unstable Old Slides (Uos) or Unstable Recent Slides (Urs), depending on the evidence for recent movement (based on observations of obvious recent slides or vegetation absence, largely done in the early to mid-1970s). Although some of these slides are readily apparent in aerial photographs or from analysis of topographic maps, more precise delineations generally require field investigation. Abundant forest cover or significant development activity can obscure landslide features.

Many of these large landslides are well known locally. These large slides often exhibit gentler and lower topography than adjacent areas of high bluff and as a result, offer favorable development opportunities. Examples include Golden Gardens and Perkins Lane in Seattle, the shoreline north of Kingston [Thorsen, 1987], the Ledgewood Beach/Bonair neighborhoods on the west side of Whidbey Island (Figure 8), the Salmon Beach community below Gibraltar Road on Fidalgo Island, and many others. Some large slides are less well-known, either because the area is undeveloped and therefore reports of slides have been few, or because movement has been infrequent enough for the slide to go unnoticed or for it to be considered completely dormant. Numerous Washington State Parks are located on big, deep-seated landslides, including Camano Island, South Whidbey, Sequim Bay, and Kopachuck [Thorsen, personal communication].

A large landslide in the Hunter Point area of Thurston County affected more than 30 homes in the eastern portion of the Carlyon Beach development in 1999. Although geologists previously recognized that the area had potentially unstable slopes, it was not until after the disaster occurred that geologists were able to carry out the detailed field investigations that showed the presence of a large, pre-existing landslide.

Figure 8. Aerial photograph of Ledgewood Beach landslide on Whidbey Island. Homes lower on slope are built on a deep-seated landslide, portions of which periodically reactivate resulting in damages to homes and roads. The toe of the landslide is located near sea level *[Ecology, 5-5-199, ISL#0415]*

Stabilization of these large slides can be extremely difficult and expensive. Simply evaluating the factors that contribute to movement may be difficult because previous slide movement may lead to jumbled geologic units and unpredictable hydrological conditions. The depth of the slide and the presence of multiple failure surfaces may require extensive drilling and other geophysical surveys. The scale of these slides means that engineering measures that rely on countering the movement of the slide must in themselves be large. Stabilization measures on individual properties are rarely sufficient to affect the movement of the larger landslide.

Mud and debris flows

When large amounts of water are present in soils and landslide material, landslides take on more fluid-like properties and become flows. Debris avalanches high on a steep coastal slope can turn into debris flows or mudflows as they travel down the slope (Figure 9). Flows often occur when a landslide enters or travels down a stream channel. Factors affecting whether a flow occurs or not depend on the character of the geological materials involved, the amount of water present, and the distance the slide has moved. The same factors may affect the velocity of a flow. Flows can cause significant damage to structures in their path, with damage generally reflecting the velocity and volume of the slide.

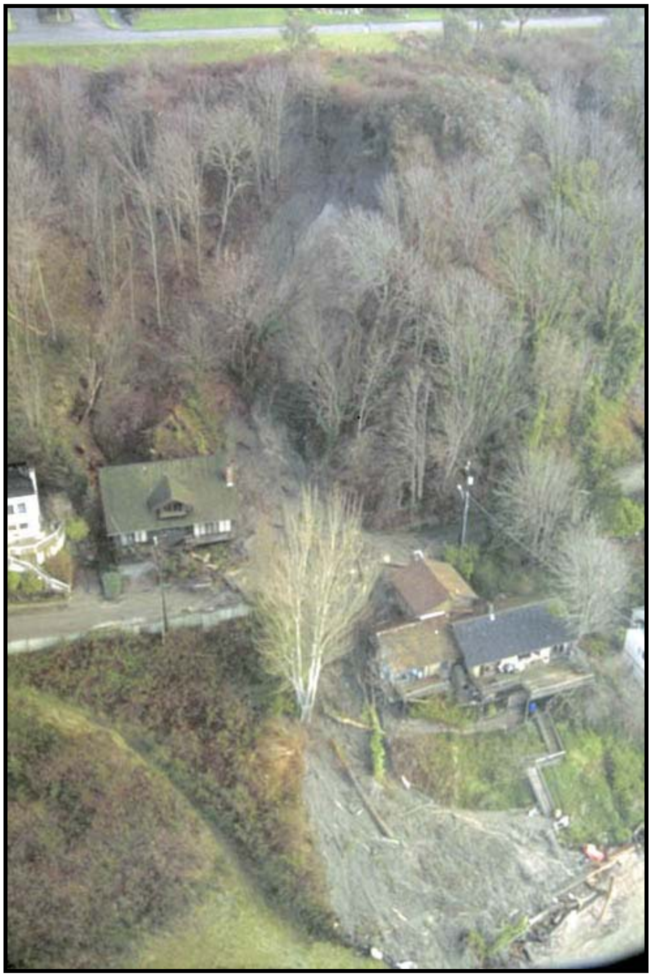


Figure 9. Debris flow downslope from a shallow landslide that occurred along Magnolia Bluff in Seattle during the 1996-97 Holiday Storm.
[Photo: 1/2/1997, #4108_12]

Factors in slides

A variety of factors influence the distribution, occurrence, and timing of landslides, including slope steepness, slope materials, hydrologic conditions, and others [Varnes, 1978; Jochim and others, 1988]. Landslides result when the stresses acting on a slope (driving forces) exceed the resistance of the slope to downward movement (resisting strength). The primary driving force is gravity and its effectiveness depends directly on slope geometry and loading. Resistance to earth movement depends primarily on the properties of the geological materials, hydrology, and the presence of additional strengthening elements, such as retaining walls or tree roots. Slides can be triggered whenever one of these factors changes sufficiently to result in unstable conditions. Erosion by wave action can steepen a slope, causing a slide. Heavy rain can saturate soils, reducing their internal strength. Earthquake shaking can also weaken soils or place additional loads on a slope[5].

Many landslides, particularly in developed areas, are aggravated by human actions. Shannon & Wilson [2000] found that 84% of the landslides inventoried in Seattle were influenced, at least in

[5] See appendix for discussion of impacts of 2001 Nisqually Earthquake.

part, by human activities. The most common contributors are the directing of runoff onto a steep slope or the failure of an existing drainage system on or above a slide-prone slope. Other situations include excavation and undermining of slopes, placement of fill material on slopes, failures of retaining walls, and clearing of vegetation.

Geologic materials

The importance of geology to landslides in the Puget Sound region has been previously discussed, but is largely related to hydrological conditions that occur in common sequences of poorly consolidated geological units found along the shoreline. The material properties of individual geological units are also important, since some geologic materials resist sliding much better than others.

Different units have different engineering properties (for a summary of properties of common geologic units found on Puget Sound, see table in Coastal Atlas, Washington Department of Ecology, 1977-1980). Unfortunately, engineering evaluations of soils, even within landslide areas, often simply provide laboratory measurements of strength. Palmer [1998] points out that stability evaluations should not rely simply on measured soil strength. Commonly, it is not the strength of the overlying and underlying units, but the contrast between them that is important. It is possible for materials within inches of a major failure surface to retain much of their engineering strength, yet this strength provides no clue as to the potential instability of the site. Such measurements are particularly problematic when based on samples obtained from boreholes where the context may be poorly known.

Glacial till tends to be highly competent and resistant to sliding, except where fractured or where other natural weaknesses extend through the rock. Similarly, the compact silts and clays found in glacial lake deposits are relatively cohesive, although their presence can be a major contributor to unstable conditions because of their hydrologic properties. Glacial outwash consisting of poorly consolidated sand and gravel may provide solid foundation support, but can be vulnerable to erosion and landsliding on or near steep slopes. Any material, as it becomes weathered by chemical and physical processes within the soil, is weakened and becomes more vulnerable to sliding.

Among the least stable materials are colluvium derived from past erosion and mass-wasting. Within historic landslide areas, the geology can be highly complicated. Materials that may have been strong in their original position may be heavily disturbed and weakened by subsequent movement and shearing. Water movement within the slide mass may be rapid and unpredictable.

Bedrock is generally highly resistant to landsliding. Slides can occur, however, in areas where fractures or bedding planes in the rock are steeply inclined and where water can penetrate, weakening the rock. Slides can also occur in glacial sediments that overlie bedrock - the bedrock acts as an underlying impermeable unit, just as lake bed clays do in other settings. When the water table above the interface rises and pore pressures increase, slides can occur. Susceptibility to sliding is higher where the buried bedrock surface slopes seaward. Bedrock in the Puget Lowland occurs on the San Juan Islands, Fidalgo Island and the northern part of Whidbey Island, the western portion of the Strait of Juan de Fuca, and the shoreline south of Bellingham along Chuckanut Drive. Limited bedrock exposures occur elsewhere, such as along western Hood Canal and portions of eastern Jefferson County, but slope stability remains primarily an issue for the non-bedrock shorelines of the Sound.

Slope Steepness

Landslides are ultimately caused by gravity and the stresses imposed on steeper slopes are generally greater than on shallow slopes. Different geologic materials have highly variable resistance to sliding, however, and hydrologic conditions can also vary from one slope to the next. Predicting landslides based on slope gradient alone provides a generally accurate picture of the areas prone to debris avalanches in colluvial soils, particularly if hydrologic factors are accounted for, but may be considerable less useful in identifying areas subject to deeper-seated landsliding.

Slope, in itself, can be a deceptive indicator of stability. Some steep slopes can be remarkably stable. Well-drained glacial till can stand vertically for many decades or centuries. When failures do occur, they are often along vertical fractures parallel to the bluff face, so the steep slope is maintained as the bluff retreats. Conversely, slides can occur on very gradual slopes if the right combination of geologic units and hydrologic conditions exists. Some of the Sound's most unstable soils exist on relatively level mid-slope benches where the upper ten or more feet of soil readily slides laterally on a saturated zone developed atop the underlying, impermeable fine-grained units. The overall slope within the large Carlyon Beach landslide north of Olympia is very low, although historic slide scarps within the slide were steeper [Geoengineers, 1999].

Angle of repose is often cited in reference to slope stability, since it represents the maximum slope angle at which materials can remain stable - other factors aside. Palmer [1998] notes that many Puget Sound bluffs approach or even exceed a 40% slope, indicating that other factors contribute to maintaining the slope. Such factors include compaction and cementation of sediments and the stabilizing contributions of vegetation. As a general rule we find the term "angle of repose" confusing and often difficult to apply properly in describing slopes consisting of multiple geological units and units with widely different material properties.

The steepness and the shape of a coastal slope depends not just on the geologic units of which it is composed, but also the geomorphological processes affecting the slope. Stream erosion and wave action at the base of a slope contribute to maintaining steep coastal bluffs. Upper bluff slumping related to perched water above underlying finer grained sediments leads to the development and widening of mid-slope benches. The presence of the bench is in itself evidence that the upper part of the slope may be retreating faster than the toe of the slope. In contrast, on some relatively stable slopes, wave action may result in the lower slope becoming oversteepened, yet it may take decades or centuries for this erosion to translate to recession of the top of the bluff.

Toe erosion and undercutting

Erosion of the toe of a slope steepens and undermines the bank, decreasing its stability. Undercutting at the base of a steep slope can set the stage for slides that progressively destabilize higher parts of the slope. On Puget Sound's shorelines, cutting into the toe of slopes most commonly occurs due to erosion by wave action. Undercutting can also occur in mid-slope areas as a result of erosion of underlying units by groundwater seepage or surface erosion. Downward movement of deep-seated landslides can undermine steep upper slopes also. Humans often cut into the toes of slopes to construct access roads or homes or even in the process of building bulkheads and retaining walls. Toe erosion may involve cutting into fresh materials exposed at the base of the slope or it can simply involve removing colluvium from past mass-wasting that may be helping to buttress the slope.

The rate of shoreline erosion on Puget Sound varies considerably and depends on a number of factors [Shipman, 1995]. These include exposure to wave action, the resistance to erosion of the geologic materials at the base of the bluff and immediately below the beach surface, and the width and elevation of the beach itself. When beaches are low and narrow, waves can erode the toe of the bluff during high tides and storm action and may directly influence slope stability, but when beaches are broad and littoral sediment abundant, wave action may seldom reach the toe of the bank and mass-wasting primarily occurs due to upslope geologic and hydrologic factors -- waves only serve to remove debris that is deposited on the beach.

Steepening a coastal bluff through chronic toe erosion is a relatively slow process that acts over many decades or even centuries, whereas landslides tend to occur in response to transient increases in groundwater and soil saturation. As a consequence, the common emphasis on toe protection is sometimes short-sighted, as it does little to alleviate the already steepened slope and does nothing to reduce the potential for heavy rains causing saturated soils to fail. Not only are numerous residential bulkheads buried beneath subsequent landslides, but most of the dramatic landslides that occurred in 1996-1997 occurred on shorelines that had been protected at their toe for many decades or longer (for example, Perkins Lane and Duwamish Head in Seattle, the Woodway landslide, or the Rolling Bay landslides on Bainbridge Island).

Shoreline management efforts relating to landslides are complicated by the fact that most of the beaches on Puget Sound consist of sediment derived from the erosion of coastal bluffs through landsliding [Downing, 1983]. Although toe protection may well be part of a stabilization solution, successful prevention of erosion and landsliding in some areas may result in significant diminishment of sediment supply to the littoral system over a period of decades and may lead to accelerated erosion in previously stable areas [Macdonald et al, 1995] elsewhere along the shoreline.

Hydrology

Hydrological factors affect both the overall stability of a slope and the timing and occurrence of landslides. As discussed previously, the presence of impermeable barriers to downward movement of groundwater can lead to zones which are particularly susceptible to landsliding. This commonly happens along the interface between weathered colluvium and underlying unweathered soil and between well-drained glacial outwash and underlying fine grained silts and clays. Again, the contrast in permeability between the two units may be much more important than the predicted or measured (in the laboratory) strength of the individual units.

When wet weather cause groundwater levels to rise, slope stability is compromised in several ways. As pore pressures increase in the sediments, the strength of the units is reduced, and slope failure can occur along the resulting zone of weakness. Increased groundwater levels also increases seepage and flow rates, which can result in erosion of the lower slope, saturation of soil below the seepage zone [Tubbs, 1974], and in some cases, erosion of the seep zone itself, undercutting the upper slope. Groundwater blowouts [Shannon and Wilson, 2000] occur when rapid erosion occurs of sediments near the bluff face as a result of anomalously high pore pressures. Finally, runoff saturates surface soils and colluvial materials on the slope, increasing their weight and further loading the slope.

Surface water enters soils, the shallow water table, and deep groundwater zones by a number of means. Deep groundwater is generally influenced by prolonged periods of precipitation over relatively large areas. Shallow groundwater levels respond more directly to rainfall events and may be extremely susceptible to modifications in natural drainage, wetlands, or vegetation cover.

The saturation of surface soils depends on soil properties and vegetation cover and responds quickly to precipitation, but can be exacerbated by directed surface runoff (natural or artificial) and groundwater seepage (particularly on the face of steep slopes where springs occur).

Tubbs [1974] found that 70% of the landslides in Seattle in early 1972 occurred on one of three days in which precipitation exceeded 1.75 inches in 24 hours. 90% occurred when 24-hour rainfall exceeded 1 inch. Shannon and Wilson [2000] notes that geologists in the region have relied on a rule of thumb that predicts significant sliding when daily precipitation exceeds 2 inches or when two day precipitation exceeds 3 inches. Intense rain is more likely to trigger landslides when soils are already saturated, explaining why landslide events occur more frequently after several days of heavy rains and why slides often occur later in the winter [Tubbs, 1974; Chleborad, 2000].

Human activities can directly impact both runoff and the rate of infiltration of stormwater into soils and the groundwater, thereby influencing slope stability. Human modifications to hydrology may increase or decrease slope stability, depending on the local geologic conditions and the combination of activities involved. Vegetation modification (clearing, landscaping) and development directly affect runoff volumes. Stormwater controls can greatly modify the location and volume of infiltration within a developed or developing area. For example, a road paralleling the top of a steep slope can intercept large volumes of surface runoff and shallow groundwater, redirecting this flow to concentrated locations at culvert crossings, and possibly modifying the stability of the slope.

On individual residential lots, concentrated drainage from driveways and roofs is often directed to the adjacent slope. If well designed and maintained, such drains may improve stability by reducing infiltration above the bluff, but if poorly designed or if failure occurs, such drains can greatly exacerbate problems by leading to concentrated infiltration on the slope itself or serious surface erosion. On-site septic systems and drainfields, which predominate along a bulk of Puget Sound's residential shoreline, can lead to increased infiltration, as can poorly planned or maintained irrigation systems.

Loading

Any process that adds weight to the top of a potentially unstable slope can increase the risk of sliding. The placement of fill on or adjacent to a steep slope can lead to slides, as can the natural deposition of material from landsliding from farther upslope. On a mid-slope bench, the sliding of material off of the upper scarp may help drive the movement of material across the bench, to the point where it slides down the lower slope towards the shoreline. Although less common, the construction of heavy structures on a slope, the stacking of clearing debris and logs, or the storage of heavy construction equipment near the edge of a slope can lead to failures.

Water itself can add a surcharge to a slope. Runoff or groundwater seepage can saturate loose surficial soils and colluvium, leading to failure as the material's mass increases. A common scenario on residential property involves the dumping of yard waste over the edge of the slope. When these materials become saturated during heavy rains, they often slide, occasionally triggering larger slides of soil and vegetation downslope. Loads can also be imparted to a slope when wind stress causes large trees to shift[6] or by earthquake shaking (see Appendix).

[6] The movement of large trees by wind is also suggested, at least by some, to cause loosening of soils and increased infiltration, also leading to slides. Although often cited as a cause of slides and a reason for removing large trees, it is unclear how significant wind stress actually is. In some cases, removal of

Vegetation

Most of the steep slopes surrounding Puget Sound are heavily forested, or were so prior to human settlement. Even where slopes themselves did not support heavy vegetation due to unfavorable geologic materials or due to rapid erosion, the upland areas above the slopes which directly affect shallow groundwater recharge were forested. The influence of vegetation on slope stability is poorly understood and loudly debated. The debate is complicated by additional considerations that are only indirectly related to slope stability, but that strongly influence opinions. Vegetation removal enhances views from shoreline property, a major consideration for property owners; large trees are often perceived as a hazard (during windstorms) or an obstacle to landscaping (shadowing and leaf litter); and extensive root systems obstruct drainfields, drain systems, and property improvements. On the other hand, vegetation along the shoreline can help stabilize steep slopes and is a critical ecological resource that provides habitat by contributing shade, woody debris, and other organic material to the beach and to the aquatic environment [Thom and others, 1994].

The primary influence of vegetation on shoreline bluffs appears to be on hydrologic characteristics - since it affects infiltration and surface runoff. Vegetation protects soils and steep slopes from surface erosion and decreases the rate and volume of infiltration of rainfall into the soil. Vegetation is an important mechanism for removing water from soils by transpiration - this may be particularly relevant for conifers that continue to transpire during winter months when precipitation is high and slides more likely. These factors may be as important for forested areas well above the slopes as they are on the slope itself, due to their impact on shallow groundwater recharge.

On the slopes, vegetation can add strength directly through the development of extensive root systems and the ability of larger trees to buttress the slope. Mature root systems not only bind weathered soils together, but can anchor these soils to underlying geologic materials. On some Puget Sound bluffs, gradual soil creep and small slides have led to the development of dense webs of woody material near the toe of the slope that act as natural bulkheads against wave action and may provide support to the slope itself.

Vegetation can also destabilize slopes. Vegetation growth increases weathering of soils and root action can, particularly in compact units like glacial till, loosen natural fractures and joints in the material, leading to failure. Movement of trees by wind stress may loosen soils, enhancing infiltration, and in some cases, may impart significant loads to the slope itself that may trigger failure. Regardless of their role in stabilizing or weakening slopes, trees can become lethal projectiles when a slope does fail, endangering structures that are not adequately set away from the toe of the slope. As a consequence, each site warrants a complete, but individual analysis.

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vegetation can in itself reduce slope stability by decreasing root strength or modifying hydrologic conditions, suggesting that decisions to remove vegetation need to carefully considered and are likely to be highly situation-dependent.

Rainfall and Landslides

The landslides observed in the Puget Sound region between 1995 and 1999 were directly related to heavy precipitation, both in the form of extremely intense periods of rainfall over several days and in the form of prolonged wet conditions over many months. Short periods of heavy rain led to extensive shallow landsliding as seen in central Puget Sound during the Holiday Storm of 1996-1997. Prolonged periods of wet weather contributed to the reactivation of deep-seated landslides during the winter of 1998-1999.

Winter 1996-1997

The winter of 1996-1997 exemplified the effect of extremely heavy precipitation on the initiation of shallow landslides and debris avalanches. The previous winter of 1995-1996 was wet and numerous landslides occurred throughout the Pacific Northwest [Harp and others, 1996][7]. Rain was again intense in late 1996, leading up to the events of the week between Christmas and the New Year. More rain in mid-January triggered additional sliding in already saturated soils. Another round of heavy rains resulted in yet another round of damaging landslides in mid-March, 1997. Table 2 summarizes the federally declared disasters in Washington during this period.

Storm Event	Disaster	Date of Declaration
February 5-9, 1996	DR-1100-WA	February 9. 1996
Holiday Storm of 1996-1997	DR-1159-WA	January 17, 1997
March, 1997	DR-1172-WA	April 2, 1997

Table 2. Federally Declared Disasters involving landslide losses in the Puget Sound region (1996-1997).

Four meteorological factors combined in late December, 1996, to trigger the landslides, flooding, and other storm damage that led to the federal disaster declaration. These were: 1) record setting 15-month precipitation, 2) heavy, low elevation snowfall, 3) freezing rain (less significant for slides than for other elements of the disaster), and 4) heavy rainfall accompanied by rapid warming [U.S. Army Corps of Engineers, 1997]. Total precipitation in Seattle for the week ending January 2nd exceeded 7 inches (Figure 10). More significantly, much of the precipitation early in the week fell as snow, which melted rapidly during the warming and continuing rains after the 31st.

[7] Federal Disaster #DR-1100-WA addressed losses occurring primarily as a result of heavy rainfall throughout the Pacific Northwest in early February, 1996. The distribution of landslides during this event is described in Harp and others [1996]. Although significant landsliding occurred in the Puget Sound region, the hardest hit areas were in southwest Washington and in the Blue Mountains of the southeastern part of the state.

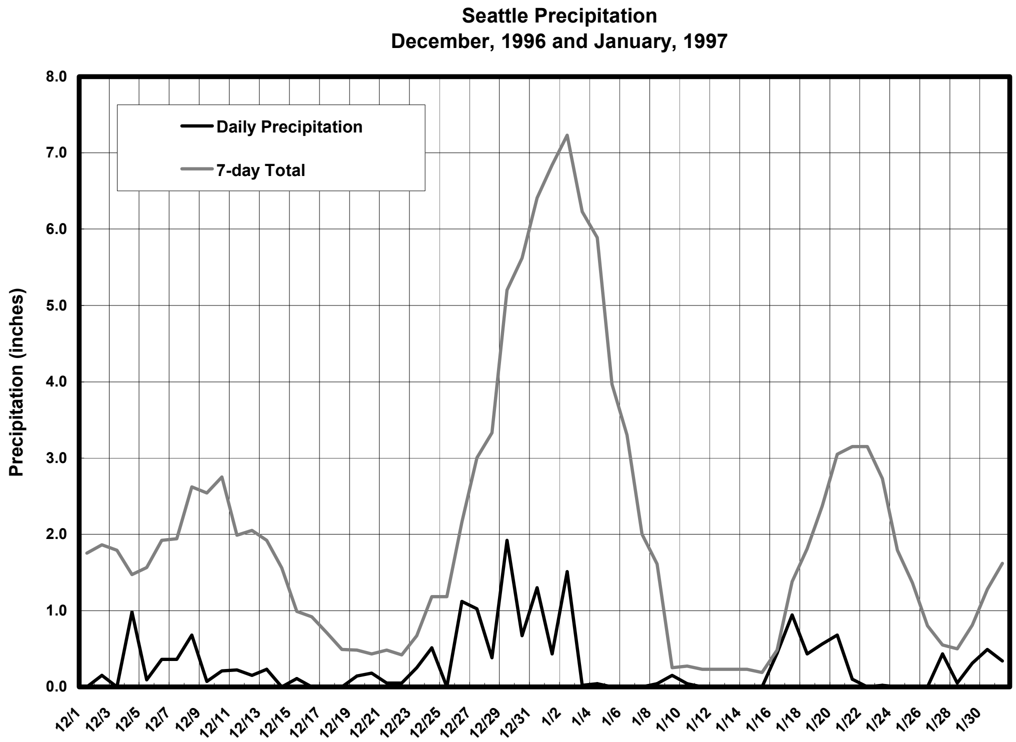

Figure 10. Precipitation records for SeaTac airport south of Seattle for December, 1996 and January, 1997. Lower curve indicates daily precipitation while upper curve shows a 7-day running total that may better predict soil saturation and landsliding.

Several factors affected the occurrence and distribution of slides during the 1996-97 Holiday Storm.

- The presence of the dense snowpack impacted surface runoff. Storm drains were plugged or blocked, forcing meltwater elsewhere or resulting in localized ponding. Large volumes of runoff were directed downslope along roadways, leading to concentrated flows at cul de sacs and low points - landslides were numerous where such low points were adjacent to steep slopes.

- Infiltration was likely inhibited in some areas by the presence of the snowpack and by frozen ground, leading to increased runoff. Infiltration increased rapidly, however, as temperatures warmed and snow melted.

- The intensity of rainfall may have varied locally depending on the tracks and evolution of individual storm cells.

Because shallow sliding is sensitive to the level and rate of infiltration, the distribution of shallow landsliding can be highly variable. Although no systematic study has been carried out of Holiday Storm landslides (and such a study would be difficult in the absence of comprehensive inventory that focused on all slides, damages or not), it is likely that the distribution of sliding may have reflected the track of particularly intense storms and the variability in the snowpack.. Just as rapid flooding can occur when a discrete storm cell passes over a small watershed, shallow landsliding responds to heavy downpours that may vary in magnitude over short distances. It may be possible to estimate areas of hardest sliding by observing storm tracks.

Winter 1998-1999

A series of La Nina episodes during the late 1990s brought almost 50 inches of rain to Seattle in three of the four water years (October through September) between 1995-96 and 1998-1999 (Figure 11). The only dryer year occurred during the El Nino of 1997-1998. As a result, the cumulative multi-year rainfall was at record levels in 1998 and 1999.

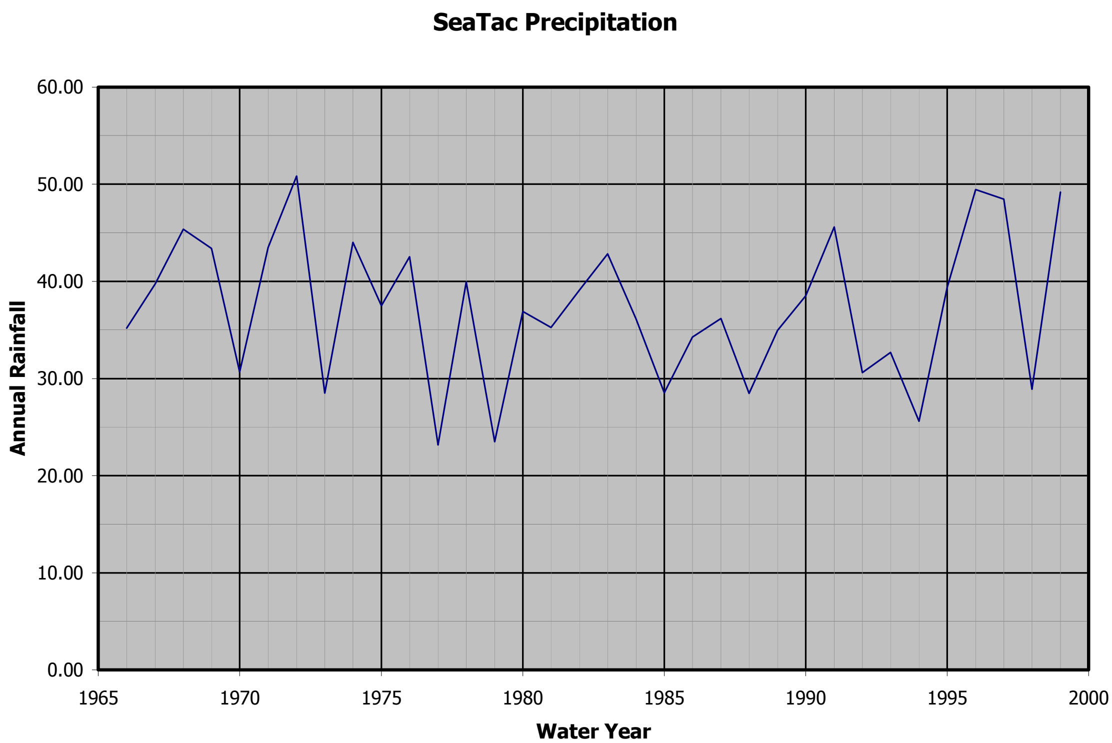

Figure 11. Plot of annual rainfall at SeaTac airport, showing above normal rainfall in water years 1996, 1997, and 1999. Water years describe precipitation between October and September (e.g. the 1997 water year extended from October 1, 1996, through September 30, 1997).

In addition, total precipitation between November, 1998, and January, 1999, was 27.36 inches (SeaTac airport), the highest three-month total on record (Figure 12). These record levels were observed throughout the Puget Sound region. Although two extremely heavy periods of rain occurred during November and December, the region did not experience the abundance of shallow landsliding seen in 1995-1996 and 1996-1997.

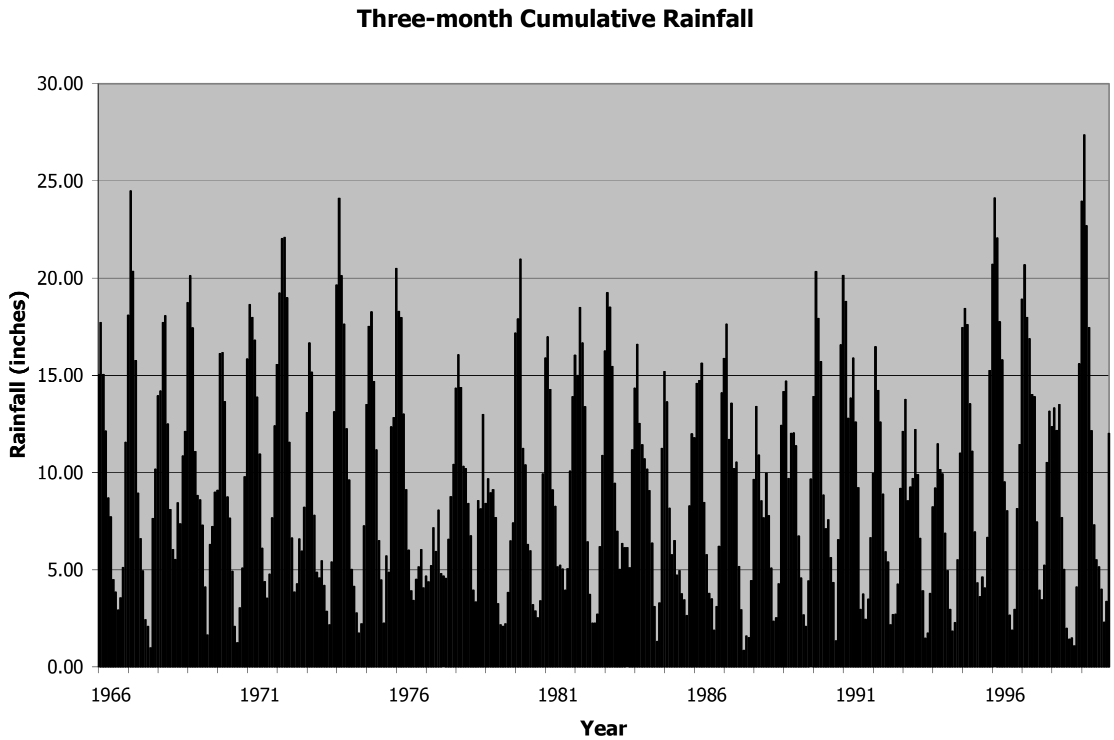

Figure 12. Three-month cumulative precipitation as measured at SeaTac airport between 1965 and 2000. Note record high levels during the winter of 1998-1999.

The superposition of record-level three-month precipitation on top of a series of very wet years would have been expected to influence regional groundwater levels significantly and may have been factors in the widespread reactivation of deeper landslides in early 1999. Highly publicized coastal landslides in south Puget Sound included those in Thurston County (Hunter Point-Carlyon Beach and Sunrise Beach) and along Highway 101 on Hood Canal in Mason County. To the north, both Kitsap and Jefferson Counties experienced numerous deep-seated landslides during February and March of 1999.

Reactivation of deep-seated landslides is more likely as deep groundwater levels rise, which requires high volumes of infiltration and in most situations, considerable time. Such events would not be expected to respond to rain bursts as shallow slides do. The geology and mechanics of individual landslides varies significantly, however, and each will respond to hydrologic conditions differently. Determination of threshold conditions for reactivation may depend on long-term monitoring of rainfall, groundwater, and slope movement - and results are likely to be different for each slide. Human influences on deep slides may be different than on shallow slides as well, possibly reflecting land use changes over broad areas and over long periods of time.

Landslides of the 1996-1997 Winter

Heavy rains led to two disaster declarations during the winter of 1996-97, both of which included landslides. The first resulted from the Holiday Storm between December 29 and January 2. The second occurred following heavy rains in mid-March. Not all landslides were restricted to this narrow range of days, as some occurred days or weeks after the rains, or were ongoing slides that continued throughout the period. Few systematic inventories of landsliding were carried out following the 1996-1997 storms and no comprehensive catalog was completed for the region. A variety of surveys were undertaken, however, and are summarized below.

Among the difficulties in inventorying and obtaining information about landslides in the Puget Sound region is that most information is collected at the local level, yet there are twelve counties and over thirty incorporated cities that include Puget Sound shoreline. Even if all jurisdictions collected information on landslides and did so in a consistent fashion, compiling data from such a wide range of sources would be extremely time consuming. As it is, documentation must be obtained from a variety of local records, news accounts, consulting reports, and interviews with local officials and residents.

Gerstel and others [1997] describe numerous examples of landslides that occurred during the Holiday Storm. This paper draws in part on a post-disaster landslide survey carried out by helicopter in conjunction with the City of Seattle immediately following New Years, 1997, so is weighted toward heavily toward Seattle slides. Several examples from southern Whidbey Island and eastern Jefferson County are also included, based on input from other geologists.

Geologists from the United States Geological Survey (USGS) documented numerous landslides from the 1996-1997 winter [Baum and others, 1998]. The authors provide brief descriptions of several landslides not well documented elsewhere, in addition to observations of highly publicized landslides such as at Perkins Lane (Seattle), Woodway (Snohomish County), and Rolling Bay (Bainbridge Island). Most examples were from coastal sites, although this may simply be an artifact of where landslides were reported and the reconnaissance strategy of the geologists.

Palmer [1998] conducted an aerial survey of extended segments of Puget Sound shoreline in April, 1997, to document the extent of coastal bluff landsliding. The study included portions of King, Kitsap, and Jefferson Counties. The author observed active (bare soil) landsliding on approximately 20% of the shoreline and relatively recent sliding (less than five years) on another 30%, indicating that about half the shoreline surveyed had experienced sliding within a five year period. The shoreline included in the study was not randomly selected - it focused on areas hit hardest in the Holiday Storm, it didn’t include hard hit portions of Island and Snohomish Counties, and for practical reasons, it was limited largely to east-facing shorelines - but generally provides an accurate picture of coastal bluff landsliding.

The Federal Emergency Management Agency's response to the 1996-1997 disaster included making geotechnical expertise available to property owners for identifying appropriate actions for minimizing additional losses or risks. The Individual Assistance Program [FEMA, 1997a] included 102 properties in western Washington, of which 39 appeared to be located along Puget Sound coastal bluffs, based on the descriptions provided by the field staff (Table 3). These accounts provide insight into the character of various slides and the perspectives of the property owners, but represent only a small subset of all landslides that occurred during the disaster. For example, only 29 sites were visited in King County, yet Seattle alone reported several hundred slides. Individual Assistance visits do not constitute a systematic inventory, since they represent only responses to property owners who had 1) suffered damage, 2) were aware of FEMA's program, and 3) were not already seeking assistance elsewhere. They only include landslides that resulted in damages.

County	Number of Sites	Sites on Puget Sound
Clallam	6	2
Island	13	10
Jefferson	1	0
King	29	10
Kitsap	10	8
Mason	1	1
Pierce	2	1
Snohomish	29	7

Table 3. FEMA Individual Assistance Program - Puget Sound Coastal Counties.
"Sites on Puget Sound" refers to reported landslides along coastal bluffs.

The remainder of this chapter describes a number of coastal landslides that occurred during the winter of 1996-97 in the region for which information was available and that I believe illustrate the range of landslide types and associated hazards. The examples are by no means a complete inventory. Rather, their purpose is to educate about the character of sliding and to provide some historical information for evaluating future sliding in the same general areas. The information was obtained from field visits, interviews, geotechnical reports, and press accounts.

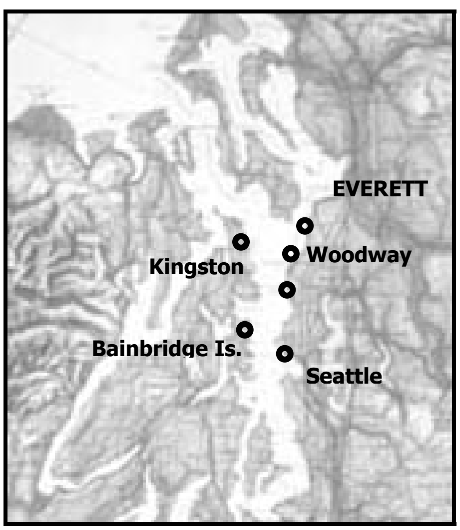

Figure 13. Location of 1996-97 landslides described in this report.
Note that all are in central Puget Sound region.

City of Seattle — KING COUNTY

Among the hardest hit areas during the 1996-97 winter was the City of Seattle, where hundreds of landslides were reported. The incidence of landsliding may not have been higher in Seattle than in more rural areas, but because so much of the City is heavily developed, few slides occurred that did not result in reports of damage to either private property or to public roads and facilities. In less developed areas many slides may simply have gone unnoticed -- or at least unreported.

Most slides occurred as shallow failures along the steep slopes surrounding Puget Sound and Lake Washington, although deeper slides on mid-slope benches were also common. The slides occurred in the same general areas as slides in previous wet years, including those of 1972 and 1986. Areas of significant sliding along Puget Sound included Magnolia Bluff, Queen Anne, Duwamish Head in West Seattle, and the bluffs north of Carkeek Park - all areas with long histories of landslide activity.

The City of Seattle recently completed a major inventory [Shannon & Wilson, 2000] of historic landsliding that includes all recorded past landslides, including those of 1996-1997, along with a detailed analysis of when landslides have occurred and in what parts of the City. The comprehensiveness of this study benefited from Seattle's extensive archive of historic landslide information. Geologists with the USGS are now using this database to begin to evaluate patterns of sliding, landslide recurrence intervals, and precipitation thresholds [Coe and others, 2000; Chleborad and others, 2000].

Duwamish Head and Alki Beach, Seattle — KING COUNTY

Duwamish Head is marked by a distinct topographic bench developed in the upper portion of the underlying Lawton Clay. This bench is overlain by a blanket of sandy material derived from the overlying glacial outwash (Esperance sands and gravels). The latter is susceptible to movement in wet conditions and tends to slide over the edge of the bench and result in slides and debris flows down the steep, lower portion of the bluff.

Historically, such sliding has damaged numerous homes along Alki Avenue SW that back on the toe of the slope. In recent years, many of the smaller residences and beach cabins along Alki and Harbor Avenues have been replaced by multistory condominium and apartment structures. These large buildings, although often extending to the toe of the slope itself, are built under strict codes that require reinforced rear walls to prevent damage from debris and design that allows the removal of mud and debris after slides occur. The March, 1997, landslides led to extensive sliding of material down the slope behind these buildings, but although this resulted in large volumes of mud being deposited against the buildings and sometimes flowing into spaces between buildings, the most serious damage occurred when woody debris damaged a concrete wall to a utility area. The City of Seattle is undertaking an extensive drainage project along the mid-slope bench to minimize risks of this type of sliding in the future.

Two large slides along California Avenue SW, one in the winter of early 1996 and another that began moving during the Holiday Storm, occurred in this same geologic setting and appeared to involve the failure of material above the mid-slope bench. California Avenue (which cuts diagonally up the slope from Harbor Avenue to the top of the West Seattle ridge) was closed by each of these slides and the City has subsequently undertaken major repair work in each of these landslides.

Figure 14. Landslide along Bonair Drive SW, above Alki Beach in West Seattle.
Note scarp cutting downslope edge of road and through the lot in the foreground. *[Photo: #4108_18, 1/2/1997]*

In some locations, deeper failures have formed in the bench, resulting in landslides of the sort observed along Bonair Drive SW in early 1997, where movement of underlying soil (sometimes of fill placed to create building sites on the sloping terrain) undermined homes or roads (Figure 14).

Perkins Lane, Magnolia Bluff, Seattle KING COUNTY

The Perkins Lane neighborhood of Seattle has an extensive history of landsliding. It lies along a rolling topographic bench that extends for over a mile below Magnolia Bluff and has been developed since at least the 1930s. Perkins Lane was one of many unstable areas in the City to receive extensive WPA-funded drainage projects, partly as a response to very heavy rains and landsliding in the winter of 1933-1934 [Evans, 1994].

Harp and others [1996] describe a landslide that occurred in early March, 1996, near the eastern end (the 1700 block) of Perkins Lane. Approximately 1,500 cubic yards of material fell onto the road and against homes, doing minor structural damage. The slide was apparently precipitated by deeper movement of a rotational slump that extends below Perkins Lane and the homes themselves. Harp and others [1996] suggested in their report that continued movement was likely along the deeper failure. During the Holiday Storm of 1996-1997, additional movement did occur, despite both public and private efforts to stabilize the slope during the previous year(Figure 15). By the summer of 1997, continued movement had largely destroyed the six homes on the active slide. By late 1999, very little of any of the structures remained (Figure 16).

Figure 15. Aerial view of southeast end of Perkins Lane taken after the 96-97 Holiday Storm. Homes are located along a mid-slope bench. Note large failure in glacial till behind homes. *[Photo: 1/2/1997, #4108_17]*

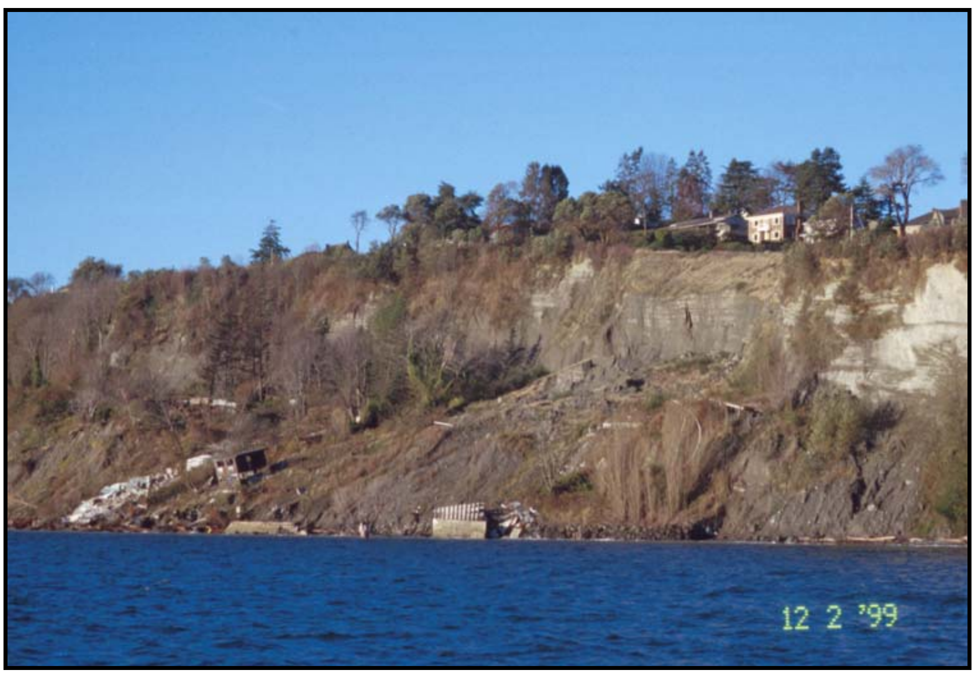

Figure 16. View of same portion of Perkins Lane taken in 1999
Little of original structures remains. *[Photo: 12/2/1999, #99-48-21]*

Magnolia Bridge, Seattle — KING COUNTY

On January 2, 1997, a relatively deep landslide occurred in the upper portion of the steep slope above the western approach to the Magnolia Bridge (Figure 17). The slide undermined the yards and decks of several homes along Magnolia Way West, destroyed bracing supporting the bridge piers, and the debris flow damaged a residential structure at the toe of the slope. This site lies a short distance north of an area impacted by significant deep-seated landsliding in the 1970s and that was involved in a large slide in 1892 (Tim Walsh, personal communication).

The Magnolia Bridge is one of the primary access routes to the Magnolia neighborhood and its closure significantly impacted the community. The road was reopened later in 1997 following extensive repairs to the slope (Figure 18). Ironically, the eastern approach to the Magnolia Bridge was seriously affected during the winter of 1998-1999 by a large deep-seated landslide on the western slope of Queen Anne hill.

Figure 17. Landslide above Magnolia Bridge.
In addition to threatening homes at top of slope, slide debris damaged bridge supports and a home located at the base of the slope. *[Photo: 1/2/1997, #4108_14]*

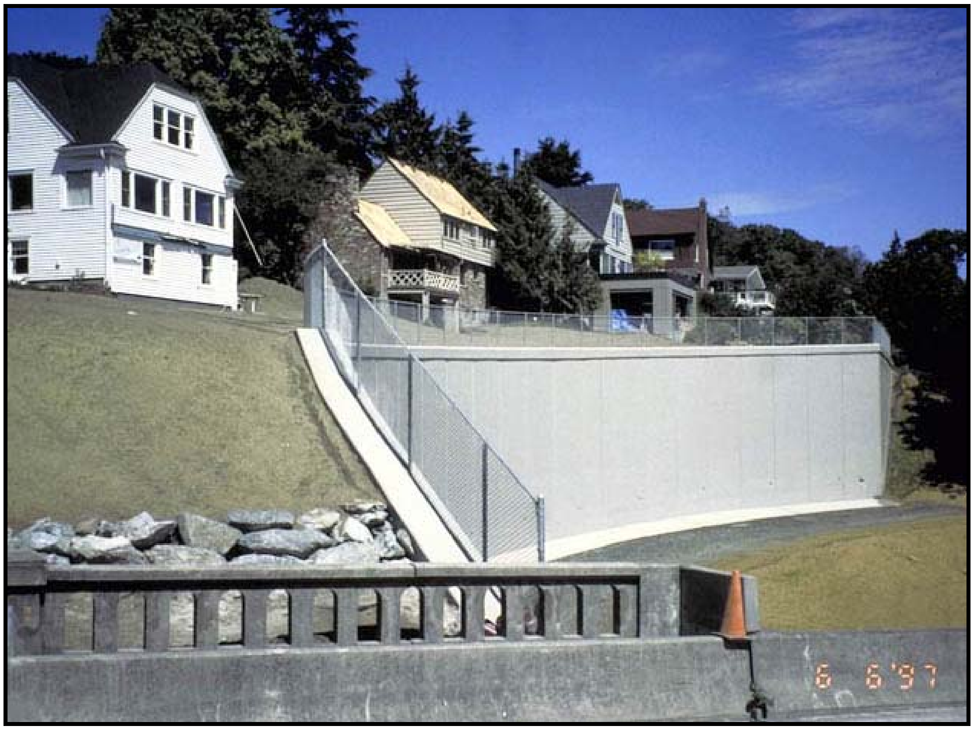

Figure 18. Repair of landslide in Figure 17, showing reconstructed slope and large retaining wall.
[Photo: 6/6/1997, #4108_15]

BNSF Railroad Grade KING/SNOHOMISH COUNTIES

The railroad grade between Seattle and Everett was impacted by as many as 130 landslides during the Holiday Storm, temporarily shutting down rail operations (Figure 19). The rail line had also been heavily impacted during the previous winter of 1996. The railroad serves as an important corridor both for transcontinental freight shipments and for local industry (Boeing relies on this line to transport aircraft assemblies between plants in the Puget Sound region). In addition, the route is used by AMTRAK and will soon be used for regional commuter rail service, raising important public safety issues.

The Great Northern Railroad constructed the tracks along the beach at the toe of the bluffs in the late 1890s. Landslides have long been an issue for the railroad (now Burlington Northern Santa Fe), requiring frequent maintenance and cleanup following storms and resulting in the relocation of the grade waterward in several locations to minimize potential impacts from slides and debris flows. The railroad uses a trip-wire warning system along the toe of the slope to alert operators to possible debris or damage to the tracks.

Figure 19. Aerial view of landslides over railroad tracks north of Seattle.
[Photo: 1/2/1997, #4108_19]

Possession Lane, Mukilteo SNOHOMISH COUNTY

Possession Lane extends north from the Picnic Point area in southwest Snohomish County, terminating in the vicinity of a privately held shoreline locally known as Shipwreck Point. The private road lies at the base of high, steep bluffs that are developed above (Figure 20). The Burlington Northern Santa Fe railroad grade runs along the toe of the slope, along the beach. In one area, a large lagoon separates the toe of the bluff from the railroad causeway - a result of the railroad being historically relocated waterward - probably to avoid landslides. Homes lie above and below Possession Lane in an area underlain by large, deep-seated prehistoric landslides, but also subject to shallow landslides and debris flows.

The 1997 damage was apparently due to the latter [FEMA, 1997a, Individual Assistance Program]. Two homes were destroyed and several others damaged by debris flows. Property owners felt strongly that problems were related to land development activities and drainage problems above the bluff, although the area is clearly the site of historic landslide activity.

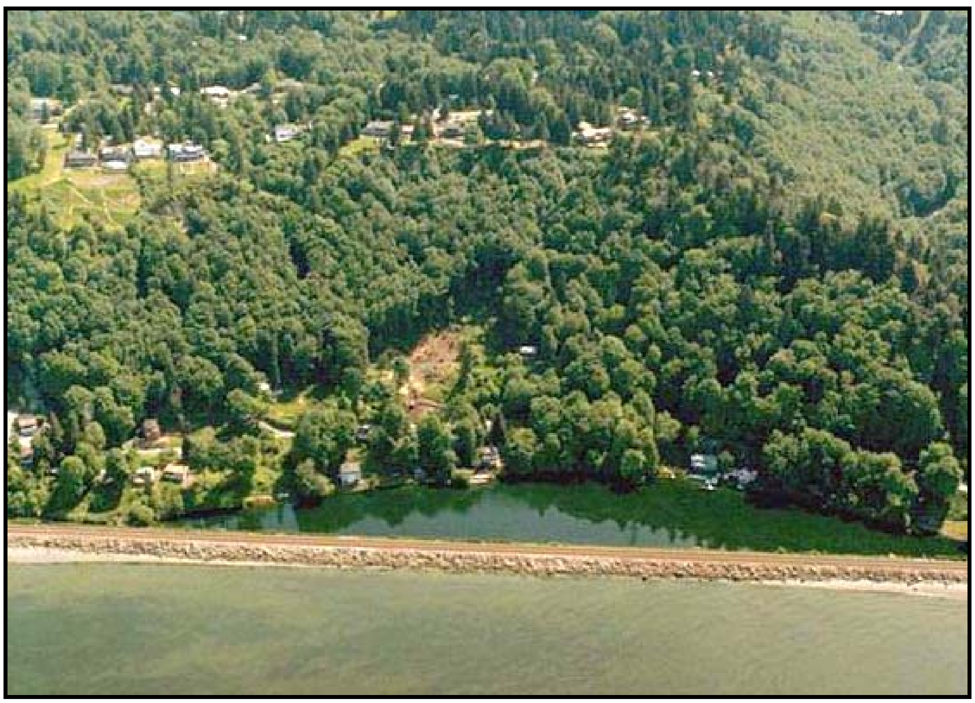

Figure 20. Aerial view of Possession Lane neighborhood, just north of Picnic Point in Mukilteo. Note distinct headscarp near top of slope and numerous homes located near base of slope along Possession Lane. A lagoon has been created by the location of the railroad grade waterward of the slope toe. *[Ecology, 5/17/1993, SNO#243]*

Woodway SNOHOMISH COUNTY

On the night of January 15th, 1997, two weeks after the Holiday Storm, but a week and a half since significant rain had fallen in the area, a large landslide occurred in Woodway, south of Edmonds, along the Puget Sound shoreline. Burlington Northern Santa Fe's tracks lie at the base of the bluff and the slide carried several cars of a freight train into the Sound.

The landslide cut approximately 50 feet into the grounds of the Dominican Reflection Center at the Rosary Heights convent and involved many tens of thousands of cubic yards of material. The slide occurred in at least two major failures over a several hour period [Arndt, 1998; Gilbert and Laprade, 1998] cutting deeply into fractured deposits of the underlying Lawton Clay.

The shoreline from Edmonds south through Woodway has experienced major slides before. In the 1950s, the high cost of keeping the line clear resulted in the Great Northern Railroad (which had built the line in the late 1890s) relocating the tracks as much as 100 feet waterward, creating a trough and tidal wetlands between the rail grade and the toe of the slope. Major slides in the early 1970s north affected large portions of the bluff to the north of Woodway filling much of the trough with debris that is now heavily vegetated. The 1997 landslide filled the trough below Rosary Heights, overtopped the railroad grade, and deposited tens of thousands of cubic yards of material over the beach (Figure 21).

Figure 21. Woodway landslide from the air. Photo taken in late March, 1997.
Prior relocation of the tracks waterward had left a broad trough at the base of the slope. The landslide filled this low trough, crossed the tracks, and formed a large point of land on the shoreline. *[Photo: 3/30/1997, #97-22-17]*

Rolling Bay, Bainbridge Island KITSAP COUNTY

The most tragic landslide of the 1996-97 winter occurred on January 19th when a debris avalanche killed a family of four in their home in the Rolling Bay community on Bainbridge Island. Ironically, a nearby house had been destroyed the previous year by a landslide and another home was damaged by a subsequent slide in March, 1997. These slides, including the one that destroyed the Herron home, were relatively shallow failures of the steep slope that lies above and behind the houses (Figure 22). The slide occurred during the first major rains that fell following the Holiday Storm, two and a half weeks earlier.

Several contributing factors were cited by media accounts and geologists, including uncontrolled drainage from the homes that perch on the top of the bluff and the failure of a small retaining wall built on the slope above the house, but ultimately the slide appears to be typical of many such slides that impact, or stand to impact, beach communities built at the base of steep slopes. Rolling Bay is just one of many small clusters of homes around the Sound built below coastal bluffs and where small, seasonal vacation cabins are being replaced by large, year-round permanent residences.

Figure 22. Site of destroyed Herron family home at Rolling Bay from the water.
Vacant lot at left edge of photo is site of house destroyed by a landslide the previous winter.
[Photo: 4/14/1997]

Hansville Peninsula, North of Kingston KITSAP COUNTY

Most of the 1996-1997 landslides described so far received considerable attention in the media and were visited by numerous geologists. Most were readily accessible and visible and involved significant damages to property. Most landslides that occurred during the Holiday Storm, however, did not receive such extensive attention. The following example was chosen as an illustration of an area subject to significant landslides and under considerable development pressure, yet that received very little, if any, publicity. I will also revisit this area in our descriptions of 1998-1999 landslides.

Much of the shoreline between Kingston and Point No Point, in north Kitsap County, consists of tall, highly unstable bluffs [Washington Department of Ecology, Volume 10: Kitsap County, 1979]. Thorsen [1987] describes deep-seated landsliding that occurred along the shoreline between Kingston and Apple Cove Point in 1974. The bluffs north of Apple Cove Point, along with those in the vicinity of Pilot Point farther north, experienced extensive landsliding in 1996-1997 (and in 1998-1999 as well).

The character of landsliding varies considerably along this shoreline, ranging from high steep bluffs subject to shallow failures to relatively large, deeper-seated landslides. Portions of the shoreline, such as the reach north of Apple Cove Point, are marked by a distinct mid-slope bench (Figure 23), portions of which also moved in 1974. Several properties were impacted by landsliding along this bench during the Holiday Storm. The largest single slide along this shoreline that I observed occurred on a site approximately one mile north of Apple Cove Point for which four homes had been proposed, but not yet built.

The site of this particular landslide was characterized by an approximately 300-foot high slope, broken by a distinct shoreward-sloping bench about 70-80 feet in elevation (as a consequence, the site has two very steep slopes, one behind the bench and another below it, extending to the beach. The vegetated bench, which ranges from 50 to 200 feet in width, displayed the uneven, hummocky terrain and disrupted drainage geologists typically associate with past landsliding. Additional evidence of past sliding included the circular, amphitheater-shaped bowl in the upper slope above the site. The Coastal Zone Atlas mapped the site as a large Unstable Recent Slide (Urs, Figure 25).

An access road was constructed in switchbacks down the very steep upper slope. Four building sites were planned above the lower shore bluff and a community drainfield was designed for the landward portion of the bench. Heavy rains in early 1996 resulted in serious damage to the road, still under construction. In early winter, 1996-1997, (prior to January 9th, and believed to have occurred during the Holiday Storm), a slump, approximately 100-120 feet wide, occurred on the upper slope, spreading as much as 20,000 cubic yards of mud and debris across the entire width of the bench. The slide affected not only the road grade, but cut into underlying sediments as well. Drain pipes, large riprap, and massive concrete guardrail posts were carried hundreds of feet across the bench in a debris flow. Fortunately, homes had not been built yet on the bench, as the debris covered the building sites to a depth of many feet. The upper portion of the landslide can be seen at the left of Figure 24.

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Figure 23. Mid-slope bench located along high bluffs north of Kingston and Apple Cove Point. Home in foreground was impacted by 1996-97 landslides. *[Photo: 4/14/1997, 97-30-18]*

Figure 24. Aerial photo of bluff near north end of map in Figure 25.
Note active landsliding, distinct mid-slope bench, distorted stratigraphy, and relatively new homes located along top edge of the bluff. The site described in the text is located at the left margin of the photograph. *[Photo: Len Palmer, 4/1997]*

A geotechnical investigation of this site had been carried out, but although there was an awareness of potential risks due to slides on the steep slope, the subsequent report did not apparently recognize the magnitude of the risk or the potential for large-scale failure, despite abundant evidence that massive landslides had occurred in the past as well as on nearby shorelines. Development of the property had been approved by the local jurisdiction, but was halted as a result of legal action precipitated by environmental concerns and conformance with shoreline regulations. Given the scale of the slide, the consequences might have been severe had homes already been built.

Extensive portions of this shoreline are vulnerable to landslides. Damage occurred to houses on the bench farther south during the 1996-1997 Holiday Storm (Figure 23). Aerial reconnaissance indicated that there are many homes located near the edge of the slope or on the mid-slope bench between Kingston and Point No Point, although the density of development remains relatively low. Ironically, the broad mid-slope bench and rolling slopes that comprise much of this shoreline are a direct result of the unstable geological conditions, yet present attractive sites for development along a shoreline that affords spectacular views of Seattle and the Sound.

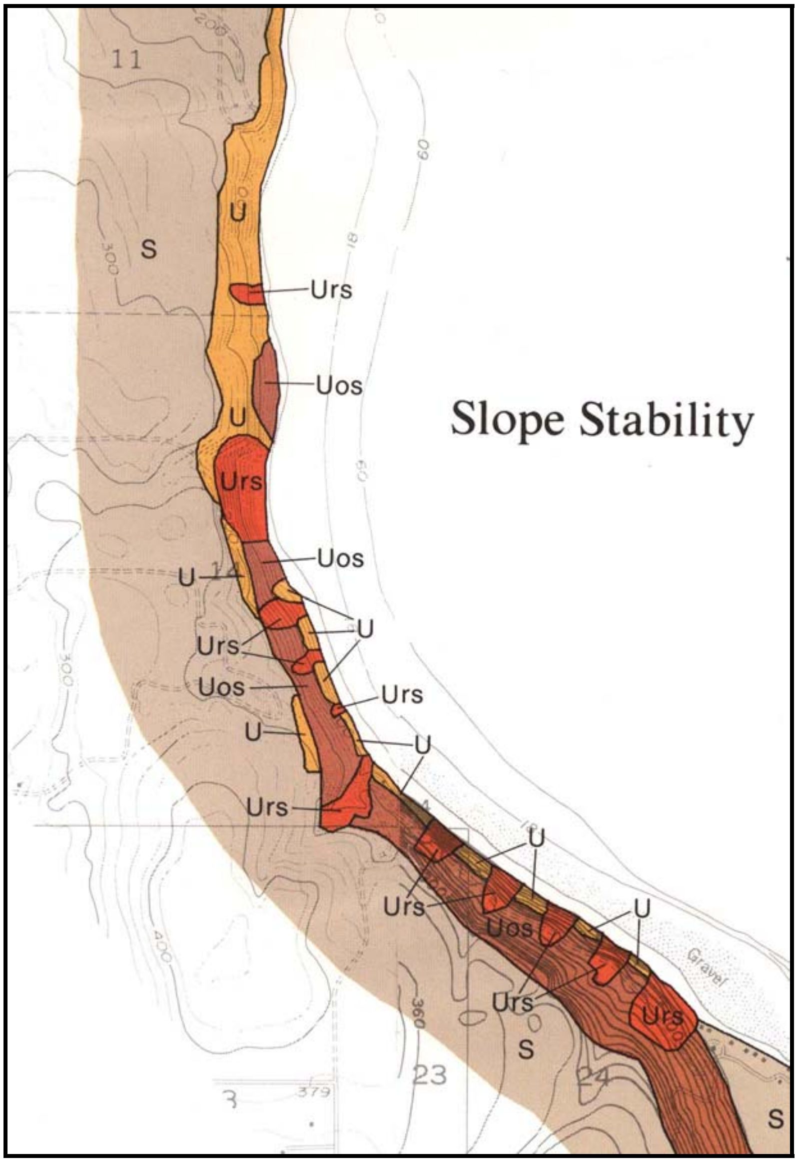

Figure 25. Slope stability map for shoreline north of Apple Cove Point in Kingston. The 300-foot coastal bluff in this area is marked by a distinct mid-slope bench, abundant and frequent shallow landslides, and extensive deeper-seated landslides *[Map from Washington Coastal Zone Atlas, Volume 10, 1979]*.

Landslides of the 1998-1999 Winter

As described previously, the three-month period between the beginning of November, 1998, and the end of January, 1999, was the among the wettest on record in the Puget Sound region. Although extensive shallow landsliding did not occur, such as seen in 1996 and 1997, by February conditions were sufficiently wet that several very large, deep-seated landslides in the region began to move.

Although detailed geotechnical studies were carried out for many of these slides, there was no regional inventory of landsliding associated with this period. This chapter describes several of the landslides that occurred during 1998-99 [Figure 26]. Our purpose is not necessarily to present in detail the timing and mechanisms of each of these slides, but to document a number of slides that affected the Puget Sound shoreline and provide historical information that may be useful when future sliding happens - which in most of these locations is highly likely.

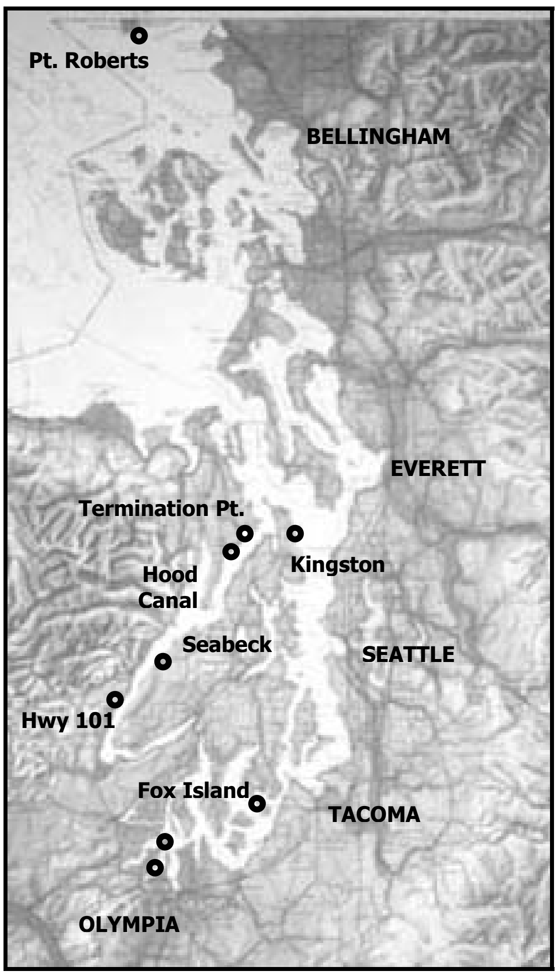

Figure 26. Locations of 1998-99 landslides described in this report.

The landslides described below do not represent a complete list of 1998-99 landslides. Many other slides occurred throughout the region; I just had too little detailed and consistent information from which to draw examples.

Most of the slides described here occurred in developed areas or in areas where development had recently been proposed. Movement was often only a few feet - sufficient to damage roads, structures, and utilities - but not enough to result in large scale landscape changes. Many of these slides would be difficult to recognize from the air and the evidence for recurrent movement is rapidly lost - due either to vegetation or, ironically, to reconstruction and new development.

Highway 101, Hood Canal — MASON COUNTY

U.S. Highway 101, along the western shore of Hood Canal north of Lilliwaup and south of Eldon, experienced two major landslides during the winter, both in locations of previous sliding. Both slides became active in early to mid February, 1999. The southern slide, referred to as the Milepost 326, or Lilliwaup, slide, destroyed several homes (Figure 27). Both this and the more northerly Jorstad Slide at Milepost 322 forced extended closures of the highway (Figure 28), which serves as a major transportation link and for which no simple alternative routes exist.

These slides are described in a field trip report prepared by the Association of Engineering Geologists [Moses and others, 1999]. Both slides were deep-seated, with their bases located along or near the contact of overlying glacial outwash sediment with underlying glacial-lacustrine sediments, where abundant seepage was present. This contact varies in elevation, but generally occurred near or slightly above the highway grade. Movement resulted in the toes of the slides pushing across the highway and debris eventually flowing or being washed into Hood Canal. Both of these areas, along with others along this stretch of highway, had experienced significant slides in the past and a variety of drainage and structural measures had been implemented historically to control movement. Since 1999, major efforts have been made to stabilize these landslides with intensive drainage, regrading of the slopes, and structural improvements.

Figure 27. House destroyed at the headscarp of the Milepost 326 landslide.
[Photo: 5/8/1999, #99-25-2]

Figure 28. Highway crews attempting to clear highway and stabilize toe of Milepost 322 landslide. *[Photo: 5/8/1999, #99-25-7]*

Thorndyke Road, Hood Canal JEFFERSON COUNTY

A large deep-seated landslide occurred during the winter of 1998-1999 in the vicinity of Milepost 3.5 on the Thorndyke Bay Road along Hood Canal. The landward extent of the movement was just east of the county road, approximately 1/4 mile from the shore. The portion of the road that crossed the slide continued to drop throughout the winter, requiring continuing maintenance to keep the road open. The landslide widened toward the shoreline, affecting over a thousand feet of waterfront. The slide area included several homes and driveways, although most of the area consisted of second growth forest. Evidence of movement, besides settling of the Thorndyke Bay Road, included a series of scarps, the highest an arcuate fissure on the embankment upslope of the road that extended in both directions across the road. Additional scarps crossed driveways running down the slope from the main road to shoreline homes. Homes themselves were damaged and had been tagged by the County. Among the most distinctive features of the slide was an extended area of uplifted beach at the toe of the slide: the beach berm, along with drift logs, had been lifted several feet above extreme high tide and formed a distinct scarp along the upper and mid beach over several hundred feet of shoreline (Figure 30).

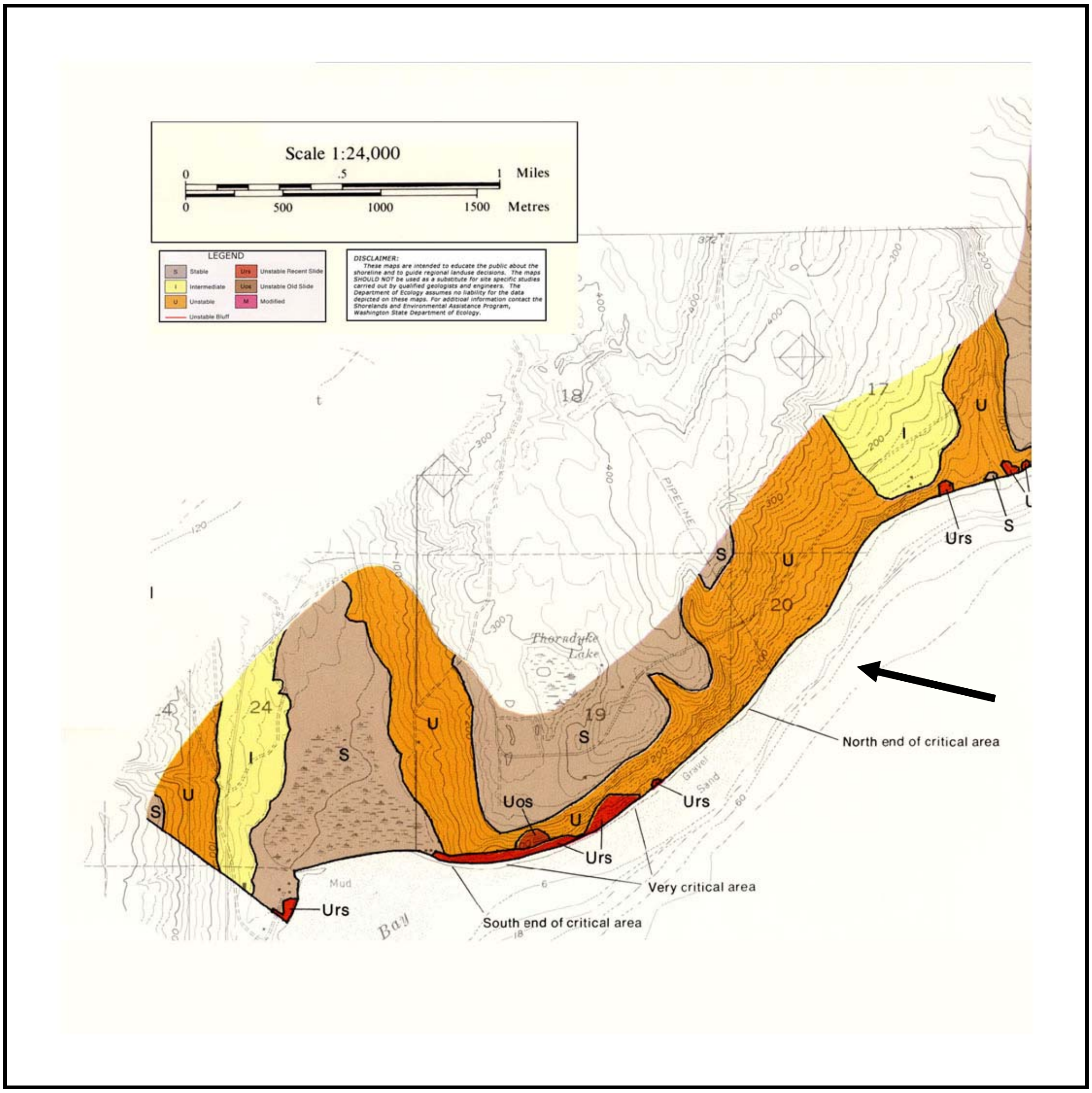

Figure 29. Coastal Zone Atlas map of Thorndyke Bay. Arrow indicates area of slides described in text. *[Washington Department of Ecology, Volume 11, 1978]*

This general area east of Thorndyke Bay Road has been the site of significant landslides in the past and likely consists of many separate slides sharing a similar geologic setting. Movement in this area was not dramatic and in the absence of cultural features such as driveways and damaged homes, would have been difficult to identify, except for the dramatic uplift of the toe at beach level. Aerial photos and personal observations from a distance indicate that landsliding may have been extremely disruptive along the shoreline to the west (noted as a very critical area in the Coastal Zone Atlas, Figure 29), where extensive fresh debris avalanches and downed forest could be observed.

Figure 30. Toe of Thorndyke Road landslide, showing steep scarp has developed in the upper beach. *[Photo: 4/20/1999, #99-21-22]*

Termination Point JEFFERSON COUNTY

The shoreline in the vicinity of the west end of the Hood Canal bridge contains many major landslide features. Partly as a consequence of active landsliding that occurred while geological mapping was being carried out in the early 1970s, the shoreline was identified as "critically" unstable in the Coastal Zone Atlas [Washington Department of Ecology, Volume 11: Jefferson County, 1978]. The risk was deemed sufficiently significant that Jefferson County imposed a building moratorium, making new construction in this particular area contingent on more detailed geotechnical studies. The height and character of the bluffs changes significantly along the shoreline, reflecting geologic variations, and as a result, a variety of landsliding conditions exist. Property ownership and the amount of development also varies along this stretch of shoreline.

During the winter of 1996-1997, numerous shallow landslides had occurred on several portions of this shoreline. Several large debris avalanches occurred along the shoreline north of Shine Tidelands State Park (north of the bridge), including one that buried the northern most portion of the small campground.

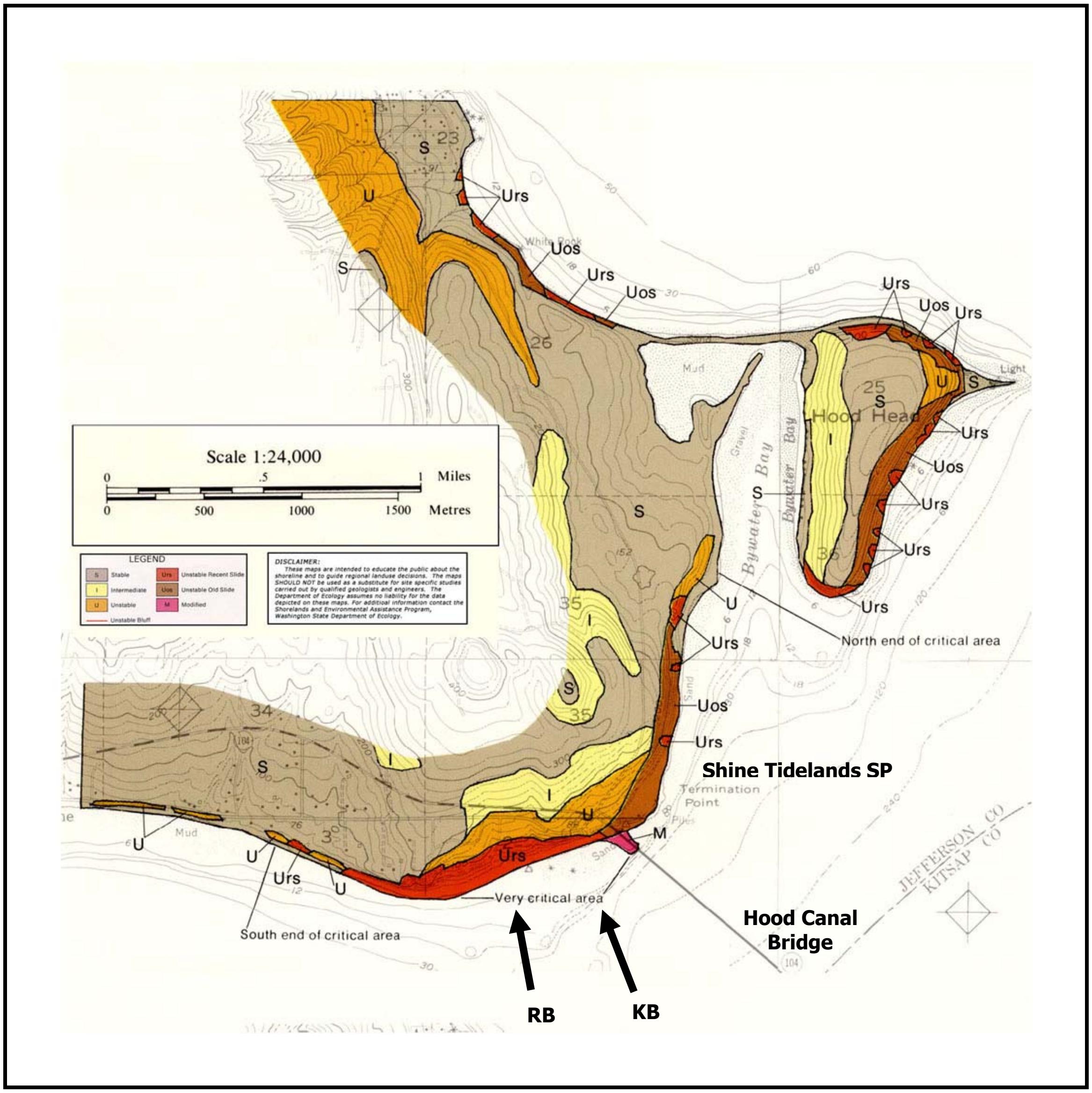

Figure 31. Coastal. Zone Atlas map of Termination Point area.
RB: Ricky Beach. **KB**: Killapie Beach.

Movement of a deep-seated failure was observed and reported along the shoreline south of the bridge during the early 1970s, below proposed development on Killapie Beach and Ricky Beach roads (see Figure 31). Scarps developed on the hillslope, and uplifted clays were observed on the beach [Gerald Thorsen, personal communication], indicating deep movement of a large rotational slump or ancient landslide. The landslide is complex, probably involving numerous separate slide blocks, and extends along half a mile of shoreline. Much of this shoreline is marked by a distinct mid-slope bench and a steep headscarp.

In 1997 and 1998, significant slumping was observed at the northeastern end of Killapie Beach Road. Initially confined to the slope between the road and the shore bluff itself (about 30 feet), in the winter of 1998-1999, the movement stepped landward, seriously damaging the turnaround at the end of the paved road. In addition, extended fissures appeared along, and parallel to, the entire lower section of the road. Currently, there is no development along the lower portion of

Killapie Beach road, so damages have been limited to the road itself and to undeveloped lots (Figure 32).

Figure 32. Disturbed asphalt at lower end of Killapie Beach Road. Shoreline is located to the right. *[Photo: 3/22/1999, #99-11-25]*

During the same period, reactivation of deep slides also occurred farther southwest along Ricky Beach Road and the bench on which it runs. The first significant movement occurred during the winter of 1996-1997, when an area to the west of the end of the road slumped, resulting in a four-foot scarp 80-100 feet landward of the shoreline. The scarp cut across a recently constructed access road and resulted in the casing of a recently drilled test hole, located within the slumped area, popping out of the soil as a result of the downward movement of surrounding ground (Ricky Beach Road was - and remains - the site of a proposed multi-lot development, and geotechnical investigations were underway at the time).

Although landslide activity on the site was initially restricted to some shallow failures off the steep slopes above the bench and to the slump at the western end, during the winter of 1998-1999 a much larger area of the bench began to show signs of reactivation. Slides on the steep bluff above the west end of Ricky Beach Road threatened homes along Linda View Drive. A series of fissures developed across the road where it drops to the bench, indicating downward movement on the shoreline side (although at this point, the shore is over 100 feet away). A single crack that had appeared down the center of the western extension of the road the previous year developed a vertical offset of more than six inches (Figure 34) - indicative of major block movement on the bench. Finally, a continuous band of fresh, contorted clay and silt appeared in an arc several hundred feet in length on the beach below the site (Figure 33). This feature, which is believed to represent the uplifted toe of the slide, lies as much as 70-80 feet out on the beach and resulted in the ponding of water on the upper beach.

Figure 33. Raised beach at the toe of Termination Point landslide.
The waterward portion of the uplifted area is marked by arcuate band of disturbed clays. Note ponded water on the upper portion of beach. *[Photo: 3/22/1999, #99-12-13]*

Figure 34. Fissure running down the center of the western portion of Ricky Beach Road.
The shoreline is located over 100 feet to the right of this photo. *[Photo: 3/22/1999, #99-12-8]*

Farther west along this shoreline, the mid-slope bench disappears and the height of the shore bluff increases substantially. In 1996-1997 a major upper slope failure occurred on the southernmost point of the bluff. This deep failure expanded significantly during 1998-1999, resulting in the relocation of a home (Figure 35).

Figure 35. Headscarp of a large upper bluff slump overlooking Hood Canal, west of Termination Point. Original bluff edge was more than fifty feet farther to the right of the most recent scarp. Note septic tank and landscaping on the upper portion of the landslide mass. *[Photo: 4-20-1999, #99-21-17]*

Kamus Road, Fox Island — PIERCE COUNTY

During the last weekend of February, 1999, a large landslide occurred along steep bluffs northeast of the end of Kamus Road along the southwest shore of Fox Island, south of Gig Harbor [Tacoma News Tribune, 3/2/99]. The slide appeared to consist of a combination of relatively deep rotational slumping and extensive shallow failure and debris avalanching.

The deep-seated movement was evidenced by a large dropped area on the lower slope and the dramatic uplift of an arcuate section of beach (Figure 36). Residents reported that geoducks (large clams typically found in lower intertidal and subtidal sediments) were exposed on the surface following the event. Profiles across the beach on May 5, 1999 (Shipman, field notes), indicated that uplift at the toe of the slide exceeded 8 feet at a point over 100 feet waterward of the bulkheads (Figure 38).

The landslide cut beneath cabins and a concrete bulkhead at the toe of the bluff, cracking the concrete wall and causing one of the cabins to tilt backwards (Figure 37). The head of the slide cut into the top of edge of the bluff, and at least one house was eventually relocated farther from the top edge of the slope.

Figure 36. Aerial view of landslide south of Kamus Road on Fox Island.
Photo was taken in summer, 2000, about a year and a half after the slide. Note how toe of slide affects shape of the beach. Arrows indicate locations of Figure 37 and Figure 38. *[Ecology, Kamus_2000]*

Figure 37. Beach cabin destroyed by landslide.
Cabin was involved both in deeper movement of landslide and by debris avalanches from above. *[Photo: 5/5/1999, #99-24-1]*

Figure 38. Toe of eastern portion of landslide, showing uplifted beach.
Note ponded water in mid intertidal and distorted clays in uplifted portion. *[Photo: 5/5/1999, #99-23-16]*

Carlyon Beach/Hunter Point THURSTON COUNTY

Perhaps the most notable landslide of the winter was a very large earth movement along the shore north of Olympia, within the Carlyon Beach community northwest of Hunter Point. Residents of over 40 homes were required to abandon their houses when a large landslide began moving in early February, 1999. The slide extended approximately 3000 feet along the shore. The eastern portion was largely, but not entirely, undeveloped, whereas the western portion included several streets and many homes within the Carlyon Beach neighborhood.

The area of sliding had been mapped in the Coastal Zone Atlas as of intermediate stability. Detailed investigations following the slide found geologic evidence that much of the area lay within a large existing landslide. The earlier mapping may have easily missed slide scarps in the heavily forested eastern portion of the site and the topography of the developed portion may have been attributed to grading activities during initial development.

Although individual property owners and consultants had noted signs of movement at least as early as 1996, these independent observations had been insufficient to trigger concerns about a larger landslide [Geoengineers, 1999]. Significant movement was detected around February 6, 1999, following heavy rains, and field investigations quickly recognized that the scope of the slide was large (Figure 39).

Property owners were asked to leave their homes and the County retained a geotechnical engineering firm to investigate the slide and propose mitigative measures. The results of this work can be found in two reports by Geoengineers, dated March 18 and May 3, 1999. Geological studies confirmed that the entire area was underlain by a large, multiple-block slide along a failure surface located as much as 100 feet or more below the surface. The Phase 2 report identified a number of remedial measures, including drainage of various types and several possible structural methods, but the estimated costs were high and there remained significant concerns about the long-term effectiveness of such measures. To date, no remedial actions have been taken and a number of homes have been dismantled or removed[8].

Figure 39. Fractures along Mariner Drive in eastern portion of Carlyon Beach neighborhood.
[Photo: 5/8/1999, #99-25-14]

Sunrise Beach THURSTON COUNTY

The Sunrise Beach neighborhood, on the west side of Eld inlet near Olympia, was the site of another large deep-seated landslide that occurred in late February of 1999. As many as 20 homes, most located between Sunrise Beach Road NW and the beach, were affected (Figure 40). The slide was approximately 1700 feet long and extended 350 feet from the shore. Total movement was only a few feet, resulting in a two to three foot headscarp upslope from the road, minor damage to structures and the county road, and the formation of a clay bulge on the beach at the toe of the slide.

Geological engineering investigations determined the approximate character of the slide and found that movement was associated with elevated groundwater levels [Shannon & Wilson, 1999]. The solution was to construct a deep trench drain along the road and to install horizontal drains into the slope. Thurston County and the property owners shared the approximate $1 million cost.

[8] A recent thesis at Western Washington University examines the socio-economic impacts of the Carlyon Beach landslide [Burke, 2001].

Figure 40. Aerial photograph of Sunrise Beach area affected by 1999 landslide.
[Ecology, 5/14/1992, THU#0241]

Hansville Peninsula. North of Kingston KITSAP COUNTY

In the previous chapter on 1996-97 landslides, I noted that the shoreline from Kingston north to Point No Point consists largely of highly unstable bluffs with a long history of movement. Although investigations along this shoreline were limited to just a few locations, plus aerial and boat reconnaissance, it appears that during the winter of 1996-97 most of the sliding north of Apple Cove Point consisted of shallow failures, a few deeper slumps, and lateral movement of material across the well-developed mid-slope bench.

One site in particular, however, where I had observed shallow failures in 1997, experienced a large deep-seated slide during the winter of 1998-1999. The owners of the property had constructed a road down the steep slope above the 100-120 foot-wide bench and had begun construction of the foundation of a large home at the edge of the lower bluff. In 1996-97, shallow slides damaged the road. At about the same time, construction of the home was stopped as a result of legal action not directly related to landsliding.

During the winter of 1998-1999, a deep-seated failure developed in the bench, resulting in a series of large, arcuate fissures cutting through the bench and dropping of some large blocks by several feet. The movement extended landward to the toe of the steep upper slope. The magnitude and distribution of the movement indicated that the slide was deep, likely involving the more coherent materials that formed the bench itself. I do not know if this was a new slide or simply the reactivation of an older feature. The failure undermined the access road and seriously damaged a pump house and a trailer on the site. The uncompleted house foundation was severely fractured and the waterward portions were at risk of collapsing to the beach.

Wilcox House, Hood Canal KITSAP COUNTY

One well-publicized slide that occurred during the wet weather of early February, 1999, affected the historic Wilcox House on the eastern shore of Hood Canal, south of Seabeck. The landslide began as increased seepage and the loss of stairs to the beach, but progressed rapidly landward as sandy soils were eroded out by rapidly flowing groundwater. The failure extended almost thirty feet landward of the bluff edge, almost to the building's foundation, before being brought under control [Seattle Post Intelligencer, February 9, 1999].

The Wilcox Slide appears to have been a large groundwater blowout followed by rapid headward erosion rather than an actual landslide, but the impacts and potential danger were serious. The failure was addressed by installing drains, filling the washed out area with large rock, and protecting the slope with a wood crib wall and vegetation.

Lilly Point, Point Roberts WHATCOM COUNTY

Numerous other large slides also occurred in the region during 1999, among them a large failure of the bluffs on the southeast side of Point Roberts in northern Whatcom County. This slide occurred on the west side of Lilly Point in an area of past, deep-seated sliding [Figure 41 and Figure 42]. Interestingly, the landslide occurred late in the season, on Memorial Day weekend in late May. The slide occurred in an undeveloped area, but was heard by people in the area and resulted in dust coating trees in the area [Doug Goldthorpe, Whatcom County, personal communication].

Figure 41. 1994 photograph of large landslide complex at southeastern end of Point Roberts, prior to 1999 failure. Lilly Point is at right edge of photo.
[Ecology, 4/28/1994, WHA#022]

Figure 42. 2001 photograph of Point Roberts landslide. Area of 1999 failure can be seen on right half of image by comparing to 1994 photo (previous figure).
[Ecology, 5/24/2001]

Character and Distribution of Puget Sound Landsliding

Landsliding is a widespread natural hazard in the Puget Sound region, creating significant risks in every coastal county. The risk of sliding is particularly severe along the steep slopes that surround Puget Sound, in part due to the steep slopes and weak geological materials, and in part due to the increasingly high level of development and relatively weak regulations on development in slide-prone areas. Events of recent years demonstrate that both rural and urbanized areas are vulnerable.

The character of landsliding varies considerably, depending on the nature of triggering precipitation events and the local geologic conditions. This affects the type of landsliding as well as the level and type of risk. Human factors influence many landslides - affecting both the onset and character of slides and the nature of resulting damages.

Timing

Most landslides occur when soils become saturated by heavy precipitation and rising ground water. The nature of landsliding differs, however, under different rainfall and groundwater regimes, because these can affect the depth at which groundwater is impacted, the rate at which pore pressures increase, and the likelihood of heavy rain coinciding with already high groundwater levels. The timing of landslides is often governed by the joint probability of certain combinations of events - heavy rainfall and rapid warming following significant snowfall, for example, as in the 1996-1997 Holiday Storm. Because of the strong relationship with wet conditions, I believe that landslides are more likely to occur in years characterized by the La Nina phases of the El Nino Southern Oscillation (ENSO) climate cycle. It may also be reasonable to expect greater landsliding during longer term wet periods dictated by the Pacific Decadal Oscillation (PDO).

During the latter half of the 1990s, the Pacific northwest witnessed two fairly distinct landslide regimes. The first, during the winters of 1995-96 and 1996-97 was characterized by heavy rainfall events and extensive shallow landsliding. The second, observed during the winter of 1998-99, involved movement on deep-seated landslides, some of which were extremely large.

Winter of 1996-1997

Two federal disaster declarations were issued in the Puget Sound region in early 1997, both of which included the impacts of landsliding (landslides were also a key component of the February, 1996, disaster declaration). All three of these precipitation-driven events resulted in extensive landsliding in the Puget Sound region - a majority of it relatively shallow landslides and debris avalanches on steep coastal and riverine slopes.

These storms all brought extremely heavy rain over a period of only a few days to soils already wet from one of the wettest years on record in this region. Rapid saturation of shallow soils led directly to slides and slumps on steeper slopes, many of which were aggravated by surface runoff or rapid infiltration, particularly in more developed areas. During the Holiday 1996-97 storm, the heavy low-elevation snow pack blocked both natural and constructed drainage systems, aggravating the flow of surface water towards unstable slopes.

Winter of 1998-99

During the winter of 1998-99, and particularly following wet weather at the end of January, a number of large landslides developed throughout the Puget Sound region. This followed the wettest three-month period in several decades or more (in the Seattle area). It also came at the end of the one of the wettest four-year periods in the region's history, although it should be noted that the previous year was considerably drier than usual as a result of a strong El Nino over the Pacific.

Shallow landsliding was relatively uncommon during 1998-1999, presumably as a result of the lack of singular heavy rainstorms as seen in 1996-97[9]. Instead, the notable landslides were larger, deep-seated failures, typically involving renewed movement on old landslide complexes. In most cases, earth movement was relatively slow and incremental, with total movement on many slides less that a few tens of feet, and sometimes much less.

Differences between two events

Although the relationship between rainfall and landsliding has been well documented for the Puget Lowland, less consideration has been given to the distinction between different types of weather conditions and resulting landslide regimes. This becomes important as we recognize that these slides are identified and mapped differently, that different types of slides cause different kinds of damages, and that the public response may be quite different between such events.

Not only are shallow and deep-seated landslides triggered by different weather conditions, their impacts differ as well. Shallow slides are typically small and cause severe damage in an almost random fashion within any given steep-sloped area. Damages typically involve the rapid movement of landslide debris downslope. Individual deep-seated slides, on the other hand, affect large areas and cause damage largely by the differential movement of the earth beneath structures. They are less likely to be lethal, because they move slowly, but are more likely to result in complete destruction of structures.

Shallow and deep landslides create different disaster scenarios. Intense, short-period precipitation events lead to large numbers of landslides over extensive areas and often create hazards other than landslides, such as urban flooding, riverine flooding, or storm damage (ice, snow, wind). Such severe storms typically lead to state and federal disaster declarations and trigger a broad-based public response. The prolonged wet conditions that give rise to deeper-seated failures, however, may not be associated with other natural hazards. The landslides affect a limited number of neighborhoods, even if severely, and the damages are generally incurred slowly and over several weeks or months. Consequently, disaster declarations are far less likely.

No info on annual rate of sliding

Unfortunately, although precipitation records are often available for extended periods of time for this region, there is no systematic record of landslide occurrence. Years with active landsliding are recognized, but years with fewer landslides are not noted nor documented. This prevents rigorous analysis of the relationship between rainfall and landslides, making determination of

[9] Another contributing factor for the lesser number of shallow landslides in 1998-99 may be that the intense rainfalls of 1996-97 cleared many of the potentially unstable slopes and that few marginally stable slopes remained two years later.

threshold conditions or of recurrence rates difficult. It also makes evaluation of the different effects of precipitation regimes on different types of landslides problematic.

Recent work on landslides in Seattle [Shannon and Wilson, 2000] provides the only detailed attempt to collect historical landslide information. The data are extremely valuable in evaluating the landslide risk in various parts of Seattle and in identifying years in which abundant landsliding occurred [Chleborad, 2000; Coe and others, 2000].

Spatial Distribution

Landsliding does not seem to be associated with a particular geographic region of the Puget Lowland, because the common factors, including geology, rainfall, and steep coastal slopes, are pervasive throughout the glacially influenced lowland. Because landsliding is more likely where relatively weak Pleistocene sediments are exposed in steep coastal bluffs, the prevalence of sliding in different counties reflects the proportion of shoreline consisting of such bluffs. San Juan County, for example, has less unstable shoreline largely because of the dominance of bedrock shorelines.

Although shallow sliding and related mass-wasting of the shoreline is common in many areas, the severity of sliding does appear to hinge on the presence of a relatively impermeable unit to concentrate groundwater. In Central Puget Sound (King and Kitsap Counties, for example), this is provided by the Lawton Clay [Tubbs, 1974]. Elsewhere, slides may occur in association with other fine grained lakebed or fluvial sediments (Thurston and Mason Counties), impermeable units within the older interglacial sediments such as the Whidbey formation (in parts of Island and Jefferson Counties, for example), or even underlying bedrock units (as in parts of Jefferson or Skagit Counties).

The distribution of shallow landsliding is dependent on rainfall intensity, which may relate strongly to the passage of individual storms. Thus the distribution of severe sliding in the 1996-97 Holiday Storm may reflect a band of particularly heavy precipitation through northern King County, Kitsap County, and eastern Jefferson County (Figure 13). This is difficult to separate, however, from the effect of the heavy snow pack and rapid temperature increase through the same part of the region.

The number of large landslides in the winter of 1998-99 was insufficient to allow conclusions about regional variations in slide-triggering conditions, but it is worth noting that deep-seated slides in 1998-99 were widely distributed throughout the Puget Lowland, from Thurston County in South Sound to the large landslide south of Lilly Point at Point Roberts, near the Canadian border.

One quite certain conclusion can be drawn about the spatial distribution of landslides in both the 1996-97 events and in 1998-99: virtually all these slides occurred in areas that have slid before. Most occurred in areas mapped and recognized as unstable in the Coastal Zone Atlas of Washington [Washington Department of Ecology, 1977-1980]. Most of the deep landslides occurred within known ancient landslide complexes that have experienced movement previously. Most of the shallow slides occurred within areas of steep slopes where sliding is known to occur with intense rainstorms every decade or so.

Human influence on landslide occurrence

Human activities influence the timing, location, and character of many landslides. Engineering measures may stabilize slopes. Improperly designed or maintained drainage systems may lead to landslides. Land development practices that affect hydrology may increase or decrease sliding, depending on site-specific circumstances. Minor earth movement may break a sewer or water main, causing a larger slide. Isolating these various influences is difficult, however, in light of the fact that increased development often leads to larger numbers of reported landslides and more widespread landslide damage, simply because more development is likely to be impacted.

Several studies indicate that a large proportion (upward of 70%) of landslides, at least in some areas, are associated with human actions [Tubbs, 1974; Shannon & Wilson, 2000]. The simplest way in which we influence landsliding is by alterations, both intentional and unintentional, to hydrologic conditions. This can occur through clearing of vegetation, increasing surface water runoff, changing rates and locations of infiltration, or the construction and operation of both small (residential gutters and downspouts) and large (urban stormwater) drainage systems. These modifications may increase or decrease the likelihood of landsliding in different situations. Humans can also alter slopes directly by excavation or placing fill.

Although there are clearly many ways in which humans can increase landslides, such conclusions should be interpreted cautiously. Landslides are much more likely to be reported, and therefore counted, in developed areas where possible human causes are readily attributed -- even if such slides were not the result of anthropogenic activity.

Landslides are perfectly natural phenomena that occur throughout the region, as demonstrated by the large number of slides observed on steep slopes far removed from human activity. Even where humans have significantly modified the landscape, landslides can occur simply because rainfall saturates soils and causes slopes to fail, and do not require a human trigger or explanation.

In many cases, human actions simply cause a slope failure to occur sooner than it would have naturally. In developed areas, the human imprint on the landscape, particularly in the form of drainage changes, is so pervasive that virtually any landslide can be associated with a human action - regardless of whether that action was a necessary condition for the slide to occur. As development in an area increases, the ability of an aggrieved property owner to point to a human-related contributing cause for a landslide becomes greater.

Although the timing of a landslide may be traced to a single event (usually a heavy rainstorm), there typically are many contributing factors. Consider the following example: a steep slope may have been originally formed by wave-induced erosion at the toe and may have been subsequently modified by a road built at its base. Stormwater from a recent upland subdivision is carried to the beach in a closed pipe, but settling of the pipe due to poor construction practices has resulted in a major break near the top of the slope. Inevitably, the slope will fail as a consequence of heavy rains, yet many natural and human conditions have contributed to the landslide.

Rural versus urbanized areas

Our investigation of landslides, including both shallow slides during 1996-97 and deeper-seated failures during 1998-99, found them to occur in both minimally populated rural areas and in more heavily developed suburban and urban areas. Urban areas, such as Seattle, reported many more landslides in a given area than less-populated areas, although this likely reflects differences in reporting as much as differences in the actual number of landslides. Palmer's [1998] survey found extensive sliding along bluffs in relatively rural parts of Puget Sound. Many landslides affected undeveloped land or damaged smaller homes or less expensive improvements than typically found in urban areas. Even where damages did occur, many were likely to go unreported, or at least undocumented, as local governments had little mechanism for compiling landslide reports or responding to requests for assistance.

Urban areas tend to have controlled drainage conditions (sanitary sewers and storm water management) and greater impervious cover (pavement and structures) that can reduce infiltration and shallow groundwater that might normally lead to landsliding on adjacent steep slopes. At the same time, such measures lead to more rapid and more voluminous flows that if not handled adequately (poor design, bad construction, insufficient capacity, or improper maintenance), can fail, leading to severe surface erosion on steep slopes or concentrated infiltration that in some locations can trigger slides. Stormwater ponds and related retention structures can result in the infiltration of water that would have otherwise run off a site. These problems can occur at the scale of a large neighborhood or of a single residence. In a densely developed area, it is far more likely that improperly directed drainage impacts development on nearby property than in a less developed area.

In general, urban jurisdictions are more likely to have stricter development regulations in steep slope areas than more rural jurisdictions and are more likely to have geologists and engineers available to review development applications. Seattle reported that little of the damage reported in 1996-1997 affected construction approved under their more recent, more rigorous building regulations for steep slope areas (although the sample size for the newer development was quite small). In contrast, many rural jurisdictions have limited staff and resources to review applications to build in potentially unstable areas.

The economics of development in landslide prone areas changes significantly from an urbanized area such as Seattle to more rural areas along Hood Canal or in southwestern Puget Sound. The cost of stabilizing a site under given conditions may not vary much from one part of the Sound to another, whereas the value of the property may. A resident along an unstable shoreline in Seattle may be able to justify several hundred thousand dollars for engineering studies, slope stabilization measures, and foundation improvements, whereas in rural Mason County such costs may easily exceed the value of the entire property. This becomes a strong disincentive for rural jurisdictions to adopt strict performance-based development and building standards, yet the potential public safety risk from inadequately designed homes is the same as in a wealthier city or county.

Greater development densities, although potentially putting more development at risk, can also lead to safer construction. Landslides and earthflows along the slope above Duwamish Head in Seattle historically destroyed individual residences at the base of the slope, whereas newer multifamily, multi-story development is built to withstand the same type of sliding with minimal damage and little risk to safety. Increased densities may provide the financial conditions to allow expensive geotechnical investigation and design and incorporation of engineering measures to stabilize the slope or limit structural damages. They can also make it easier for existing neighborhoods to form Local Improvement Districts (LIDs) that can identify and fund community-scale solutions.

Landslide stabilization

Among the most significant human influences on landslides is our ability to design and construct measures to increase slope stability or to reduce the damages to development when landslides do occur. We have little information on which to evaluate the overall effectiveness of engineering measures to reduce the likelihood of slope failure, and consequently minimize landslide damages. One of the difficulties is that although sound engineering can reduce landsliding, it is often associated with high levels of development, and consequently greater exposure to landslide risks in the first place. Slope engineering may actually raise risks in some areas because it allows for the construction of structures on or adjacent to slopes that might not be built on otherwise, placing them in danger if the engineering is inadequate for the conditions or the measures are not maintained over time.

Effective management of drainage can greatly reduce the risk of slope failure, but once water is collected and concentrated, a failure in design or in construction may lead to more water infiltrating soils than would have occurred under natural conditions. On steep slopes and in unstable areas, drainage systems are in themselves vulnerable to slope movement. Minor sloughing that jeopardizes the integrity of a drain system may lead to larger failure.

Retaining walls are the most common methods of physically restraining a hillslope and of contouring steep slopes to facilitate road construction, house placement, or landscaping. A wide variety of walls and related structures exists and can be found along Puget Sound's bluffs, but the quality and sophistication of these designs varies greatly. Problems often include failure of the geotechnical design to adequately anticipate the nature of slope movement and more commonly, the tendency for walls to be constructed with little geotechnical evaluation at all and poor adherence to construction standards. Many retaining structures on residential property escape rigorous review by local building officials and it appears are often built by contractors with little geotechnical oversight. Slope problems that arise during excavation or construction may not be recognized or understood by either contractors or building officials.

On Puget Sound, bulkheads and related forms of toe protection are commonly installed to address erosion and slope failure, but their value, at least for stabilizing slopes, may be overestimated on steep coastal bluffs where slopes have been steepened by many decades or even centuries of erosion and where future slides are most likely to result from saturated soils, not additional toe erosion. Many of the most notable landslides of the last several years on Puget Sound have occurred on coastal slopes that have been armored against toe erosion for many decades (for example, Perkins Lane and Duwamish Head in Seattle, Carlyon Beach in Thurston County, and Rolling Bay on Bainbridge Island). In addition, on many deep-seated landslides, the failure surface lies below any shoreline bulkhead and the structure simply moves along with the slide.

The bluffs between Seattle and Everett have been completely protected from wave action for a century by the railroad grade and its associated seawall, yet significant slides continue to occur, sometimes with devastating consequences (Woodway, for example). The railroad's practice of removing debris from ditches and tracks mimics the action of waves in removing colluvium, but generally does not result in additional cutting of the slope's toe. The widespread presence of mid-slope bench, combined with observations of sandy material sliding across and over the edge of the lower bluff during the winters of 1995-96 [Harp and others, 1997] and 1996-97 [Gerstel and others, 1997; Baum and others, 1998], suggest that landslides are influenced primarily by upslope geomorphological processes, triggered by groundwater, not erosion of the toe. At some point, the slope may achieve a more stable configuration, but quite clearly 100 years of toe protection has not been sufficient to allow this.

Vulnerability to coastal landslide damages

Landslides can impact areas above steep slopes and existing landslides, at the base of such steep slopes, and on the slope themselves. The latter category can be further divided to include construction on steep slopes, on mid-slope benches, and within the boundaries of preexisting, deep-seated landslides.

Top of slope

Damages to structures located above steep slopes are relatively rare, largely because the more common shallow landslides do not cut deeply into the slope. On the other hand, deeper slumps and slides, including failures of the capping glacial till, can threaten structures located near the crest of the slope. Clearly, structures built with minimal setback, or older homes which have lost ground in multiple previous slides, are most at risk from such landslides.

When slides cut close to structures at the top of the slope, repairs can be difficult and expensive. Reclaiming lost ground may require substantial retaining walls, complex engineering designs, and regrading of the slope, possibly through the addition of large amounts of engineered fill. With development located close to the crest of the slope, there is little room for uncertainty and conservative solutions may result in high costs. Relocation of the structure, though also expensive, may be a preferred solution on sites where alternative building sites are not precluded by shallow lots or by required setbacks for drainfields or from adjacent rights of way.

The greatest risk appears to be homes located with very minimal setback from the bluff edge or to structures in areas prone to deeper failures (areas not easily identified). Legal setbacks vary around the Sound and are tied to a variety of factors, some of which have little to do with the stability of the slope or the likelihood of a major failure. Many older homes may have been built with no setback requirements, or may simply be in jeopardy because slides in previous decades have progressively removed what may have at one time been perceived as an adequate setback.

There is enormous pressure to build close to the edge of bluff in an effort to maximize views and proximity to the water. Even where counties or cities require 50 or 75 foot setbacks, variances are often sought by property owners believing that the threat of landsliding to their proposed home is minor and able to secure a professional opinion that building closer is acceptable. As a result, homes are often located at distances that, although safe in the short term, become significant risks in the future.

Fortunately, most failures along the top edge of coastal bluffs tend to be shallow - often only a few feet - and do not occur too often - maybe once every several decades. Occasional, very large slumps, such as at Woodway near Edmonds in 1997, can cut landward fifty or more feet, but little is known about where they are likely to occur. Were such a slide to occur in an area of dense shoreline development, the consequences would be large, for homes and safety both above and below the slope.

Bottom of slope

The greatest risk to public safety appears to be development located at the base of steep slopes, where vulnerability to debris avalanches and shallow landslides is severe. The Rolling Bay landslide of January, 1997, underscored the risk, but it was only unique in the tragedy that resulted. Many homes in similar beach communities around the Sound have been knocked off their foundations, but remarkably they have either been unoccupied or residents have simply clambered out. Other places where homes have been lost in recent years include Prospect Point and Fragaria in south Kitsap County, Salmon Beach in Tacoma (Figure 43), Point Vashon on Vashon Island, Hat Island near Everett, and several small communities on south Whidbey and Camano Islands.

Figure 43. The Salmon Beach community in Tacoma is built on piles at the base of a steep, unstable bluff. A large landslide developed on the slope above this community following the February, 2001, Nisqually Earthquake - see Appendix. *[Ecology, 5/16/1992, PIE#0116]*

Small, shallow landslides commonly move very rapidly and carry enough mud and debris to severely damage structures. Trees and woody debris contained within a debris flow can become projectiles, causing damage that might not occur by flowing mud alone. Damages can include debris breaking through walls and entering structures, collapsing or burying structures, or simply pushing buildings off their foundations. The level of danger is related to a variety of site-specific conditions, including the size of the failure, the height and steepness of the slope, the kind of material involved, the distance from the toe of the slope, and the type of construction, among other factors.

Shallow landslides result in significant property damage at the toe of coastal bluffs to improvements besides homes. Even if homes avoid direct impact, communities at the toe of the bluff are impacted when access roads are buried, utilities disrupted, or when vehicles and accessory structures are struck by slide debris. Even in areas where homes are built above the bluff, we commonly hear reports and observe damage to beach stairs, tramways, boat houses, guest cabins, and bulkheads. These damages are less likely to be life-threatening than where homes are built at the slope toe, but the value of property affected may be comparable or greater, simply because so many more of these situations exist.

Threats to development at the toe of the slope are by no means limited to residential areas. The impact of slides on transportation corridors may be large and possibly more significant. The 1996-1997 landslides resulted in extended closures of the Burlington Northern Santa Fe railroad grade between Seattle and Everett. Besides impacting operations, such slides periodically result in direct hits on trains. The 1997 Woodway slide pushed several freight cars into the Sound. AMTRAK runs several trains daily along this route and the region plans to shortly commence commuter rail along the same stretch.

Debris from shallow landslides frequently closes or restricts use of numerous public roads in the region located along the shoreline. Examples include Cromwell Drive near Gig Harbor, North Shore Road on Hood Canal, and the Illahee Road and Brownsville-Gilberton Roads in Kitsap County, and many others. More urban examples include Ruston Way in Tacoma and Dexter and Aurora Avenues in the Queen Anne neighborhood of Seattle. Large landslides in 1998-99 impacted U.S. Highway 101 along Hood Canal, Highway 160 west of Port Orchard, and State Route 3 between Allyn and Belfair.

Faces of steep slopes

The faces of steep slopes are rarely developed - engineering costs are high and there is little ambiguity about the risk - except in those areas where property values are sufficiently high to drive demand for these lots and to support the costs of rigorous geotechnical analysis and complex structural designs. In an urban area such as the city of Seattle, considerable development has occurred on steep slopes, although the level of engineering sophistication may vary enormously.

Structures on steep slopes can be vulnerable to damage from slide debris from above, from undermining by slides lower on the slope, or may become actively involved in a slide that includes the structure itself. Engineering and construction techniques exist to mitigate some of these hazards in some situations. For example, a pile foundation may be used support the structure on deeper, more stable materials and to allow slides to pass beneath a structure without significant damage. In intensively developed areas, and particularly in multi-family and commercial development, construction may involve digging into the slope, completely removing unstable materials, and designing foundation walls as retaining structures for the slope itself[10].

Along much of the Puget sound shoreline where single family residential development predominates, the greatest danger of landsliding on the slope face is typically not to homes themselves, but to accessory structures, beach stairs, utilities, drain systems, or ironically, improperly designed and constructed retaining walls. The access roads, pump houses, waterlines, and other utility lines for many beach-level communities are often located on steep slopes and are vulnerable to damage from even minor slides. The risk is compounded by the fact that during severe weather, when emergency access and egress are most important, even a relatively small slide can cut off a small community.

Mid-slope benches and large landslides

Unlike the steep slopes themselves, benches and the rolling terrain of large slide complexes are often interpreted as attractive locations for building. Plats based on topography may place many "buildable lots" on a single slide bench. Many large landslide complexes around the Sound were subdivided decades ago and may have been partially developed. Pressure to build in these areas is often high.

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[10] The eastern slope of Seattle's Queen Anne hill, above Lake Union, and the steep hillside above the Factoria area of Bellevue, provide good local examples of high density development of steep slopes.

Structures located within large landslide complexes or on mid-slope benches heavily influenced by sliding are at particularly high risk of slide damage. Deep-seated landslide movement, even if limited to just a few feet, can damage foundations and cause irreparable structural damage. Repairs may not be an option unless the entire landslide can be successfully stabilized - a prohibitively expensive solution for many communities - and one that requires an effective community organization.

Development on mid-slope benches may be vulnerable to failures of the headscarp above the bench, to slides and slumps along the lower bluff, or from movement of material on the bench itself. Access roads, often cut down the steep upper slope or traversing extended lengths of the bench itself, are often vulnerable to damage and can seriously affect emergency access and egress from residential areas.

Risks to public infrastructure are generally greater in these larger landslide areas. Public roads and utilities may pass through large landslides[11] or serve neighborhoods and subdivisions located on them. Ironically, where stability has been an issue in the past, there may be a considerable public investment in drainage improvements and earlier stabilization efforts that may in themselves be at risk from additional slope movement.

Damage to inhabited structures is clearly the greatest threat, but slides can also disrupt utilities, on-site septic systems, wells and water supplies, and can destroy or seriously impact accessory structures such as garages and outbuildings, as well as vehicles, decks, landscaping, swimming pools, play structures, and so forth.

[11] Examples, of which there are many, include U.S. Highway 101 along Hood Canal, Humphrey Road on Whidbey Island, Gibralter Road on Fidalgo Island, Thorndyke Bay Road in Jefferson County, Sunrise Beach Road in Thurston County, or Perkins Lane and California Street in Seattle.

Addressing Puget Sound Landslide Hazards

Based on their experience with landslides on a national scale, Schuster and Kockelman [1996] identified several key steps to reducing landslide risks. These include 1) restricting development in hazardous areas, 2) developing ordinances to address construction-related activities such as excavation, grading and landscaping, 3) designing engineering measures to stabilize landslides or reduce landslide risks, and 4) developing warning systems.

In order to successfully achieve these results, Schuster and Kockelman [1996] noted that several prerequisites conditions were important. For example, technical information must be available, so that the factors affecting landslide occurrence and mitigation are understood and the location of landslide prone areas known. The geological and engineering community must be capable of evaluating this information and improving on it. Local governments must be capable of reviewing and evaluating the technical information and applying it to local circumstances and officials need to be committed to reducing landslide risks in their communities. Finally, the general public must be aware of the issue and willing to support implementation of polices and regulations addressing landslide risk.

In Washington State, a report by a panel of landslide experts following the 1996-97 landslide disaster identified a number of areas where landslide risks in the region could be reduced [FEMA, 1997b]. Their recommendations, which reflect many of the points listed above, fell into the following areas:

- **Assessing and mapping landslide risk areas.** The report recognized the need for improved landslide maps and better guidance to local governments regarding managing potentially hazardous areas.

- **Technical review of development proposals.** Washington State has no standard approach to defining or assuring the quality of geotechnical work carried out in support of development proposals in slide-prone areas.

- **Land use and construction controls .** Local governments can improve local ordinances affecting construction practices in unstable areas, such as excavation and grading controls, vegetation management, drainage and on-site sewage disposal, and structural stabilization methods.

- **Post-landslide mitigation.** Acquisition and relocation may be valuable tools for addressing areas impacted by slides and likely to be impacted in the future.

- **Warning and education.** Public awareness of landslide risks, combined with monitoring of landslide conditions, can reduce the potential threat to public safety.

- **Emergency response.** When landslides occur, state and local agencies need to understand and implement tools for evacuating or protecting vulnerable areas.

- **Education programs**. With proper public education and-improved understanding of landslide risks, many landslides might be preventable and damages when slides occur could be reduced.

In this chapter, I chose to focus on several specific methods of reducing landslide risks on Puget Sound. I emphasize approaches that reduce the vulnerability to risk in future landslides, rather than those that fall more in the category of emergency response. Landslide mapping (1) and inventory (2) provide crucial information about the character and distribution of landsliding in the region. Land use and development regulations (3), along with competent technical review of development proposals in hazardous areas (4), directly impact public safety. Where landslides cannot be avoided, appropriate engineering techniques (5) can reduce risks. Monitoring and warning systems (6) may provide protection to individuals in areas susceptible to landslides. Finally, effective reduction of landslide risks depends on well educated local officials and a knowledgeable public (7).

Landslide Mapping

Landslide maps take many forms, including landslide inventories, landslide susceptibility maps, loss evaluation maps, or risk determination maps [Schuster and Kockelman, 1996]. There is often confusion, even among the geotechnical community, about the nature and application of these different types of maps. Valid disagreements can arise over interpretations or the adequacy of available data. Local officials charged with making land use planning decisions or with implementing construction regulations in slide-prone areas often have little guidance about the appropriate use and potential limitations of such maps.

Landslide inventory maps identify the positions of actual landslides that were observable at the time of mapping or that may have occurred in a particular event. Such maps are useful for identifying vulnerable areas or for cataloging damages associated with a storm or earthquake. Inventory maps are not necessarily based on field investigations - they may be compiled from damage reports or other accounts and records. In addition, inventory maps may simply map the location of a landslide (or report of a landslide), not the actual extent of a landslide.

Landslide susceptibility maps might typically include slope stability maps that indicate which hillsides are most vulnerable to landsliding. Slope stability maps are usually derived from existing maps of geologic units and topography, combined with interpretation of landslide features from aerial photo interpretation, field observations, and possibly, recent landslide inventories. In most cases, the result is relative stability maps, which rank slopes in terms of their stability (high, medium, or low, for example). Slope stability maps may also be generated using a model that calculates stability or risk based on specific criteria. For example, maps might be generated directly from digital topographic information by assuming a simple relationship between slope gradient and landslide potential. More sophisticated maps might add additional factors, such as lithology (geologic materials), hydrology, seismic characteristics, or the distribution of past landsliding.

Landslide risk maps take into consideration additional factors that relate not simply to the likelihood of sliding, but to the risk of damages from landslides. The level ground at the base of steep slope may be relatively stable, but is highly vulnerable to landslide debris carried from above - so a risk map might include areas vulnerable to landslide runout. A house one hundred feet back from the edge of steep coastal bluff may lie on stable materials, but if the bluff is retreating due to shoreline erosion at a rate of 2 feet per year, the risk from landsliding is significant in the near future - a risk map might include information about average or maximum possible slope retreat rates.

Landslide mapping on Puget Sound

The primary source of landslide mapping for the marine shoreline of the Puget Lowland is the Coastal Zone Atlas of Washington [Coastal Zone Atlas, Washington Department of Ecology, 1977-1980], published in twelve volumes for each of the twelve counties that border the Sound. The Coastal Zone Atlas (which also contains maps of other coastal information) includes color maps of relative slope stability and of recent landsliding (*recent* as of the late 1970s). The slope mapping was carried out by the Washington Department of Natural Resources during the mid-1970s[12], as part of a larger project coordinated by the Department of Ecology. Maps were based on aerial photo interpretation, field observations from the water, and existing maps of geology and soils. Unstable slopes were identified on the basis of their geological composition, their slope, and geomorphological expressions of historical landsliding.

The Coastal Zone Atlas maps relative slope stability, not landslide risk or hazard (the danger posed by slides to humans or to development). It does not address erosion rates and long-term bluff retreat nor does it consider runout zones at the base of steep slopes. The geographic scope of the Atlas is limited. Although it covers all twelve counties in the Puget Lowland, including Clallam County along the Strait of Juan de Fuca, it only maps slope stability within 2000 feet of the marine shoreline. For historical and political reasons, mapping was not carried out on Indian Reservations or on federal property, such as the U.S Navy's Bangor Submarine Base along Hood Canal.

The Coastal Zone Atlas was not intended to guide site-specific decisions - neither the scale of the mapping (1:24,000 -- one inch equals 2000 feet) nor the rigorousness of the field mapping warrants such use. Rather, the maps were intended to educate the public about the landslide risk along the shoreline and to provide local governments with mapping sufficient to determine if detailed, site-specific investigations are necessary. Most coastal jurisdictions use the Atlas in this way -- requiring geotechnical evaluation of project proposals if the Atlas indicates they are in a potentially unstable area. With the adoption of Critical Areas Ordinances for Geologically Hazardous Areas (under the Growth Management Act of 1990), jurisdictions often specifically referred to the Coastal Atlas in defining areas of potentially unstable slopes along the shoreline.

The inclusion of recent landslides makes the Atlas a comprehensive inventory of coastal landsliding - as of the 1970s. Unfortunately, whereas the relative slope mapping remains generally sound several decades later, the inventory element does not. It reflects landslides that occurred in the 1960s and 1970s, although significant additional landsliding has occurred subsequently and is not reflected on the maps. The mapped slides emphasize shallow failures, which leave more distinct evidence, and likely missed much deep-seated landsliding. The maps provide a useful historical reference, however, and the general patterns of landsliding seen in the 1970s do not appear substantially different than those seen in more recent events - only the locations of specific slides have changed. The scale of the Atlas precluded the inclusion of many smaller landslides, which were simply integrated into the broader *Unstable* mapping unit.

[12] These included numerous studies of individual counties, such as Artim, 1976; Birdseye, 1976; Carson, 1976; Hanson, 1976; Miller, 1973; and Smith and Carson, 1977. For a complete bibliography of landslide mapping in the Puget Sound region, see Manson, 1998.

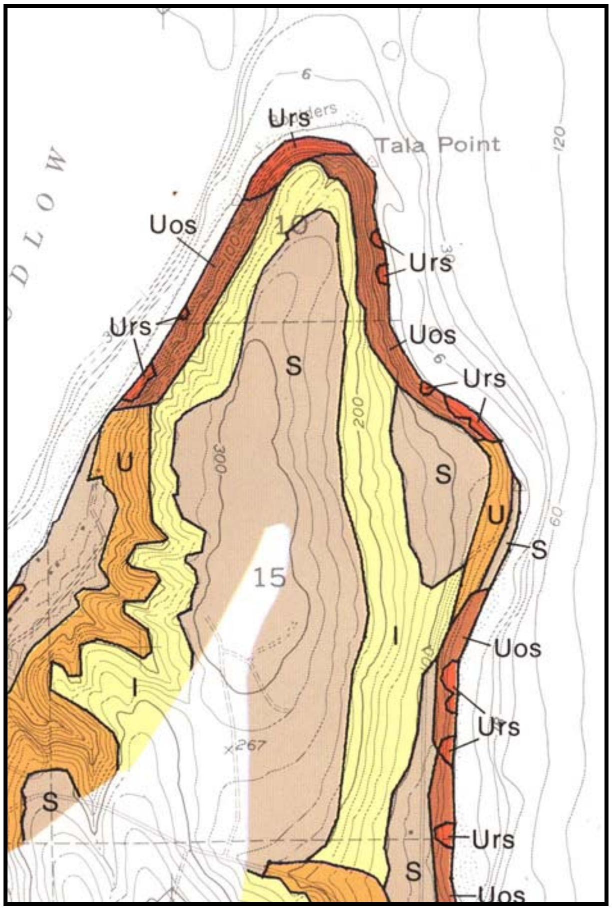

Figure 44. Example of Slope Stability maps from the Coastal Zone Atlas of Washington.
Note that mapping extends 2000 feet inland from shoreline. Relative slope stability is mapped as Stable, Intermediate, and Unstable. Distinct prehistoric landslides slides are identified. Delineation of recent landslides constitutes a comprehensive inventory as of the late 1970s mapping.

The Coastal Zone Atlas has been out of print for many years, although a limited number of copies are maintained by local government offices and some libraries. The maps remain a valuable tool for increasing public awareness of coastal landsliding and are essential tools used by coastal jurisdictions to identify properties on which further geotechnical work must be required under local ordinances. The Department of Ecology republished these maps on the internet in early 2001[13]. This is not a substitute for updated mapping, but will greatly improve access to the maps for coastal property owners, consultants, real estate professionals, and local governments.

Since the publication of the Coastal Zone Atlas, there has been no systematic effort to update the information or to develop improved landslide maps. With the adoption of Critical Areas Ordinances in the 1990s, local jurisdictions have generally chosen to reference the Coastal Zone Atlas maps or related maps from the same period. Although some local jurisdictions have refined the criteria for identifying landslide hazard areas, few have actually undertaken new landslide mapping.

New geologic mapping is proceeding, however, under the direction of the United States Geological Survey, the Washington Department of Natural Resources, academic institutions, and

[13] These maps can be found at: http://www.ecy.wa.gov/programs/sea/landslides/maps/maps.html

selected local governments. This mapping has the potential to lead to improved landslide susceptibility mapping - but this will require additional steps not currently underway. The increased availability of digital topographic data[14], combined with the development of improved computer models of slope stability, may lead eventually to the creation of new landslide maps. The relatively low resolution of existing topographic data may be a limiting factor, as much landsliding is related to features too small to be recognized or delineated without updated topographic information.

The relative slope stability maps currently used on Puget Sound could be improved upon in several ways. For example:

- Improved field work and the use of high resolution digital topography could be used to greatly refine the mapping of steep slopes and old landslides,
- Additional information could be incorporated, such as seismic factors, slope runout, erosion rates and characteristics, and hydrological information, so as to create landslide risk maps based on clearly defined criteria, and
- Mapping of landslide susceptibility and risk could be carried out using the same criteria specifically identified in local Geologically Hazardous Areas ordinances.

Inventory

Landslide inventories can take many forms, but their common objective is to catalog the distribution of existing landslides. Inventories may seek to identify the landslides associated with a particular storm, that have occurred in a certain location over a period of time, or simply to map the location of landslides at the time a geologic or slope stability map is being developed. An inventory does not necessarily result in a map, since some inventories may be in tabular or list form. Even where a map does result, an inventory may simply identify the location of individual landslides as a single point in space, providing no information as to the spatial extent or the boundaries of a slide.

Landslide inventories may be carried out for a variety of quite different purposes. Following a landslide disaster, inventories help local governments interested in identifying the extent of damages and emergency response agencies wanting to target assistance to areas where slides have occurred (or wishing to avoid paying for damages to properties repeatedly impacted by the same hazard). Given that one of the best indicators of landslide risk is that an area has slid previously, the value of accurate inventory cannot be overestimated.

Geologists may view inventory as a critical element in preparing maps of slope stability or landslide risk. They may also use inventory data to calibrate models of landslide susceptibility or to confirm model-based predictions about the distribution of landsliding. Understanding which areas are and are not impacted by landsliding under particular conditions provides useful data about the factors that generate slides. Whereas the emergency response community is often primarily focused on where damages have actually occurred, geologists may need to know as much about slides that resulted in no damages as about those that did.

[14] Recent aerial topographic surveys using LiDAR (Light Detection and Ranging - an airborne system that uses reflected laser light to precisely determine the elevation of the earth's surface) in the Puget Sound region indicate that it may a valuable tool for collecting high-resolution topographic information that will be useful in identifying landslide-prone slopes and prehistoric landslide complexes.

With the exception of the Coastal Zone Atlas [Washington Department of Ecology, 1977-1980], no systematic inventory of landslides has been carried out of Puget Sound shorelines. The Atlas, as described in the previous section, specifically delineated "Unstable Recent Slides" based on mapping during the mid 1970s. This inventory, unlike many, involved delineating (usually from air photos) the extent of the slides on the map, so that it is possible to distinguish between very large failures (that may have impacted multiple properties) and the more numerous smaller slides. It is likely, however, that many small slides went unmapped, simply because they were overlooked in the field or because they were too small to show at the map scale of 1:24,000[15] [Thorsen, 1989].

The City of Seattle recently completed the most extensive local inventory of landsliding we are aware of on Puget Sound [Shannon & Wilson, 2000]. The study includes over 1300 landslides that have occurred within the City since the 1890s. The study relied on excellent historical records of sliding, rigorous field investigation and verification of landslide locations, and considerable analysis of geological conditions in the Seattle area. The inventory includes both tabular data indicating the timing and character of slides and maps showing the actual locations of landslides (slides are mapped as points - the actual landslides are not delineated). The data refine, but largely reinforce, earlier, more general maps of landslide prone areas in Seattle[16] and provides a basis for beginning to identify strategies for mitigating landslide risk in various parts of the city.

Following the 1996-1997 landslide disasters numerous agencies and teams surveyed landslides and collected reports of landslide damages, but there was no systematic or regional compilation of this information. The types of information collected about individual landslides varied, geographic coverage was incomplete, and the reporting of landslides was highly selective (generally reflecting the level of damages). Little of this information was formally documented.

Reconnaissance efforts were typically carried out from the air (some were followed up with limited field investigation) and covered small geographic areas [Gerstel and others, 1997; USGS, 1997]. Palmer's aerial survey and photo documentation of coastal bluff landslides following the 1996-97 landsliding [Palmer, 1998] covered more of Puget Sound's shoreline than any other effort. Several local jurisdictions carried out surveys of their shorelines and steep slope areas, but the emphasis was on reconnaissance and on documentation of a limited number of specific landslides - not systematically cataloging or mapping landslides.

Individual agencies at the state and local levels logged numerous reports of landsliding from the general public and from work crews and agency staff, but each handled and recorded the information differently. This reflected a lack of a standard protocol, but more importantly, resulted from each agency having a different objective in obtaining the information. Many reports, particularly to emergency managers, came as requests for assistance from property owners impacted by slides. Examples of these reports include city and county lists of slide-damaged property or FEMA's Individual Assistance Program [FEMA, 1997a]. Agencies also receive reports of landslides from their own field staff, such as road crews, building officials, and public works departments. Building department records of red-tagged or condemned structures provide a direct link to landslides, whereas road maintenance records may indicate activities such

[15] A map scale of 1:24,000 is equivalent to one inch equals 2000 feet. At this scale, even a relatively large slide 200 feet across would only occupy one tenth of an inch of map space. A more typical shallow slide less than 50 feet across would not be mappable.
[16] The new inventory confirms the high proportion of landslides that occur on steep slopes along the so-called "Contact" first described by Tubbs [1974], marking the boundary between the overlying Esperance Sand and the underlying Lawton Clay.

as ditch clearing, debris removal, or pavement patching, but may not be clear measures of landslide activity.

The Washington State Department of Transportation maintains a database of road maintenance activities that provides some indication of landslide activity, although clearly only slides that impact state highways would be noted - limiting its usefulness for inventorying landslides along most shorelines. Pipeline companies and railroads also maintain similar records of repair and maintenance activity, but access to such databases may be restricted or at best, difficult.

Another potential source of information about slides are local and state permitting agencies with regulatory jurisdiction over activities carried out in response to landslides. Local planning and building departments review proposals for retaining walls, slope stabilization measures, bulkheads, and related actions. The Washington State Department of Fish and Wildlife (WDFW) reviews projects along the shoreline, such as bulkheads and retaining walls. The Washington Department of Ecology (WDOE) also reviews some shoreline projects. As a consequence, agency staff may be familiar with particular landslides in their jurisdictions, but such knowledge is unlikely to be useful for compiling a comprehensive inventory.

Geological and engineering consulting firms typically have the best opportunity to collect technical information on landslides, but many different consultants and contractors operate in this area and the experience of any one company will be limited to those slides that they are hired to investigate. Where reports are carried out on behalf of a public agency or as a requirement of a building or permit application, the records would typically be public, but often letters and reports generated by these investigations are confidential and proprietary.

Media accounts, typically newspapers, are a common source of information about landslides, particularly when researchers are trying to recreate a landslide inventory from scanty historical records [Cuesta and others, 1999]. Unfortunately, such records are extremely selective, focusing on newsworthy landslides or on slides for which information is readily available. Newspapers are a useful method for identifying previous episodes of significant landsliding, even if they are limited as an inventory tool.

Regulation of Unstable Slopes on Puget Sound

In Washington, construction in landslide-prone areas is regulated at the local level, largely through land use zoning, development regulations, and building codes. Zoning regulations provide communities with a tool for guiding development away from hazardous areas or for controlling densities and types of development on hillslopes [Olshansky, 1996; FEMA, 1997b].

The state's Growth Management Act (1990) requires jurisdictions to adopt Critical Areas Ordinances that meet state-established minimum guidelines [Brunengo, 1994]. Critical Areas include Geologically Hazardous Areas, a subset of which is Landslide Hazards. Several jurisdictions already had development regulations for steep slopes and landslide hazard areas prior to the Growth Management Act (King County's Environmentally Sensitive Areas ordinance or Thurston County's Marine Bluff ordinance, for example) and have subsequently adapted the earlier codes to meet the requirements of the GMA. Other jurisdictions had little, if any, regulation of slide-prone areas in place in 1990, and have subsequently developed new ordinances.

The Uniform Building Code (UBC) contains elements that address construction practices on steep or unstable slopes [Laprade, 1989]. The Hazard Mitigation Survey Team (HMST) [FEMA, 1997b] recommended that local jurisdictions adopt, at a minimum, those standards set forth in Appendix Chapter 33 of the UBC. Scullin [1983] describes in detail the excavation and grading requirements in the Uniform Building Code. The HMST noted that in addition to implementing strict building standards in potentially unstable areas, local jurisdictions should assure that geotechnical standards are complied with and that inspectors are trained and empowered to recognize problems and to enforce codes in this area.

Another area of regulation that significantly affects development in many unstable areas are laws designed to protect shorelines and other environmentally sensitive areas. Landslides frequently occur along river and marine shorelines and therefore development in landslide prone areas, along with activities carried out to mitigate for landslide risks, is often subject to environmental regulation. Although landslides into bodies of water may be an environmental concern, largely due to the input of high volumes of sediment and the burial of habitat, biologists and resource managers are increasingly more concerned about the impacts of slope engineering measures on particularly sensitive riparian or aquatic habitat. In addition, on Puget Sound, where a majority of beaches are built of sediment eroded from coastal bluffs, there are serious concerns that widespread erosion control may lead to diminishment of beaches and habitat loss [Macdonald and others, 1995; Thom and others, 1995; Shipman and Canning, 1995].

The state's Shoreline Management Act (1971), which is implemented by cities and counties through local Shoreline Master Programs, regulates many activities that occur along the shoreline, including in many cases, structures and related activities carried out to address erosion and landsliding. These regulations attempt to balance property owner's interests in reducing erosion with concerns about these activities on the environment, on public resources, or on the private property of others. Similarly, the Hydraulics Code, administered by the Washington Department of Fish and Wildlife, address activities that occur along the shoreline or that directly impact fish. Depending on the nature of a proposed project, other agencies, such as the U.S. Army Corps of Engineers or the U.S. Fish and Wildlife Service may become involved.

Numerous local plans and regulations can affect areas within or adjacent to unstable slopes and it may be difficult to assure that zoning, development, critical area, and other environmental ordinances are consistent with one another. Examples include evaluation of how storm water management within a large subdivision might impact nearby steep slopes, reconsideration of density requirements within known landslide areas (either decreased or increased densities might be appropriate, depending on the circumstances), or decisions regarding planning for roads and infrastructure or for siting critical facilities.

Strict regulation of landslide hazard areas remains a challenging task for local governments. Effective oversight requires geotechnical information and staff resources many communities do not have or cannot afford. Reducing landslide risks often dictates avoidance of landslide areas in the first place, yet this triggers both political and legal opposition as it may greatly restrict development of private property.

Technical review of development in landslide prone areas

The Hazard Mitigation Survey Team noted that one of the major problems facing local jurisdictions was obtaining high quality geotechnical submittals with development proposals in hazardous areas [FEMA, 1997b]. This was compounded by the lack of resources at the local level to effectively review geotechnical submittals or to place conditions on projects. In general, the quality of geotechnical reports reflected 1) inconsistent and sometimes poor quality work by consultants, 2) the lack of clear guidance as to what constituted an adequate or complete geotechnical investigation or submittal, and 3) difficulty on the part of local government in properly reviewing these reports.

Individuals and consultants conducting work on potentially unstable sites on Puget Sound vary greatly in their technical training and level of experience. In most cases, such work is carried out by geologists or geotechnical engineers, but soil scientists, environmental specialists, civil engineers, and others may also be capable of providing guidance in this area. This complicates efforts to dictate the standards for geotechnical reports based on purely on a consultant's discipline or professional practice. There is also no systematic means of assessing competence or experience in slope stability issues among any of these groups. In 2000, Washington approved legislation that will lead to the registration of geologists, an important step identified in the HSMT report [FEMA, 1997b]. Licensing of geologists, and certification of geotechnical engineers (although engineers must be licensed, Washington does not offer a specialty certification in geotechnical engineering), could provide individuals and jurisdictions with a means of identifying those professionals trained and experienced in landslide work. This measure in itself, however, does not preclude licensed geologists unfamiliar with landslides from providing consulting in this area, nor does it provide a means of certifying soil scientists or civil engineers with extensive landslide experience.

Another effective means of improving the quality of landslide investigation is to clearly stipulate the scope and depth of geotechnical submittals and to improve the rigor with which reports are reviewed. The lack of clear guidelines for geotechnical submittals can result in poor quality, incompleteness, inconsistency - and often overly narrow analyses "dictated by the amount of financing of the project proponent or home owner, rather than the severity of the hazard [FEMA, 1997b]." Some jurisdictions (Kitsap County, for example) have begun to adopt standard requirements for the content of geotechnical reports. In some cases, this process recognizes that different situations may require different levels of effort and different analyses.

One commonly cited problem is that many local jurisdictions lack the technical staff or resources to appropriately review geotechnical submittals, contributing to the poor quality of submittals and the failure to identify potential problems with projects. Most jurisdictions require such submittals for slopes that meet basic criteria for instability, but it appears that in many cases, local governments are not able or do not choose to substantively review or critique such reports. Rather they rely on such reports to inform applicants of potential problems and to transfer some of the responsibility to private consultants. This use of geotechnical reports may be reasonable, but the lack of rigorous and competent review can result in inferior or flawed project proposals and ultimately can lead to extensive development of highly problematic sites without appropriate mitigative measures.

Controlling and Preventing Landslides

It is outside the scope of this report to undertake a comprehensive review of the methods commonly utilized to stabilize steep slopes and to control landslides. A wide variety of techniques can be applied , ranging from drainage improvements to large-scale reengineering of the slope through grading and the construction of retaining structures [Jochim and others, 1988; Macdonald and Witek, 1994].

Common measures employed to address unstable slopes on Puget Sound include bulkheads to protect slopes from toe erosion, drainage improvements aimed at reducing surface runoff and shallow groundwater from affecting the slope, and removal of trees to reduce stress on soils during high winds (the latter is a particularly controversial solution, in part because trees also provide significant stabilizing benefits).

These are only the most common approaches found and they generally reflect a combination of relatively low cost and simplicity, familiarity with the technique (by both property owners and by contractors and engineers), and in the case of bulkheading and vegetation removal, ancillary benefits in the forms of improved beach access and expanded views, respectively. Many other approaches are also used, and as property values increase and property owners are more prepared to spend large sums of money, there has been an increased use of upslope retaining walls, deep vertical and horizontal drainage systems, reinforced soil embankments, soil nailing, and extensive slope regrading and engineering.

Failures of slope engineering measures are not rare on Puget Sound, although no data are available to document the number or type of problems that occur. Many occur simply because the basic measures employed on a site did not adequately address the character of the landslide danger. Many bulkheads built at the toe of slopes, ostensibly to protect bluffs from erosion and sliding, are buried or damaged when slopes fail above them. The problem may be that on these steep coastal slopes, toe erosion over a period of many decades or centuries may have set the stage for sliding, but that the actual trigger for a slope failure is related instead to soil saturation and pore pressures, possibly combined with weathering processes. On sites where deep-seated failures occurred at or below beach level, bulkheads and seawalls may have simple ridden along with the slide. Many of the most notable landslides that occurred during the last several years on Puget Sound affected properties on which toe protection had been present for decades.

In recent years we have seen the failure or partial failure of numerous multiple-tiered retaining walls on shoreline bluffs. These may reflect inadequacies in engineering design, failure of contractors to accurately carry out engineering plans, or incomplete understanding of geological conditions. Unfortunately, some of these larger retaining walls appear to have escaped rigorous review by local building officials. Another source of problems reflects a long tradition of property owners implementing their own creativity in solving erosion problems on waterfront lots - without the benefit of solid engineering guidance. I have seen some remarkably high walls constructed of decorative, interlocking blocks of the kind now readily found in home centers, apparently without the benefit of any additional reinforcement of the slope itself nor adequate drainage or backfill. Such structures do very little to strengthen a slope, may actually precipitate failure by impeding free drainage, and may be hazardous when they fail.

Along Puget Sound shorelines, there is increasing emphasis on avoiding disturbances to hydrology and vegetation that might lead to landsliding, rather than structurally stabilizing slopes. This emphasis reflects several concerns: 1) poor drainage and injudicious removal or modification of vegetation are common contributors to landsliding, and avoiding problems is far less expensive than fixing them later, 2) effective stabilization may be extremely expensive and often is not justified on residential property [Kockelman, 1996; Thorsen, 1987], whereas avoidance, primarily through careful site planning and substantial setbacks, may be more appropriate, 3) much of the regulatory concern directed at shorelines is driven by the need to minimize impacts of development on neighbors and to preserve the natural shoreline environment - drainage and vegetation management are consistent with this goal, whereas structural modifications such as bulkheads and retaining walls, extensive slope re-engineering, and vegetation removal, are less likely to be.

Monitoring and Warning

Monitoring landslides has been proposed by Kockelman [1996] as one component of a landslide risk reduction program. Based on the review of the 1996-97 landslide disasters in western Washington, the Hazards Mitigation Survey Team recommended monitoring of potentially unstable slopes [FEMA, 1997b]. Landslide monitoring encompasses a variety of measures, some of which may be more appropriate to certain landslide regimes. Shallow landsliding brought on by intense precipitation is difficult to predict directly, but the rainfall itself can be observed and systems put in place to warn or evacuate at-risk homes when rainfall reaches critical levels, although this may by aided by better understanding of the relationship between slides and threshold precipitation levels. Regular inspections of steep slopes in vulnerable areas for signs of incipient sliding may be implemented locally, but shallow slides often provide few visible clues prior to their failure A number of Puget Sound beach communities undertake this type of monitoring, often enlisting the residents themselves.

In the case of deep-seated landsliding, the option exists to monitor the landslide itself for signs of movement. With sufficient study, we may learn enough about these larger landslides that monitoring of groundwater levels will provide useful warning information. The USGS has monitored the large Woodway landslide in south Snohomish County since shortly after it occurred in early 1997 and posts the rainfall, groundwater, and slope movement data on the internet.[17]

Finally, observations of landslide prone areas along transportation and utility corridors can be valuable. Natural gas and fuel pipelines are subject to ruptures and leaks from both gradual slope movement and from rapid slides and monitoring of critical areas would allow shutting down lines prior to a catastrophic failure. Burlington Northern Santa Fe employs a "trip-wire" system along the railroad grade north of Seattle, providing warning to train crews when slide debris may be present on the tracks. As passenger use increases over the next few years with the introduction of commuter rail service on this corridor, it may be appropriate to enhance this warning capability and to begin to anticipate not only the presence of slides, but the conditions that give rise to them.

Education and Outreach

Educating the public about landslides has many direct benefits. Property owners become more aware of landslide risks, learn to recognize signs of slope movement, and begin to avoid practices that might lead to landsliding. Individuals considering purchasing property can factor the risk into their plans and financial decisions. Geotechnical professionals become better informed of techniques for investigating and stabilizing landslides. Government officials obtain a better sense of the public risks and of the range of tools available to manage landslides. Communities aware of the risks and potential long-term public costs associated with unmanaged development in unstable areas are likely to be supportive of regulations and programs designed to reduce risks.

In the Puget Sound region, public education on landslides and landslide hazards has largely been limited to local programs, often developed in response to landslide disasters. Local officials periodically organize workshops or public meetings at which the public can ask questions of technical experts and obtain guidance materials. Several WSU Cooperative Extension offices in Puget Sound counties have included landslides in public education and professional development classes, typically oriented toward shoreline property owners and real estate professionals. The

[17] Monitoring information on Woodway can be viewed at: http://landslides.usgs.gov/woodway/index.html

City of Seattle has arranged numerous public workshops directed at residents of slide-prone neighborhoods over the past several years.

Some local governments have produced and distributed materials on landslide issues. Seattle, in particular, has developed numerous documents aimed at educating property owners about landslide hazards. The Washington Department of Ecology has published a series of three booklets for owners of Puget Sound bluff property that describe drainage and vegetation on steep slopes [Menashe, 1993; Myers, 1993; and Myers, 1995]. The emergence of the internet has led to numerous efforts to put landslide related educational materials on the World Wide Web[18].

Professional organizations, such as the American Society of Civil Engineers and the Association of Engineering Geologists, occasionally sponsor workshops for the professional community on slope stability issues and have participated in local efforts to educate the broader public (such as the recent Seattle workshops). For example, the ASCE organized a seminar in the spring of 1998 addressing landslides in the region [American Society of Civil Engineers, 1998].

[18] The Department of Ecology, as part of this FEMA-funded project, has recently launched a web site targeted specifically to educating the public about landslides on Puget Sound. It can be found at: http://www.ecy.wa.gov/programs/sea/landslides.

Conclusions and Recommendations

The purpose of this report has been to describe and document landsliding that occurred on Puget Sound in the latter half of the 1990s and to provide background helpful to drawing conclusions about future landsliding and means of reducing landslide risks in the Puget Sound region. Our emphasis has been on coastal landslides, in part because the bluffs that surround the Sound were the site of most of the notable landslide activity in this period and in part because our own focus has been on coastal geologic processes and on managing coastal hazards.

Landslides of two winters: 1996-97 and 1998-99

A comparison of the landslides that dominated the news during the winter of 1996-1997 and those that did so two years later, in early 1999, provides some interesting contrasts, but also reinforces many lessons. The widespread, shallow landsliding of 1996 and 1997 was directly associated with high rainfall events. Most slides occurred rapidly, and with few exceptions, in a few very narrow time windows during or following the rains. Damages were most severe where landslide debris was carried down the slope into structures. Damages also occurred, though less commonly, where homes built on the edge of steep slopes were undermined. The landslides occurred during the same storms that also caused extensive damages in other areas (urban flooding, groundwater flooding, snow and ice damage) and consequently were included in federal disaster declarations.

In contrast, the reactivation of many very large, deep-seated landslides in 1998-1999 did not happen as a consequence of particular rain storms, but rather was the consequence of very high cumulative rainfall . Damages were also significant, although not singularly catastrophic as two years earlier. The damages emerged over time as a result of condemnation of homes in expanding slide areas or due to prolonged closures of major highways. The landslides were seen as distinct events and were not associated with a particular storm, nor did the conditions that gave rise to the slides cause other types of damage. No disaster was declared, probably because no single disaster could be defined.

Location of landslides

Landslides during both periods occurred in largely predictable locations. Although sometimes it appears that slides strike quite randomly, they actually occur within narrowly bounded areas and along the shoreline. The types of areas that are vulnerable are fairly well understood. In general, landslides occur on steep slopes, often where characteristic geological conditions exist or where surface water or groundwater becomes concentrated. More gradual slopes can also fail, but typically this happens within existing prehistoric landslides or in close proximity to steeper slopes. Existing mapping of unstable areas around Puget Sound provides an excellent first-order indication of areas subject to future landsliding.

Within landslide-prone areas, damages can result in a variety of settings and from a variety of types of slides. The Rolling Bay tragedy of January, 1997, underscores the high danger to lives and public safety to homes or structures located below steep slopes, where even small slides can result in severe consequences. Such settings are common around Puget Sound, both in developed and more rural areas, and are readily identified. Structures perched above steep slopes are also vulnerable, but the likelihood of catastrophic losses may be considerably less due to the shallow nature of most slides and possibly, an increased awareness of the possible danger.

Whereas shallow slides can result in significant damages, most do not completely destroy structures, and often repairs and rebuilding occur quickly. Deeper slides, although less likely to cause injury because they typically move slowly, can result in more serious property damages as entire structures can be destroyed and entire neighborhoods may be abandoned. Total movement on the Carlyon Beach slide in Thurston County in 1999 was not large, and the direct danger to residents was minimal, but the consequences of condemning more than thirty homes and displacing that many families were major.

Among the most dangerous scenarios along Puget Sound would be a large, rapid Woodway-like landslide that affected a heavily developed area or that directly involved a large number of people. Fortunately, such catastrophic slides occur relatively infrequently throughout the region, and the probability of one occurring in a shoreline residential community or impacting a passenger train may be small. The potential consequences, however, remain large, and little is understood of the conditions that give rise to them.

Recommendations

This report has identified a wide variety of areas where improvements could be made to the manner in which we address landslides in the Puget Sound region. There are a number of fairly specific recommendations, however, that I believe would greatly reduce landslide risks in the future.

Numerous of these recommendations must be implemented at the local level, yet we are fully aware that most jurisdictions lack the technical capabilities and financial resources to effectively carry out these tasks. We believe this speaks to the need for the state to take a more active role in providing guidance, technical information, and ultimately, in providing the necessary funds.

Mapping and Inventory

Mapping of landslide risk in the Puget Sound region is not adequate to address public safety and in an expanding metropolitan region. In addition, development is rapidly moving into rural areas where knowledge and management of unstable and regulation of unstable slopes is poor, setting the stage for significant future problems. Relative slope stability mapping is available for coastal slopes, but it is out of date and for many inland areas it is available only at an insufficiently small scale for effective local decision-making.

Landslide Mapping

- Develop improved landslide susceptibility and landslide risk maps for the entire Puget Sound region, taking advantage of updated geologic mapping, recent efforts to collect regional high-resolution topographic data, and new models of landslide occurrence.

Landslide Inventory

- Establish a systematic and comprehensive approach to inventorying landslides that addresses the need for consistent region-wide landslide data for mapping and model development, as well as the need for locally specific inventory from which to identify vulnerable communities, carry out post-disaster damage assessments, and to guide effective response and recovery efforts. This might involve a combination of periodic aerial landslide surveys and the development of a simple, standard reporting form for local agency use.

Regulation of landslide-prone areas

Although current regulation of landslide-prone areas through the state's Growth Management Act and local Critical Areas Ordinances provides a framework for addressing landslide risks, many local governments lack the resources, knowledge, and motivation to develop and implement effective rules.

Improved landuse and development regulations

- Many local ordinances lack sufficient detail or rigor to effectively guide development away from unstable slopes or to require adequate geotechnical evaluation to assure that stabilization measures are effective and appropriate. Ordinances should be reviewed for technical adequacy and for consistency with other local regulations and landuse plans.

Improved technical review

- Local governments need the technical capability and the resources to effectively review geotechnical submittals associated with development applications in unstable areas.

Geologists at the local level

- Local governments should be encouraged to add geological staff to planning and community development departments to aid in identifying local landslide risks, developing locally tailored ordinances, reviewing projects in landslide areas, and educating local elected officials, other staff, and the public about geologic hazards. In many jurisdictions, such expertise could also be utilized in areas other than landslides, including groundwater management, floodplain development, natural resource planning, and shoreline management.

Landslide mitigation and slope stabilization

Avoidance of landslide-prone areas is often the most cost-effective, long-term approach to minimizing landslide risks, but where existing development or other factors make avoidance impractical, slope engineering methods have to designed, constructed, and permitted adequately.

Engineering guidance

- Technical guidance should be developed that addresses standard methods for assessing unstable areas, for selecting appropriate engineering techniques, and for constructing stabilization measures on steep slopes. Such documents would raise the standard among design and contracting professionals and would assist local governments in reviewing and permitting projects.

Environmentally sensitive areas

- Growing environmental concern about sensitive shorelines and habitat areas requires improved guidance on selecting and designing geotechnical measures that preserve or restore ecological functions while achieving stabilization objectives.

Local Improvement Districts

- Formation of Local Improvement Districts (LIDs) within landslide-prone neighborhoods provides for more effective long-term planning and mitigation of slope hazards.

Monitoring and Warning

Vulnerable areas

- Monitoring and warning systems should be implemented in those areas where potential risks are narrowly defined and well known, such as along heavily used highway or railroad corridors, or in particularly vulnerable communities such those built on historically active deep-seated landslides or those constructed along the foot of steep bluffs.

Better understanding of thresholds

- Encourage research directed at understanding threshold conditions of precipitation or groundwater necessary to trigger landsliding.

Education and Outreach

Property owners

- Create educational materials and programs aimed at owners (and potential purchasers) of landslide-prone property and at the real estate community, with the goal of informing people about possible risks and methods of reducing or avoiding damages.

Local officials

- Workshops and guidance materials can be developed that inform local officials about both the geotechnical and the legal aspects of managing unstable areas and responding to landslide emergencies

Broad recommendation

State hazards initiative

- Washington State lacks a comprehensive state-level geologic hazards program that combines science and mapping with outreach and education. Current efforts to address geologic hazards are poorly funded and poorly connected. A strong program could provide much-needed assistance and guidance to local governments and would greatly help leverage federal funding for mapping, research, and hazard mitigation efforts. An effective state program could be modeled after those in other states and would require committed agency leadership and strong legislative support.

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Appendix: Landslides resulting from 2001 Nisqually Earthquake

At 10:54AM on Wednesday, February 28, 2001 a strong earthquake shook Puget Sound. The earthquake had a moment magnitude of 6.8 and was centered about 30 miles beneath the Nisqually Delta northeast of Olympia. The Nisqually Earthquake resulted in widespread impacts to unstable soils and buildings, although severe damage and loss of life were remarkably limited [Nisqually Earthquake Clearing House, 2001].

Relatively few landslides resulted from the earthquake, possibly due to the winter's particularly dry conditions. The following list only includes coastal slides and is not an exhaustive inventory.

- *Maplewild Avenue, Burien*. Sliding occurred along approximately 200 feet of Maplewild Avenue SW north of Three Tree Point, impacting at least two homes and the road itself. The earthquake appeared to initiate the movement, although the slope has not completely failed.
- *Salmon Beach, Tacoma*. A large failure occurred on the steep slope above the Salmon Beach community on the Tacoma Narrows (see Figure 43). As in the previous example, the earthquake resulted in limited movement, not catastrophic failure of the slope, although residents and local officials have strong concerns about additional movement.
- *Hwy 302, Mason County*. A large, deep-seated landslide south of Victor along the eastern shore of North Bay reactivated, resulting in several feet of vertical offset along Highway 302 along two different portions of the landslide.
- *Capital Lake, Olympia*. A 400-foot long slide occurred along the northeast side of Capital Lake [Nisqually Earthquake Clearing House, 2001].
- Several shallow landslides were observed on marine bluffs in the South Sound, including along the western side of the Key Peninsula and along Nisqually Reach.

Figure 45. Reactivation of landslide along Highway 302 near Victor in Mason County.
Field assistant is approximately 4.2 feet high *[Photo: 3/3/2001]*.

In summary, the Nisqually Earthquake resulted in relatively few landslides along Puget Sound, despite its large magnitude. In general, the amount of shaking associated with the quake was less than expected. In addition the weather had been unusually dry and widespread sliding triggered by rainfall during previous years may have reduced the number of incipient landslides.