Coastal Erosion Management Strategy

Management Options for Unstable Coastal Bluffs in Puget Sound, Washington

Coastal Erosion Management Studies, Volume 8

WASHINGTON STATE DEPARTMENT OF ECOLOGY

August 1994
94-81

printed on recycled paper

Management Options for Unstable Bluffs in Puget Sound, Washington

Coastal Erosion Management Studies, Volume 8

August 1994

Prepared by:

Keith Macdonald, CH2M Hill, Seattle, Washington, and
Bonnie Witek, Geo-Dynamics Consulting, Inc.

Report 94-81

Shorelands and Environmental Assistance Program
WASHINGTON DEPARTMENT OF ECOLOGY
Olympia, Washington 98504-7600

Coastal Erosion Management Strategy

This report is one in a series or reports commissioned or completed by the Shorelands and Coastal Zone Management Program of the Washington Department of Ecology in fulfillment of the Coastal Erosion Management Strategy project. The project is dedicated to seeking answers to questions on appropriate technical standards for coastal erosion management, the environmental impact of shoreline stabilization techniques, and the assessment and development of policy alternatives. The reports in the series are listed on page iii. Inquiries about the Coastal Erosion Management Strategy project should be directed to the project manager and series editor:

Douglas J. Canning
Shorelands and Environmental Assistance Program
Washington Department of Ecology
P. O. Box 47600
Olympia, WA 98504-7600
Telephone: 360.407.6781
Internet: dcan461@ecy.wa.gov

The Coastal Erosion Management Strategy was funded in part through a cooperative agreement with the National Oceanic and Atmospheric Administration with funds appropriated for the Coastal Zone Management Act of 1972 through a grant to the Department of Ecology. The views expressed herein are those of the authors and do not reflect the views of NOAA or any of its sub-agencies.

Recommended bibliographic citation:

Macdonald, Keith B. and Bonnie Witek. 1994. *Management Options for Unstable Bluffs in Puget Sound, Washington. Coastal Erosion Management Studies Volume 8.* Shorelands and Environmental Assistance Program, Washington Department of Ecology, Olympia.

Coastal Erosion Management Studies

Volumes in the Coastal Erosion Management Studies series will be published over a period of time. At the time of publication of this volume, the printing schedule was as follows.

Volume	Title	Status
Volume 1	Coastal Erosion Management Studies in Puget Sound, Washington: Executive Summary	Published January 1995
Volume 2	Coastal Erosion Management: Annotated Bibliographies on Shoreline Hardening Effects, Vegetative Erosion Control, and Beach Nourishment	Published June 1994
Volume 3	Inventory and Characterization of Shoreline Armoring, Thurston County, Washington, 1977 - 1993	Not published
Volume 4	Engineering and Geotechnical Techniques for Coastal Erosion Management in Puget Sound	Published June 1994
Volume 5	Shoreline Armoring Effects on Physical Coastal Processes in Puget Sound, Washington	Published August 1994
Volume 6	Policy Alternatives for Coastal Erosion Management	Published June 1994
Volume 7	Shoreline Armoring Effects on Coastal Ecology and Biological Resources in Puget Sound, Washington	Published August 1994
Volume 8	Management Options for Unstable Coastal Bluffs in Puget Sound, Washington	Published August 1944
Volume 9	Regional Approaches to Address Coastal Erosion Issues	Published June 1994
Volume 10	Coastal Erosion Management in Puget Sound: Final Environmental Impact Statement	Not published
Volume 11	Coastal Erosion Management in Puget Sound: Technical and Policy Guidance for Local Government	Not published

Preface

The shores of Washington's inland coast—greater Puget Sound—undergo both shoreline erosion and landsliding. The overall rates of shoreline retreat are usually minor, maybe an inch or two a year, but in some areas may average as much as half a foot per year. This is usually due to a combination of bluff undercutting and steep slope failure, resulting in landslides. At any particular location, landslides occur infrequently, often decades apart. Simple shoreline wave erosion *by itself* is not often the problem in Puget Sound.

Marine shoreline erosion is a concern to both coastal property owners and the users and managers of coastal public resources. Coastal property owners are naturally concerned with protecting their investments in land and buildings. Unfortunately, houses and other buildings are often built dangerously close to the shoreline. Most property owners react to incidents of erosion by erecting erosion control structures such as concrete or rock bulkheads. If properly constructed, these shoreline armoring structures can slow most forms of wave induced shoreline erosion for a period of time, but will probably do little to prevent continuing landsliding. Many shoreline property owners consider shoreline armoring critical to the protection of their real estate.

Resource managers are, of course, concerned about any adverse effects on the habitats which support biological resources such as fish and shellfish and are charged with protecting the public property right in those resources. The scientific literature seems to indicate that shoreline armoring (and the associated vegetation clearing) typically results in the following adverse effects:

- Sediment supply to nearby beaches is cut off, thus leading to "starvation" of the beaches for the sand and other fine grained materials that typically make up a beach.

- The hard face of shoreline armoring, particularly concrete bulkheads, reflects energy back onto the beach, thus exacerbating beach erosion.

- In time, a sandy beach is transformed into gravel or cobbles, and may even be scoured down to bedrock, or more commonly in the Puget Sound basin, a hard clay. The footings of bulkheads are exposed, leading to undermining and failure.

- Vegetation which shades the upper beach is eliminated, thus degrading the value of the beach for spawning habitat.

- Any transformation of the character of the beach affects the kind of life the beach can support.

Request for Investigation and Assessment

The Thurston and Mason County Commissioners, and the Pierce County Executive, in 1991, requested that the Department of Ecology (Ecology) investigate the effects of wide spread shoreline armoring and prepare a programmatic environmental impact statement on the cumulative effects of bulkheading and other forms of armoring. These elected officials were reacting to the large numbers of bulkhead permit applications in recent years, and were voicing concern over their uncertainty about the wisdom of permitting large scale unmitigated shoreline armoring.

Legislative Action

In an action unrelated to the local government requests, the Washington State Legislature in 1992 passed *Engrossed Senate Bill 6128* which amended the Shoreline Management Act to provide for the following:

- Local governments must have erosion management standards in their Shoreline Master Programs. While most local governments have erosion sections in their SMP, these existing regulations may not be as comprehensive as ESB 6128 requires.

- These standards must address both structural and non-structural methods of erosion management. Structural methods are typically bulkheads or rip rap. Non-structural methods include building setbacks and other land use management approaches.

- The standards must give a preference for permitting of erosion protection measures for residences occupied prior to January 1, 1992 where the erosion protection measure "is designed to minimize harm to the shoreline natural environment." This implies no preference for protection measures first occupied after January 1, 1992.

- ESB 6128 expands erosion protection from just a residence to "single family residences and appurtenant structures."

- Permit application processing by local government must be carried out in a timely manner. Shoreline property owners testifying for the bill cited local government delays in permit approval as onerous. Local governments report that most permit delays are caused by incomplete or inaccurate information on the permit application.

The Coastal Erosion Management Strategy

The legislature was unable to provide local governments or Ecology with the funds necessary to carry out the intents of ESB 6128 because of reduced tax revenues. Fortunately, Ecology was successful in obtaining a grant under the federal Coastal Zone Management Act to carry out a comprehensive Coastal Erosion Management Strategy.

CEMS—the Coastal Erosion Management Strategy—is a three year, multi-task program aimed at (1) satisfying local elected officials' requests for assessment of the cumulative effects of shoreline armoring, (2) developing the standards for shoreline erosion management mandated by ESB 6128, and (3) assessing regulatory alternatives for erosion management. Tasks 1 - 4 were completed in 1992-93. Tasks 5 - 7 were completed in 1993-94, and tasks 8 and 9 in 1994-95.

Task 1. Inventory and Characterization of Shoreline Armoring, Thurston County, Washington, 1977 - 1993. Thurston County was selected as the study area for a pilot project because of the availability of large amounts of relevant information already in data management and GIS (geographic information system) computer file formats. This study provides quantitative estimates of the rate and character of shoreline armoring which are not readily available for most of Puget Sound.

Task 2. Engineering and Geotechnical Techniques for Shoreline Protection in Puget Sound. The generally accepted engineering and geotechnical techniques for selected erosion management alternatives (bulkheading, revetments, wave attenuation, beach nourishment, etc.) appropriate to the tidal range, wave energy, and geologic conditions characteristic of Puget Sound are assessed. This report provides the basis (in part) for development of State guidance recommendations to local government for adoption of standards for appropriate erosion management measures.

Task 3. Shoreline Armoring Effects on Physical Coastal Processes in Puget Sound. The key assumptions and questions about the effects of shoreline armoring on coastal processes are evaluated based on the technical literature, and sensitized to Puget Sound conditions. Selected local case examples are provided.

Task 4. Coastal Erosion Management Regulation: Case Examples and Critical Evaluation. Regulatory approaches to coastal erosion management in Puget Sound and other states are evaluated, and policy alternatives for Washington are assessed. This report will provide the basis (in part) for development of State guidance recommendations to local government for adoption of coastal erosion management procedures.

Task 5. Shoreline Armoring Effects on Biological Resources and Coastal Ecology in Puget Sound. Following on from Task 3, the direct effects of shoreline armoring and the secondary effects of changes to coastal processes and conditions upon biological resources are assessed. Selected local case examples are provided.

Task 6. Coastal Bluff Management Alternatives for Puget Sound. A large measure of bulkheading is in reaction to slope failures, not shoreline erosion *per se*. Slope instability is caused by a combination of inherent geologic weaknesses, ground water loading, and toe erosion. Following on from tasks 2 and 4, this task addresses management of coastal bluffs.

Task 7. Regional Approaches to Coastal Erosion Management. Traditionally, shoreline management and erosion control permitting has been on a case-by-case basis. Many "soft" approaches to erosion management (e.g. beach nourishment) or mitigation for adverse effects must be carried out on a regional basis to be effective. Both the technical and political feasibility of regional erosion management is assessed.

Task 8. Coastal Erosion Management Environmental Impact Statement. This task will integrate the special study reports and other information into a programmatic environmental impact assessment.

Task 9. Coastal Erosion Management Recommendations for Puget Sound. Based largely on the foregoing studies, this task will formulate specific model elements which can be recommended as amendments to local Shoreline Master Programs. The guidance will be published as a chapter in Ecology's *Shoreline Management Guidebook*.

Task 1, Inventory and Characterization, was completed by Thurston Regional Planning Council. Tasks 2 through 7 were completed CH2M Hill and Battelle Memorial Laboratories under contract to Ecology. Tasks 8 and 9 will be completed by Ecology.

Tasks 1 through 7 are each designed to answer a relatively narrow set of questions, therefore each task completion report presents only a very limited portion the study. Until the entire project has been completed, the analytical studies have been integrated (Task 8), and Ecology has developed its guidance to local government (Task 9), no conclusions should be drawn from the individual study reports.

This volume, *Management Options for Unstable Bluffs in Puget Sound, Washington*, is a companion to Volume 4, *Engineering and Geotechnical Techniques for Shoreline Erosion Management in Puget Sound*. Both volumes report on various techniques which are *technically* appropriate for application to coastal erosion management or bluff stabilization in Puget Sound, but not necessarily under all environmental, regulatory, or economic circumstances. The Department of Ecology is not endorsing these techniques as universally useful. The purpose of these tasks in the CEMS project was to provide Ecology with some of the information necessary to make recommendations to local government for amending their Shoreline Master Programs in accordance with the mandates of ESB 6128. That guidance will be issued by Ecology in a later volume in this report series.

The CEMS project is a balancing of concerns and mandates. The Shoreline Management Act (SMA) has goals of both "planning for and fostering all reasonable and appropriate uses" while at the same time "protecting against adverse effects to the public health, the land and its vegetation and wildlife, and the waters of the state and their aquatic life." ESB 6128, in amending the SMA, gave a preference for permitting of erosion protection measures for residences occupied prior to January 1, 1992 where the erosion protection measure "is designed to minimize harm to the shoreline natural environment."

Douglas Canning and Hugh Shipman
Shorelands and Coastal Zone Management Program
Washington Department of Ecology
Post Office Box 47600
Olympia, WA 98504-7600

Acknowledgments

This report has been prepared by CH2M HILL and Geo-Dynamics Consulting for the Washington State Department of Ecology, Shorelands and Coastal Zone Management Program under Memorandum of Agreement C9300102 for development of a Coastal Erosion Management Strategy. The report documents the results of work done under Scope of Work *Task 6, Coastal Bluff Management Alternatives for Puget Sound.* We kindly thank Douglas Canning and Hugh Shipman, Program Managers for the Washington Department of Ecology, for their support and guidance during the conduct of this task.

Information, including data, reports, and personal observations, used in this report was generously provided by the following individuals: Douglas Canning; Hugh Shipman; Neil Rickard and Robert Zeigler of Washington State Department of Fish and Wildlife; Dick Coon, Bill Derry, Ken Green, and Jane Gendron of CH2M HILL; Thomas Terich and Anthony Gabriel of Western Washington University (Department of Geography and Regional Planning); Jack Cox of Michael Baker Jr., Inc., Alexandria, Virginia; and Carol Fielding of CH2M HILL, who provided valuable library research support. We also thank Van Nostrand Reinhold, New York, for generously granting permission to reproduce selected copyright illustrations from Gray and Leiser (1982).

Report graphics were prepared by Garry Anderson, Jon Hegstrom, and Dennis Kirby; text word processing was done under the direction of Beth Paveglio and Mary Morris. Editor Jill Irwin smoothed assembly of the final report.

We are also particularly indebted to Bill Derry for help in formulating our approach to the task, and to Douglas Canning and Hugh Shipman for providing their technical peer reviews of the document.

Contents

Contents (continued)

Appendices

Fact Sheets

Tables

Contents: Tables (continued)

Figures

Contents: Figures (continued)

Contents: Figures (continued)

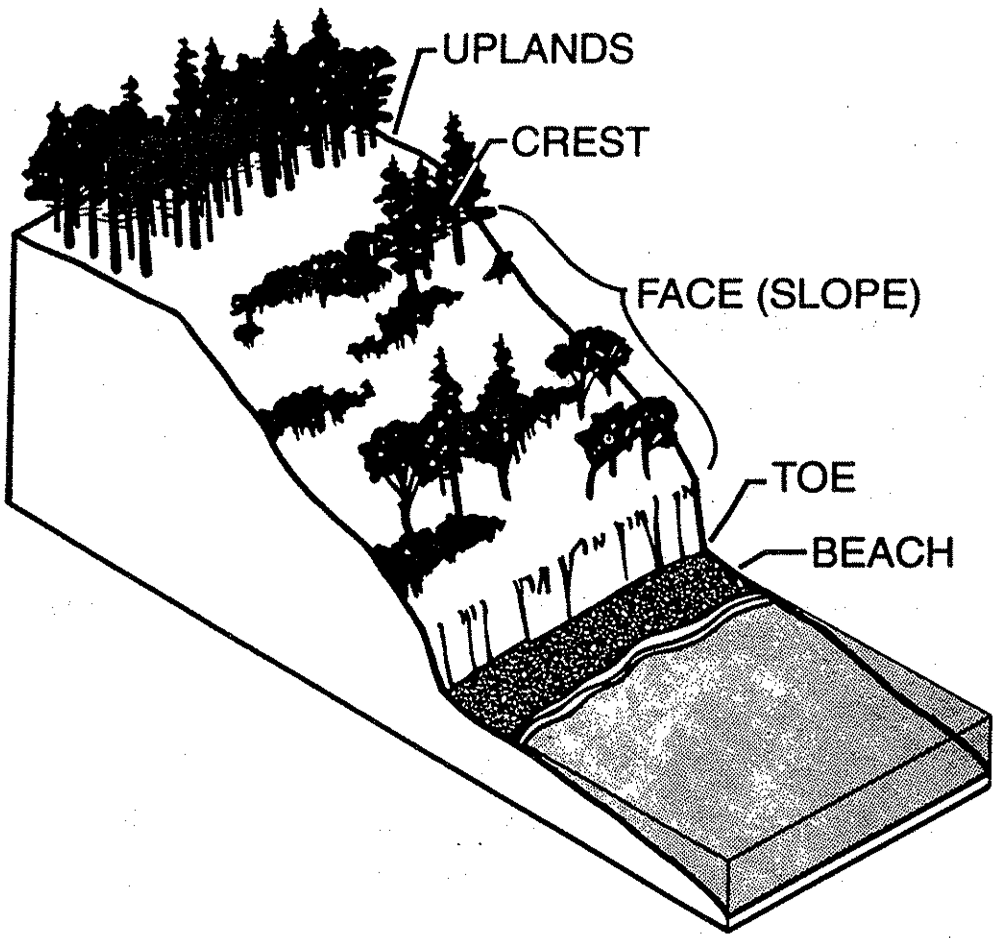
1.0 Introduction

1.1 Background

Development along coastal areas of the United States has been extensive. Culliton et al. (1992) estimated that between 1970 and 1989 approximately half of all residential and non-residential construction in the United States occurred in the federally designated coastal zone. During this same period, approximately 640,000 permits were issued for construction in coastal counties of Washington State. It is not known exactly how many projects were directly located on Puget Sound shorelines. However, waterfront property is prime real estate and substantial development is continuing to occur along Washington's shorelines.

Many structures are built dangerously close to the shoreline where wave erosion or unstable slopes can threaten coastal property (Canning and Shipman 1993, Macdonald et al., 1993). To protect these properties, erosion control structures such as concrete or rock bulkheads are often erected. While bulkheads often temporarily slow wave induced toe erosion at the foot of coastal bluffs (Figure 1-1), they cannot halt surficial erosion and slumping higher up the bluff face caused by poor vegetation management practices, surface runoff or groundwater seepage. Depending on specific site conditions "shoreline armoring" may not be an appropriate solution to handle a perceived erosion "problem"—and indeed it can do more harm than good. Further, adverse effects of shoreline armoring can occur which, in the worst case, can totally alter the physical structure of the beach and adjacent upland habitats (Downing 1983). Alteration of the physical conditions of the shoreline can cause changes in the structure and functioning of shoreline habitats and alter use of the habitats by fish, shellfish, birds, marine mammals and other organisms.

To minimize harm to the "natural environment" of the shorelines of Puget Sound while still allowing erosion control measures, the Washington State Legislature passed *Engrossed*



Source: Menashe (1993)

Figure 1-1
Elements of a Coastal Bluff

Senate Bill 6128 which requires local governments to develop standards for structures used to protect shoreline properties. The Washington State Department of Ecology (Ecology) Shorelands and Coastal Zone Management Program initiated a three-year strategy to resolve coastal erosion issues (Canning and Shipman, 1993). This strategy involves ten tasks that investigate the effects of alternative shoreline protection technologies on both the physical features of the beach and bluffs, and the ecology of the nearshore zone. The present report deals with **Task 6: Coastal Bluff Management Alternatives for Puget Sound.**

1.2 Objectives

As noted in the Preface, a large measure of bulkheading that has occurred around Puget Sound is in reaction to bank and bluff slope failures, rather than shoreline erosion *per se*. Slope instability can be a complex issue and usually reflects some combination of inherent geological weaknesses, poor vegetation management practices, and surface and groundwater loading, as well as wave induced toe erosion. The objectives of this **Task 6** report are therefore as follows:

- To describe some general characteristics of Puget Sound shoreline banks and bluffs
- To describe common forms of slope failure experienced around Puget Sound
- To describe the principal causes of slope failure
- To outline a range of slope management techniques available to address potential causes of failure

- To describe an approach for selection of slope management methods most appropriate to site-specific concerns.

- To identify data gaps and future study needs.

As with the other reports in this series, our emphasis—in keeping with *Engrossed Senate Bill 6/28*—is on single family residential development along Puget Sound shorelines.

1.3 Approach

Since this was the last report in the series to be completed to date (i.e., Tasks 1-7), we have learned substantially from the knowledge and understanding gained from prior study tasks. Of the six topics researched by the CH2M HILL/Battelle Study Team, **Management of Unstable Slopes** clearly has the most adequate general database of relevant information; as well as some excellent resource materials that focus directly on Puget Sound.

The general database reflects a broad engineering interest in solving the construction challenges engendered by unstable slope conditions. There is also much less concern that the unstable bluffs that rim Puget Sound are somehow uniquely different from unstable slopes in other regions. The **Task 3** report (Macdonald et al., 1993), in contrast, concluded that shoreline erosion within the Sound *really is different* from more commonly studied "open ocean coast" examples (see also Nordstrom, 1992). Slope management is a much more generic concern than coastal erosion and shoreline armoring, and much available information can be safely and realistically transferred to Puget Sound bluffs (with appropriate caveats) from other regional and upland settings.

The availability of some excellent local studies focused specifically on Puget Sound bluffs partly reflects serious landsliding and property loss problems experienced in the Seattle region during the winter of 1971-1972 (Tubbs, 1975). More recent contributions—Manashe (1993) and Myers (1993), for example—reflect Ecology/Shorelands and Coastal

Zone Management Program's proactive stance, responding to the increasing risks of slope failure, property losses, and the disruption of nearshore processes that reflect ever-increasing population pressures around Puget Sound.

The study approach taken for this task is quite simple and reflects the availability of good reference materials: **Identify the common causes of local slope instability—and then identify methods to either minimize or eliminate them.**

In-hand references were assembled and key-word dialog literature searches were conducted on the National Technical Information Service (NTIS) and Aquatic Sciences and Fisheries Abstracts (ASFA) databases. NTIS covers federal government reports and conference proceedings; ASFA includes a broad range of materials—journal articles, books, monographs, conference proceedings, and technical reports—focusing on science, technology, and management of marine and freshwater environments. Published and unpublished reports from Puget Sound and elsewhere that focus on the causes of slope instability or alternative methods for stabilizing slopes where assembled and reviewed. Individuals knowledgeable of Puget Sound slope instability issues were contacted to identify additional reference materials, study site examples, and representative site photographs. The assembled materials were then synthesized into four report sections, as follows:

- General characteristics of Puget Sound bluffs
- Common types of shoreline slope failure
- Causes of shoreline slope instability
- Alternatives for managing unstable shoreline slopes

Our synthesis focuses on regional geology, vegetation management, water management, and geotechnical engineering issues. A strong emphasis has also been placed on using figures and photographs to illustrate regional field examples.

1.4 Organization of Report

The report is organized into seven sections and two appendices. This Introduction is followed by a brief regional overview of some common characteristics of shoreline slopes—banks and bluffs—around Puget Sound. To provide perspective, a folio of photo-examples is included at the end of this second section.

The three major sections of the report follow in succession: (3) Types of Slope Failure, (4) Causes of Slope Instability, and (5) Managing Shoreline Slopes. Section 6 summarizes some of the preceding material and focuses on how to select appropriate management solutions for a particular site. References Cited are presented in Section 7. Appendix A includes examples of homeowner questionnaires that help identify potential slope instability problems associated with development of a specific site. Appendix B provides a list of coastal geological literature and slope-hazard map sources, organized by county around the Sound.

sea100290DA.wp5

2.0 Regional Overview: Shoreline Slopes of Puget Sound

Three local publications provide excellent background material for this study: *The Shape and Form of Puget Sound* (Burns, 1985) describes the three-dimensional form of Puget Sound and the processes that created it. *The Coast of Puget Sound: Its Processes and Development* (Downing, 1983) focuses on shoreline physical processes and general concerns related to coastal development. *Living With the Shore of Puget Sound and the Georgia Strait* (Terich, 1987) describes the entire Puget Sound coastlline and details specific issues related to shoreline residential development. A fourth very important resource is the *Coastal Zone Atlas of Washington* (Ecology, 1977-1980), thirteen folio-sized atlas volumes containing detailed shoreline maps for each of Puget Sound's coastal counties. A set of six maps for each shoreline segment respectively document geology, slope stability, coastal flooding, sand and gravel/critical biological areas, coastal drift,[1] and land cover/land use data. In addition to the narratives included with each atlas volume, two additional summary text volumes are also available (Albright et al., 1980).

This section of the report builds on these background materials to provide a brief overview of shoreline slopes around Puget Sound. The significance of unstable slopes as a regional coastal hazard is outlined, and their regional geologic setting and historical modifications are described. The section closes with a photo-folio that illustrates regional examples of natural and developed shoreline slopes.

The quote Terich (1987):

> "Puget Sound is different. What most people think of as a broad expanse of water is actually a collection of long, narrow straits and passages, sheltered bays, and quiet coves.

---

[1]More recent information on drift sectors around Puget Sound is contained in a series of Department of Ecology research reports titled *Net Shore-drift in Washington State, Version 2.0* (June 1991). These reports are based on master's theses completed under the guidance of Professor Maurice Schwartz, Department of Geology, Western Washington University, Bellingham, Washington. Ecology no longer recommends use of drift sector information in the *Coastal Zone Atlas* (Douglas Canning, Ecology, March 1993).

> Puget Sound's numerous islands also make it unique. These picturesque islands are mantled under a dense cover of Douglas fir, red cedar, and ferns, but a few are little more than shields of bare solid rock protruding above the water."

Puget Sound is a series of fjordal estuaries, which display most of the coastal features found worldwide in temperate latitudes. Major and minor rivers form deltas at their junction with Puget Sound. Formed relatively recently by glaciation, much of the sediments along the shorelines are glacial tills. Because of its narrow profile and deep central basin (i.e., 600 feet), the shoreline is relatively steeply sloping in many areas (Burns, 1985). Beaches are nourished primarily by erosion of shoreline bluffs and secondarily by sediment from rivers and streams. Compared with open ocean coast locations, long-term erosion rates are modest, but can increase in the short-term under the high tidal amplitudes and winter storm conditions experienced in Puget Sound. Substratum types and temporal changes in both beach sediments and profiles are dictated by adjacent sediment sources and local erosional/depositional processes (Downing, 1983).

Puget Sound shoreline consists of an intertidal zone and a shallow subtidal zone (between -1 m and -15 m mean lower low water (MMLW)), that together can be referred to as the *nearshore zone*. This is probably the zone most directly affected by alterations in physical conditions of the shoreline, including armoring. It contains all major vegetated habitats from high intertidal marshes to subtidal kelp forests. The mean tidal range within Puget Sound is on the order of 2 to 3 m.

Landward of the nearshore zone, shoreline slopes come in a variety of shapes and sizes (Figure 2-1; Myers, 1993). High bluffs fronted by coarse sand and gravel beaches are the most common shoreline landforms around Puget Sound. Fine sand and mud occurs primarily at the mouths of larger rivers and in quiet bays. Shoreline boulder fields and rock benches are both relatively rare (Downing, 1983).

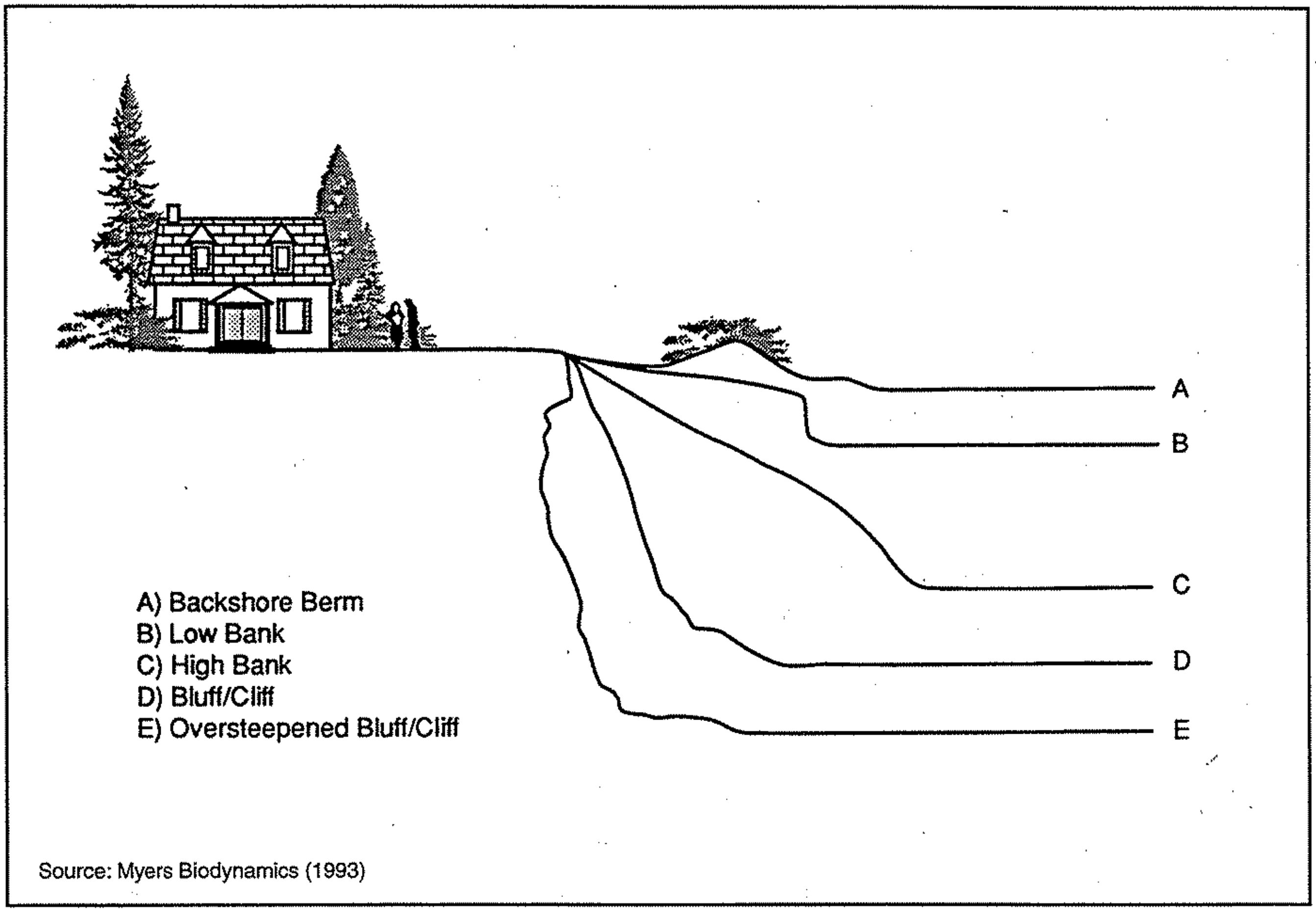


Figure 2-1
Typical Puget Sound Coastal Slope Profiles

2.1 Unstable Slopes as a Regional Coastal Hazard

Downing (1983/Table 5.2) provides a classification of coastal features around Puget Sound that are generally indicative of erosional versus depositional conditions. An inventory of such features conducted by Ecology in the late 1970s (Downing, 1983/Table 5.3) concluded that about one-third (32 percent) of Puget Sound's shoreline exhibited erosional conditions—reflected by large erosional scarps cut into bedrock or unconsolidated sediment by marine processes (typically in areas of vigorous wave action). The same inventory noted that an additional 24 percent of Puget Sound's coast had already been modified with structures—seawalls, piers, log booms, etc. Presumably, installation of some of these structures also reflected at least a perception of shoreline erosion problems. Thus, up to half the entire shoreline of Puget Sound may be experiencing active—although probably modest—shoreline erosion.

These areas of active shoreline erosion are also the most likely to experience bluff toe retreat, slope oversteepening (Figure 2.1E), and slumping. Since other processes besides toe erosion can result in slope instability—poor vegetation and water management practices, for example—far more than half of Puget Sound's shoreline may be subject to some risk of slope instability. Even this estimate may be too conservative. The U.S. Department of Commerce (White, et al., 1976, in Gabriel, 1988) estimates 80 to 90 percent of Washington State's coastal zone is subject to ground failure and erosion.

Downing (1983/Table 8.3) also ranks the relative likelihood of slope instability hazards associated with different coastal landforms. On a scale of 1 to 4 (low to high risk), he ranks the likelihood of landslides, rockfalls, and soil creep, for low (<10 feet) and high (>10 feet) bedrocks cliffs as 1 and 2, respectively.

Downing (1983) identifies three landform categories for coastal bluffs composed of glacial and alluvial sediments: low bluffs (<10 feet); high bluffs (>10 feet) fronted by a beach with a protective backshore area; and high bluffs with a beach, but no protective backshore. He ranks the likelihood of landslides for the first two categories at 3, while the high bluffs/no backshore category ranks 4—the highest risk. The same three landforms draw ranks of 1, 2, and 3, respectively, for the likelihood of slope instability due to soil creep.

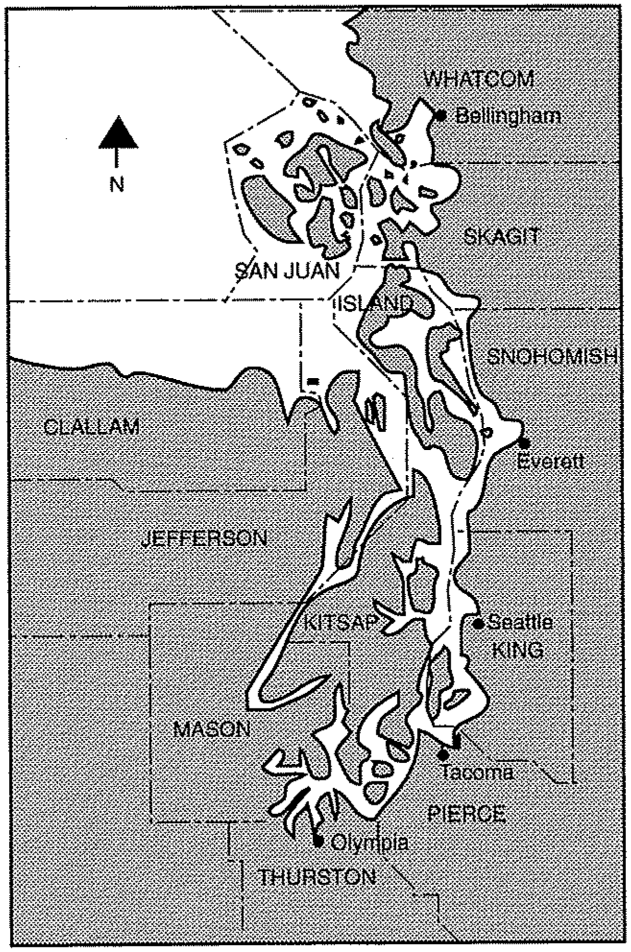
Gabriel (1988) provides another perspective on coastal hazards along Puget Sound shorelines. Using the *Coastal Zone Atlas of Washington*, he inventoried coastal hazards—principally erosion, flooding, and ground failure—by shoreline length, and county, around the Sound. He also categorized and tabulated federal, state, and local Coastal Zone Management legislation and policies designed to manage coastal hazard-related problems. His coastal hazard data for unstable slopes, recent landslides, and eroding beaches are reproduced in Figure 2-2.

An interesting inconsistency was revealed between the frequency of various coastal hazards and their recognition and management through county shoreline master programs. Policies pertaining to erosion, nonspecific hazard issues, or flooding consistently dominated most Puget Sound country shoreline master programs. Ground failure and eroding bluff policies represented the lowest percentage of hazard policy types. Gabriel (1988) concludes, quote:

> "The Puget Sound county shoreline master programs tend to give erosion and flooding hazards considerable attention. Ground failure and eroding bluffs, prevalent hazards along the many Puget Sound shorelines consisting of unconsolidated glacial deposits, are still to be properly addressed in the shoreline master programs. When proper recognition of the coastal hazards present in each county exists, compliance with Federal coastal hazard management policies will finally be a reality."

Gabriel (1988) also stresses the potential significance of future sea level rise due to global warming (see also Shipman, 1989; Canning, 1990):

> "...sea level rise...(will)...increase erosion rates of beaches and bluffs, inundate low-lying coastal areas, increase the impact of storm waves and storm surges, as well as undermine structural defense works. Proper management of coastal hazards, in view of future sea level rise, should concentrate on non-structural defense works and setback legislation which considers the rate of sea level rise."



County	Total Shoreline	Unstable Slopes	Recent Slides	Eroding Beaches
Whatcom	170	34	2	9
Skagit	212	80	3	30
Island	324	178	4	28
Snohomish	72	32	4	11
King	189	84	11	4
Pierce	233	115	9	12
Thurston	150	80	1	3
Mason	476	149	8	41
Kitsap	352	77	18	92
Jefferson	227	24	46	14
Clallam	200	99	6	3
San Juan	599	22	2	46
Total	3204	974	114	293

Shoreline distances as Kilometers (km).

Source: Gabriel (1988), after Ecology (1977-80)

Figure 2-2
Some Shoreline Characteristics of Puget Sound

2.2 Regional Geologic Setting

One of the striking features of Puget Sound is the diversity of its coastal land forms. To quote Downing (1983):

> "Rock cliffs rising vertically more than 100 meters (328 feet) from breaking waves, broad tidal mud flats of imperceptible relief, and smooth sandy beaches all exist within a distance of fewer than 50 kilometers (30 miles)."

These dramatic coastal features and the variable sedimentary deposits exposed along Puget Sound's shoreline reflect the impacts of recent, regional glaciation (McKee, 1972). During the Pleistocene Epoch, northwest Washington was impacted by as many as four successive periods of glacial advance and retreat. As ice sheets pushed south from Canada, they gouged out a series of deep, narrow, north-south oriented troughs that eventually became the major water features of Puget Lowland (Burns, 1985). As the most recent glacial ice sheet receded from the area about 13,000 years ago, the Puget Sound Lowland became a primarily depositional area where ice and meltwater streams deposited thick sequences of glacial till, outwash sands, and glacio-marine drift. These deposits, poorly sorted sands and gravels, often overlying clayey till, are exposed in the steep bluffs—ranging from 10 to 500 feet in height—which rim much of the Puget Sound shoreline. Section 4.3 (Local Geology) of this report provides a more detailed description of regional glaciation and also outlines the distribution and geotechnical characteristics of glacial sediments.

One way to gain an overview of shoreline characteristics around Puget Sound is to leaf through the maps of the *Coastal Zone Atlas of Washington* (Ecology, 1977-1980). Some examples of these maps are included in four **Fact Sheets** located at the end of Section 4.0. The geology maps include measured vertical sections of banks and bluffs located at intervals along the shore (Ruotsala, 1979). Note that both the height of the bluffs and their geologic composition can change quite dramatically over short distances.

Gabriel's (1988) overview of coastal hazard management around Puget Sound includes the following summary of coastal landforms present in each county. While it is difficult to characterize their diversity in a few sentences, several generalizations can be made—keep in mind, however, that there are also unique features in each county:

"Whatcom County has perhaps the greatest variation in shoreline characteristics of all the twelve counties studied. Seventy-five percent of the county's mainland shoreline has irregular sand and gravel beaches, often backed by eroding shore bluffs. Several major bays are present along the coast, usually connected with extensive tidal flats. The county shoreline also contains two major spits--Sandy Point and Semiahmoo Spit. Within the county, Lummi Island is characterized by high eroding bluffs. Skagit County's shoreline is dominated by 3 major bays and their related marshy, mud flats. The shoreline also contains some high cliffs, narrow sandy beaches, rocky headlands, eroding bluffs and a few pocket beaches. The 172 islands that make up San Juan County have irregular coastlines with many small bays, high, rocky points, and narrow channels. Thirty-five percent of the shoreline consists of rocky headlands without beaches. Some eroding bluffs are also present; there are very few spits. Island County is characterized by many high bluffs, narrow sand and gravel beaches, and some rocky headlands. The low, wide, marshy tidal flats associated with the deltas of the Snohomish and Stillaguamish River are the main coastal features of Snohomish County. Some unstable bluffs are also present. King County's coastline is generally composed of narrow sand and gravel beaches backed by high bluff uplands. Some low-lying areas also exist. One of the dominant coastal features in Pierce County is the Nisqually River delta. For the most part the coast is comprised of narrow sand and gravel beaches adjacent to high bluffs. Both Thurston and Mason counties are characterized by irregular shorelines with narrow sand/gravel beaches generally adjacent to high bluffs. Kitsap County's coastline is much like that of Thurston or Mason, but the narrow beaches do not have as many adjacent bluffs. The county's shoreline contains some marshy areas at the heads of the numerous narrow inlets found throughout the county. Jefferson County's shoreline characteristics are of two types. The Puget Sound shoreline is irregular with narrow sand and gravel beaches sporadically interspersed with rocky headlands. The Strait of Juan de Fuca coastline is comprised mostly of narrow sand and gravel beaches backed by high bluffs. Some low-lying areas are also present. Clallam County's Strait of Juan de Fuca shoreline is much like that of Jefferson County, although rocky outcrops are more prevalent. Clallam County contains two of Washington State's largest spits--Dungeness Spit and Ediz Hook.

"As each county has its unique blend of geology, climate, topography, and coastal landforms, one would expect certain coastal hazards to be more prevalent in some counties than in others."

2.3 Historical Slope Modifications

Timber Harvest

Historically, western Washington included the most densely forested region in the United States. Temperate coniferous forests predominated and the size and longevity of the dominant species was unrivaled elsewhere in the world (Franklin and Dyrness, 1988). Explorers and early pioneers describe old-growth forest coming right down to the shore—an occurrence now limited to scattered inaccessible sites along the outer ocean coast of the Olympic Peninsula (Egan, 1990; Dunagan, 1991; Kruckeberg, 1991).

Most Puget Sound shorelines were logged off at the turn of the century. Shoreline forests were readily accessible and once cut and slid to the Sound the trees could readily be rafted to local mills (Dunagan, 1991). Many shoreland banks and bluffs still contain old tree stumps from past logging and clearing activities. Old growth conifers were often 8 feet or more in diameter and over 200 years old when cut. Old-growth stumps found today thus probably indicate the site has experienced no appreciable mass movement for at least 300 years. Buried or partially buried stumps can indicate soil movement from upslope in the form of debris avalanches (Menashe, 1993).

Railroad Construction

The turn of the century also saw establishment of the railroad along the eastern shores of Puget Sound. The Great Northern Railroad first crossed Skagit Pass into the Puget Lowlands in 1893; additional lines were soon added north and south along the coast. Today, railroad tracks follow the eastern shores of Puget Sound for most of the distance between

Nisqually Reach and Bellingham Bay. Railroad tracks also run along sections of Clallam County coastline between Port Townsend and Port Angeles.

The railroad needed a relatively level but narrow right-of-way and much of it was constructed along the beach at the foot of the Sound's coastal bluffs. The raised embankment on which the railroad was built is protected from wave action and erosion by extensive use of riprap. Railroad track maintenance crews now replace wave erosion as the means of removal of slide materials from the toe of the bluffs.

A significant result of this railroad construction and associated riprap was to cut off extensive lengths of beach from the feeder bluffs that previously supplied sediment to the beaches. In some places, the riprap-protected rail line is itself fronted by narrow beaches; however, sediment delivery to these beaches—normally supplied from the eroding bluffs—is now mostly entirely blocked by the rail line (Terich, 1987; Thorsen, 1987).

Residential Development

Puget Sound is characterized by an irregular shoreline with narrow gravelly beaches fronting high banks and bluffs. Numerous bays, rocky headlands, accretionary bars and spits (Shipman, 1993), and limited floodplains and deltas are dispersed along the shore.

The high bluffs so common around the Sound proved to be a "topographic hindrance" to development (Gabriel, 1988) so the limited tidal estuarine and flatland areas were initially appropriated for commercial, industrial, and residential uses. As the regional population has increased, the pressure for waterfront residential property and blufftop "view lots" has also greatly increased. Vegetation removal to enhance views and the increased drainage into these coastal and blufftop properties has dramatically increased the slide hazard potential. Terich (1987) notes:

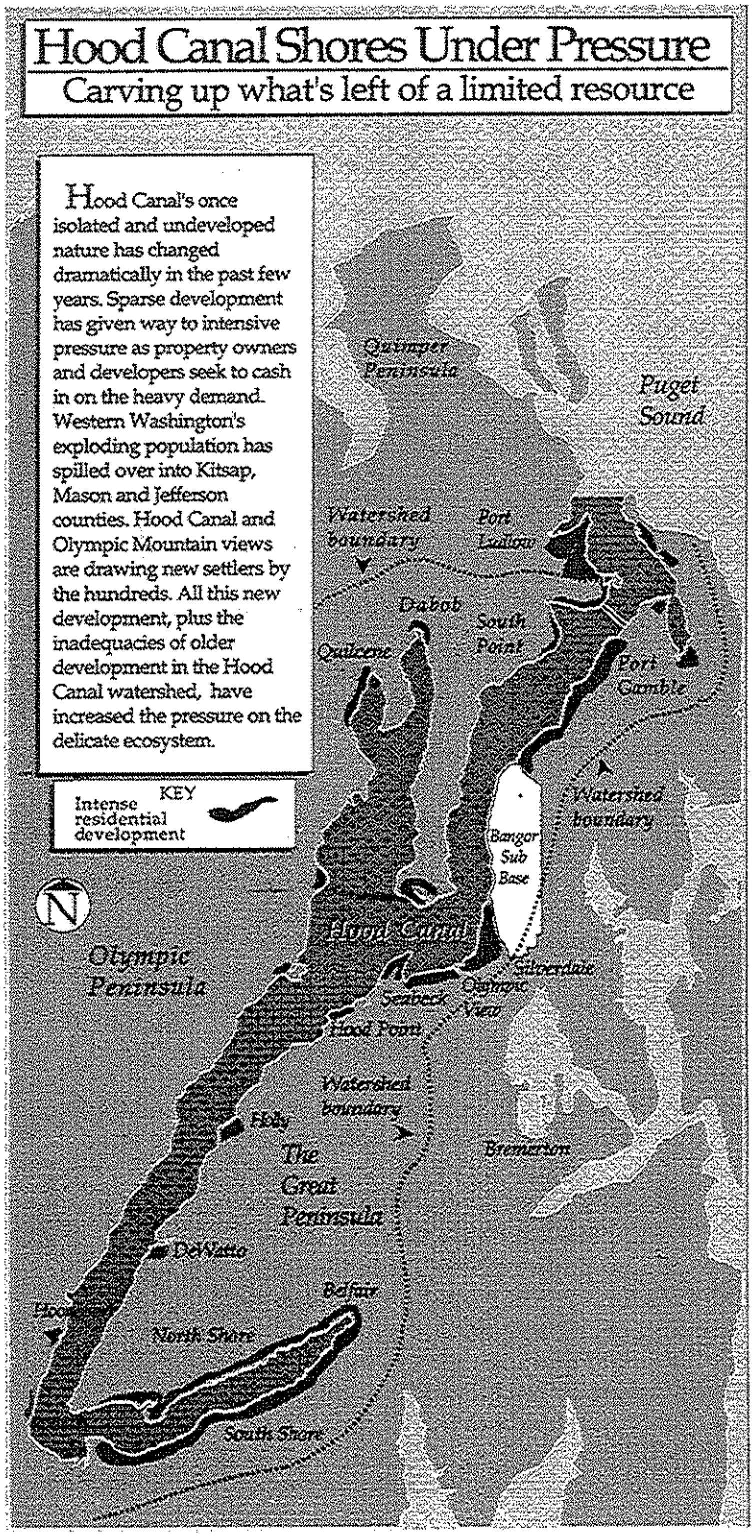
> "Puget Sound, like most coastal areas around the United States, is under tremendous development pressure. It is obvious that demand for coastal space will continue and perhaps

accelerate as western Washington realizes its potential in Pacific Rim trade and commerce. What is not so obvious are the impacts these developments will have on the shoreline.... Obviously risks cannot be eliminated, but they can be minimized. Americans' have had a great deal of experience with shoreline development elsewhere. The rush to the Puget Sound shore comes relatively late. We can benefit from the mistakes made elsewhere."

Over the past few years, the Puget Sound region has experienced extraordinary growth in its population, economy, and related development. The basin's current population is about 3.4 million people, of which three-quarters live in King, Pierce, and Snohomish Counties. Between 1980 and 1990, the basin's population grew by almost 620,000 people, some 23 percent. Some of the highest growth rates were recorded from previously more rural counties: San Juan (28 percent), Island (37 percent), Jefferson (28 percent), and Kitsap (29 percent). The state Office of Financial Management projects that these development trends will continue with another 1.1 million people moving into Puget Sound basin by the year 2010 (PSWQA, 1992).

The recent **Task 1** inventory of shoreline residential bulkheading in Thurston County (Morrison *et al.*, 1993; Macdonald, *et al.*, 1993) documents an increase from 16 to 35 miles of armoring between 1977 and 1992. During this same period, the county population grew from less than 120,000 to over 160,000. Thurston County's population is forecast to reach 240,000 by 2010; if shoreline development and bulkheading continue at their present pace, virtually the entire county shoreline will have been developed by 2010.

The dilemmas and land management choices caused by intensifying shoreline development are eloquently documented in *Hood Canal: Splendor at Risk.* This outstanding publication, put out by Bremerton's *Sun Newspaper* (Brody, 1991), outlines challenges faced by Kitsap, Mason, and Jefferson Counties, searching for ways to manage growth that is threatening to overwhelm both the shoreline and watershed of Hood Canal (Figure 2-3).



Source: Brody (1991)

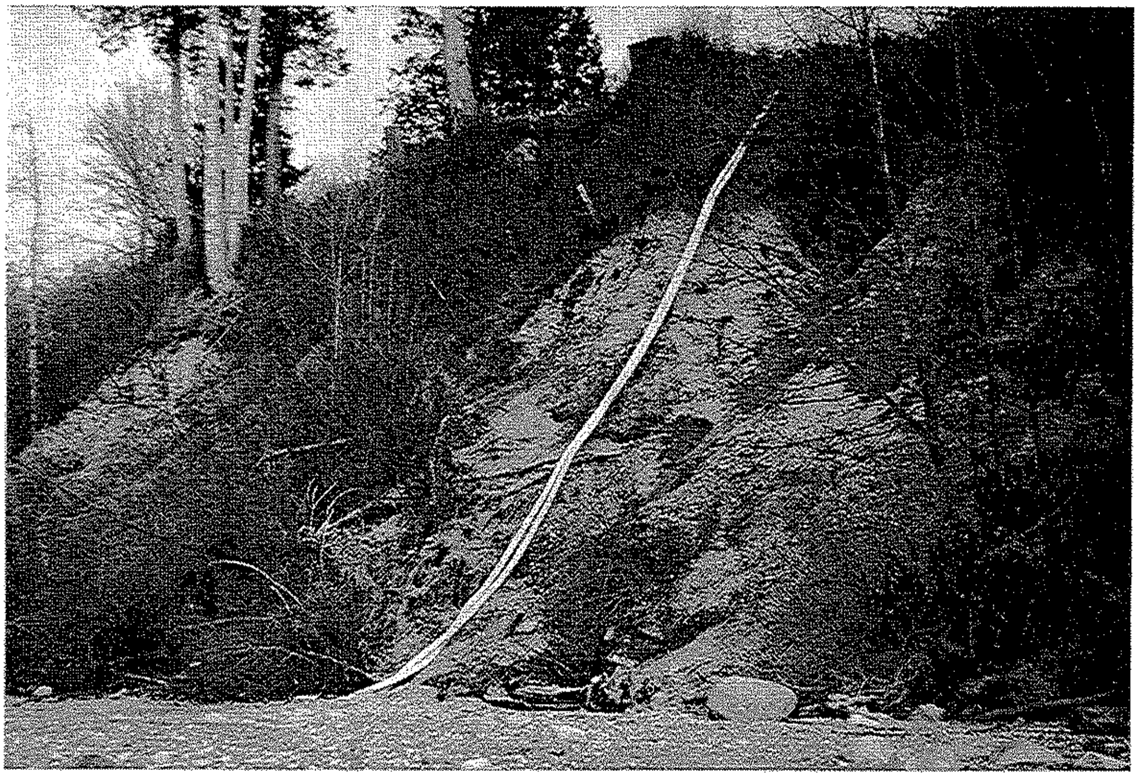
Figure 2-3
Hood Canal: Projected Shoreline Development

2.4 Photo Examples

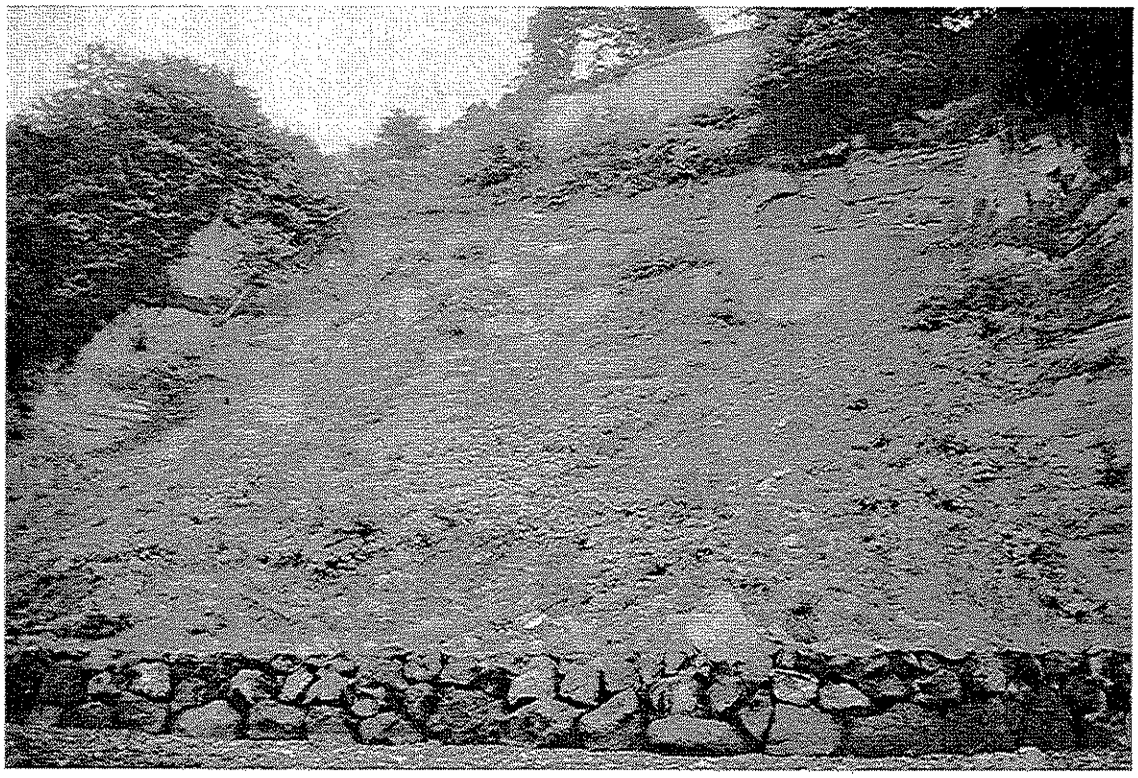
This brief regional overview of Puget Sound's shoreline slopes concludes with a collection of photographs that illustrate both undisturbed and developed banks and bluffs around the Sound. The photographs and accompanying descriptions were generously provided by Hugh Shipman of Ecology's Shorelands and Coastal Zone Management Program.

While the original color slides are much more impressive, these photo examples demonstrate the variety and habitat complexity of undisturbed bluffs; the "simplification" or loss of complexity that often accompanies development; and the fact that installation of shoreline armoring does not necessarily increase upslope bluff stability.

sea10028C8D.wp5

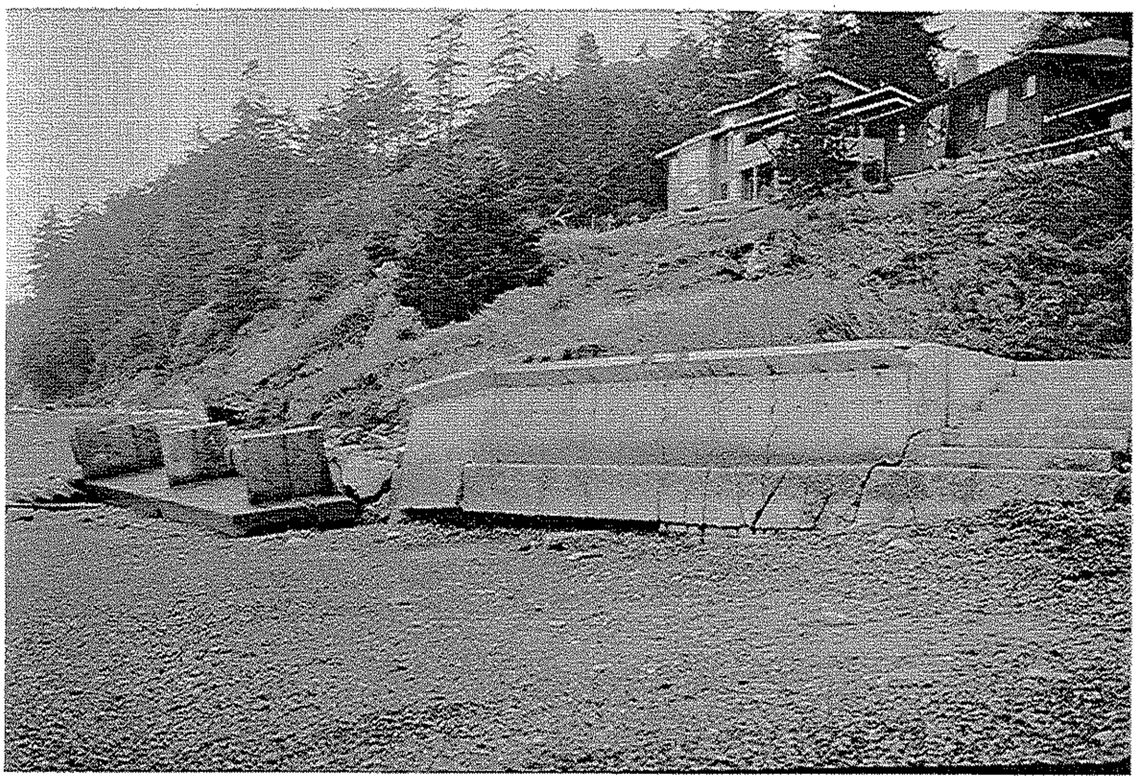


Whatcom County: Typical "tightlines" carrying runoff over the bluff to the beach.

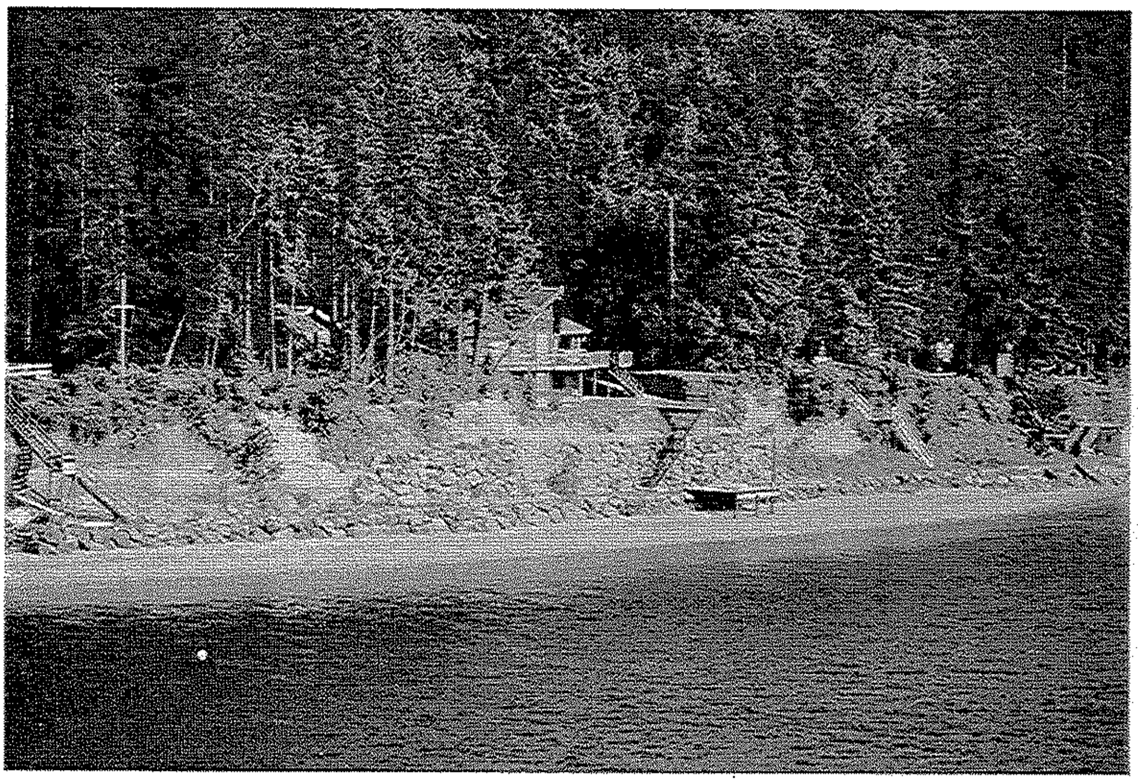


Whatcom County: Rock wall used to stabilize the toe of a landslide.

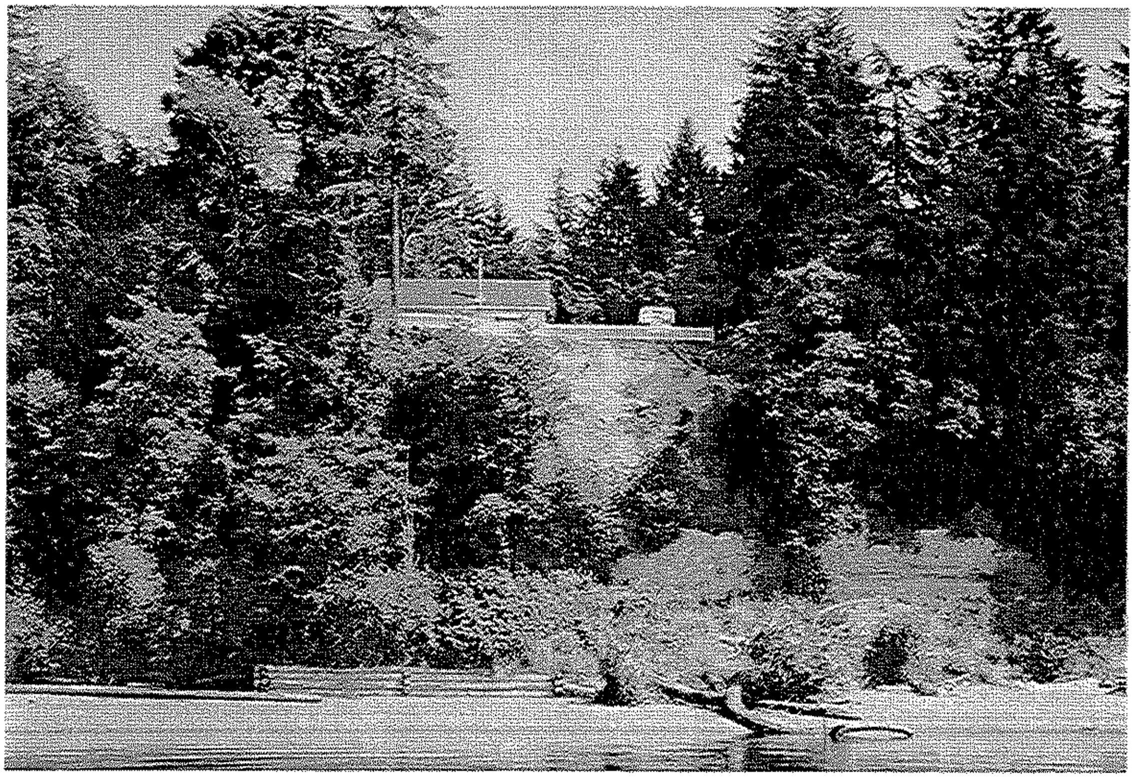

Whidbey Island, Island County: Exposed bluff at West Beach.


Whidbey Island, Island County: Failed bulkheads at the toe of a large rotational slide.

Bainbridge Island, Kitsap County: Vegetated bluff with setback upland home site.

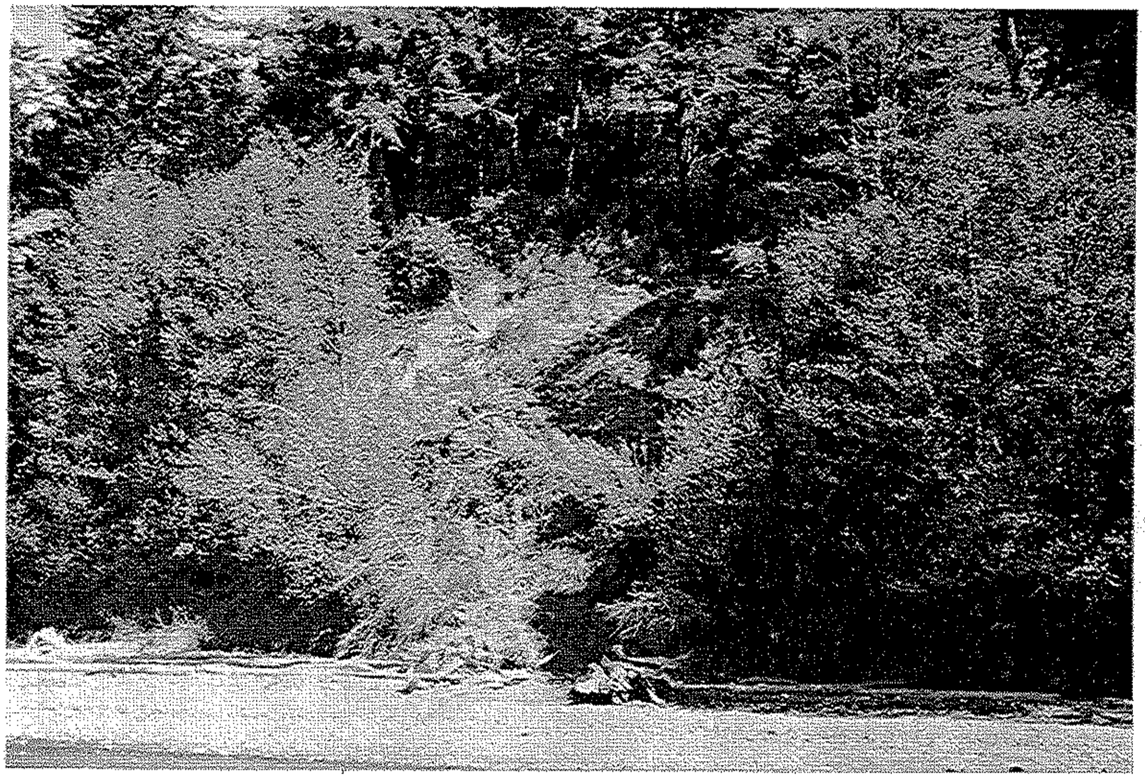


Bainbridge Island, Kitsap County: Medium bank with extensively modified shoreline.

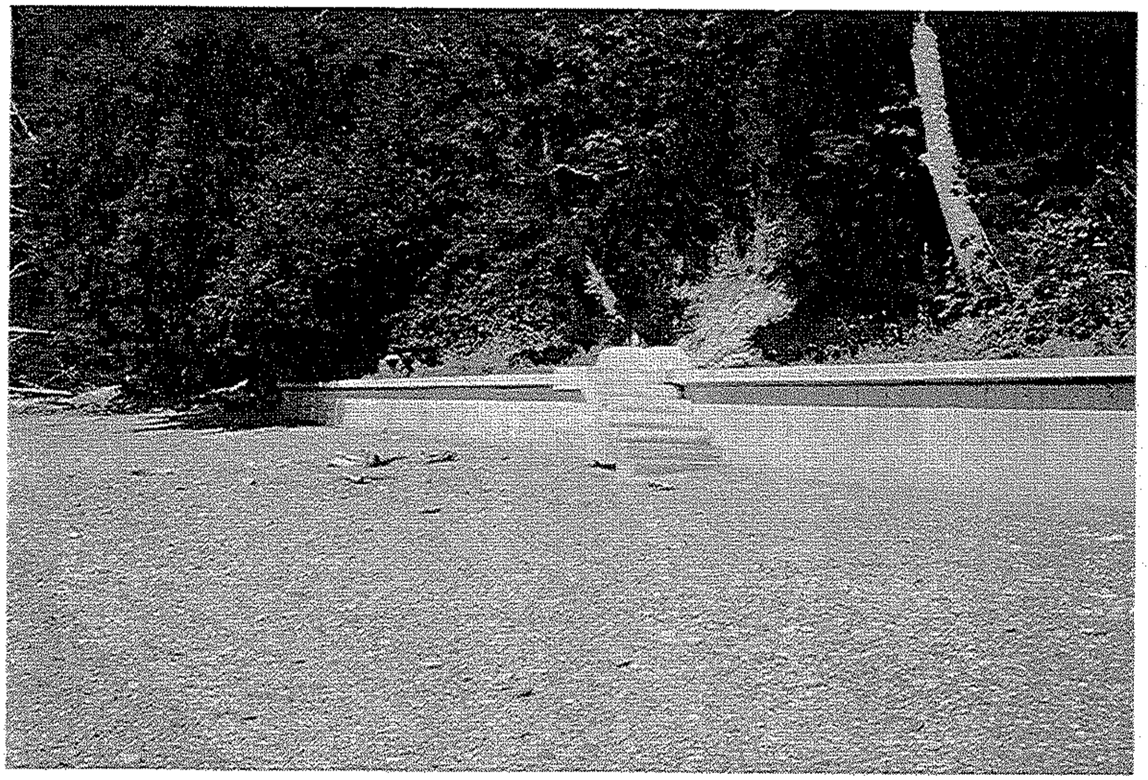


Jefferson County: Bluff below homesite has failed and overtopped the timber bulkhead below.

Thurston County: Debris slide-debris avalanche immediately below a bluff homesite.

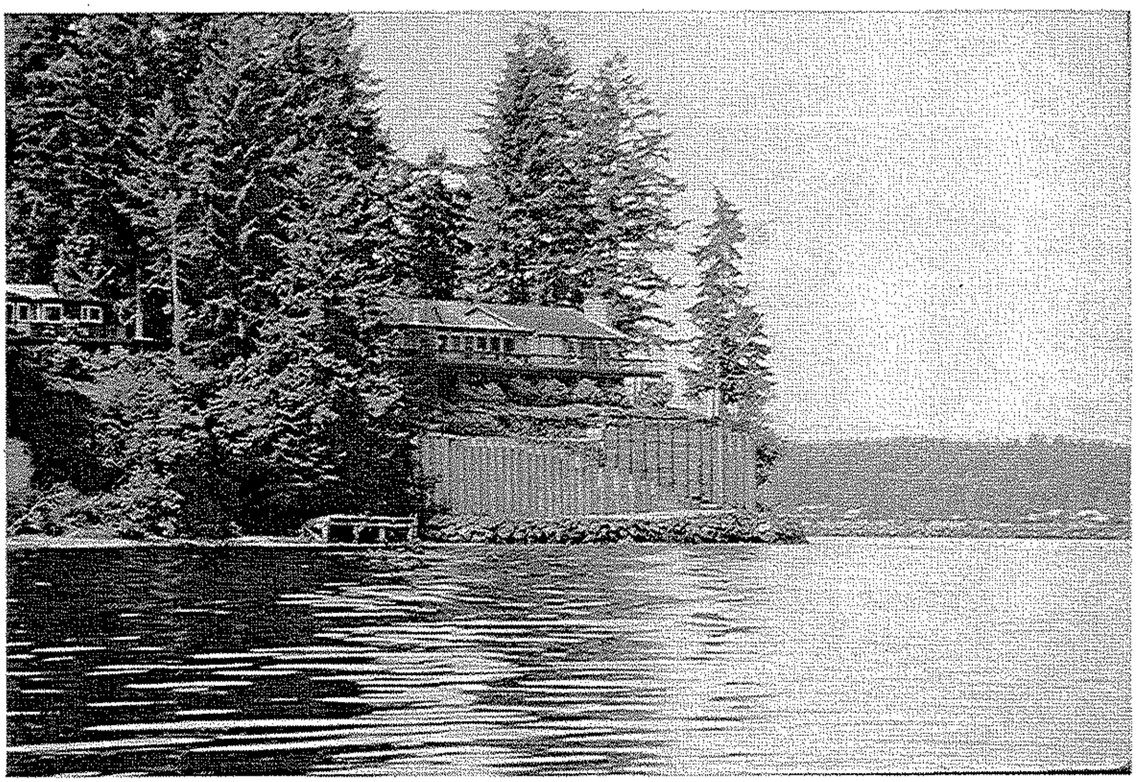


Cape George, Jefferson County: Small slide below a blufftop home site (not visible).

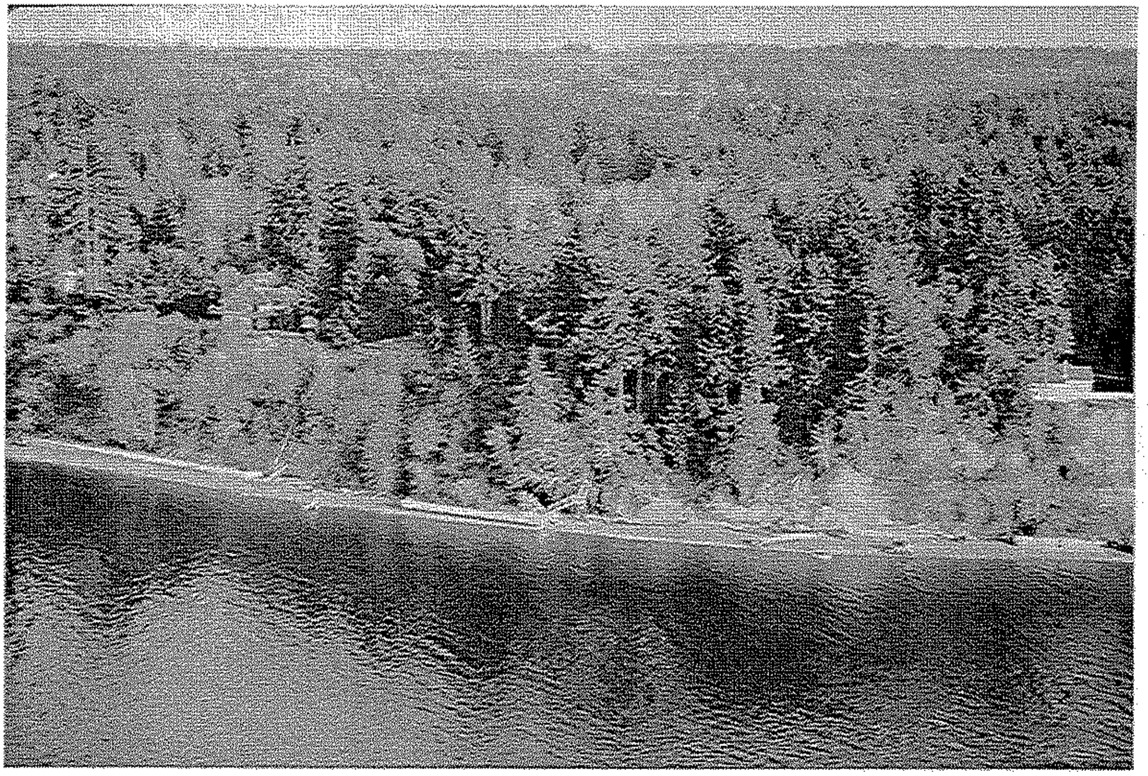


Thurston County: Concrete bulkhead built to stabilize toe of slope.

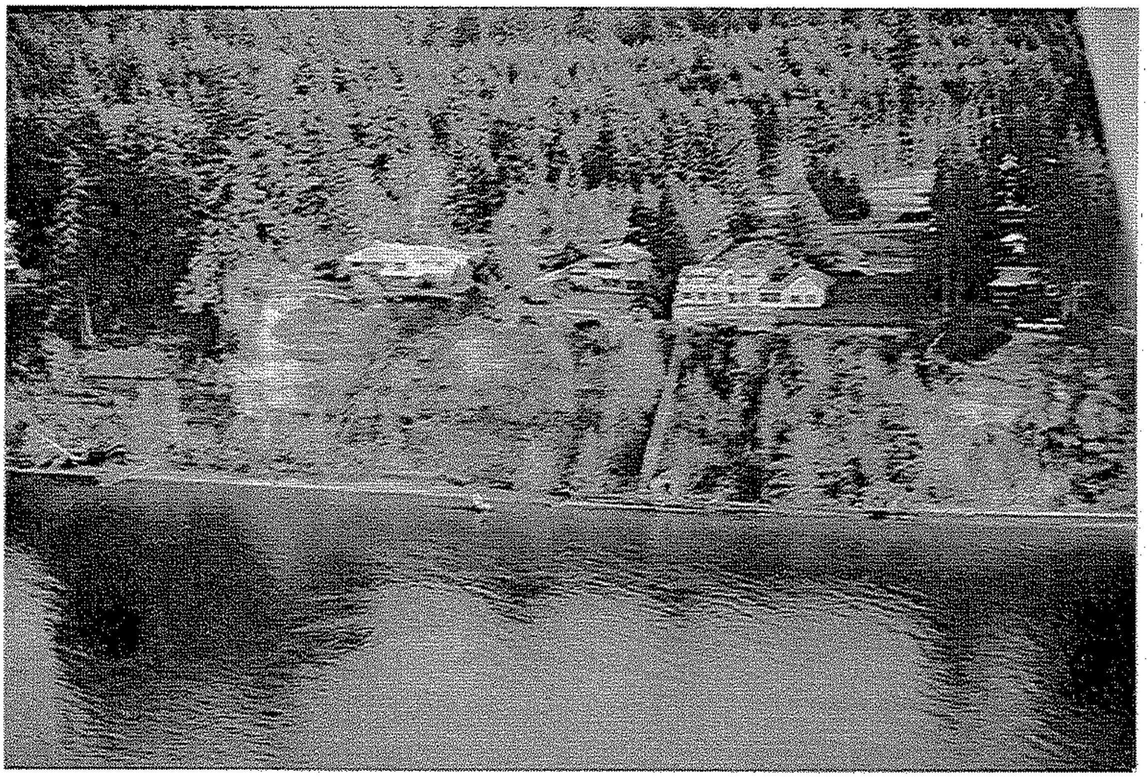
Green Point, Pierce County: Relatively undisturbed forested bluff. Note shading and large organic debris.



Pierce County: Showing extensive shoreline modification, rock bulkhead and slope buttressing.

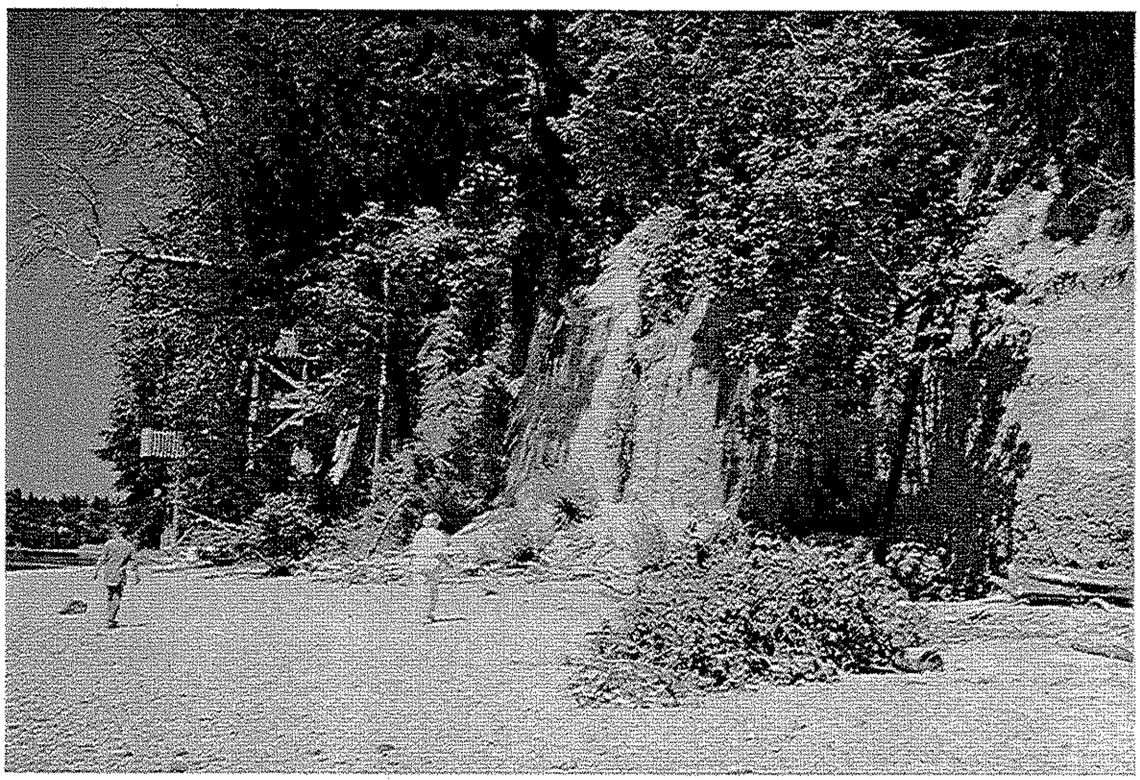


Pierce County (Winter): Bulkheading has not stopped shallow slides and slumps on this steep bluff.

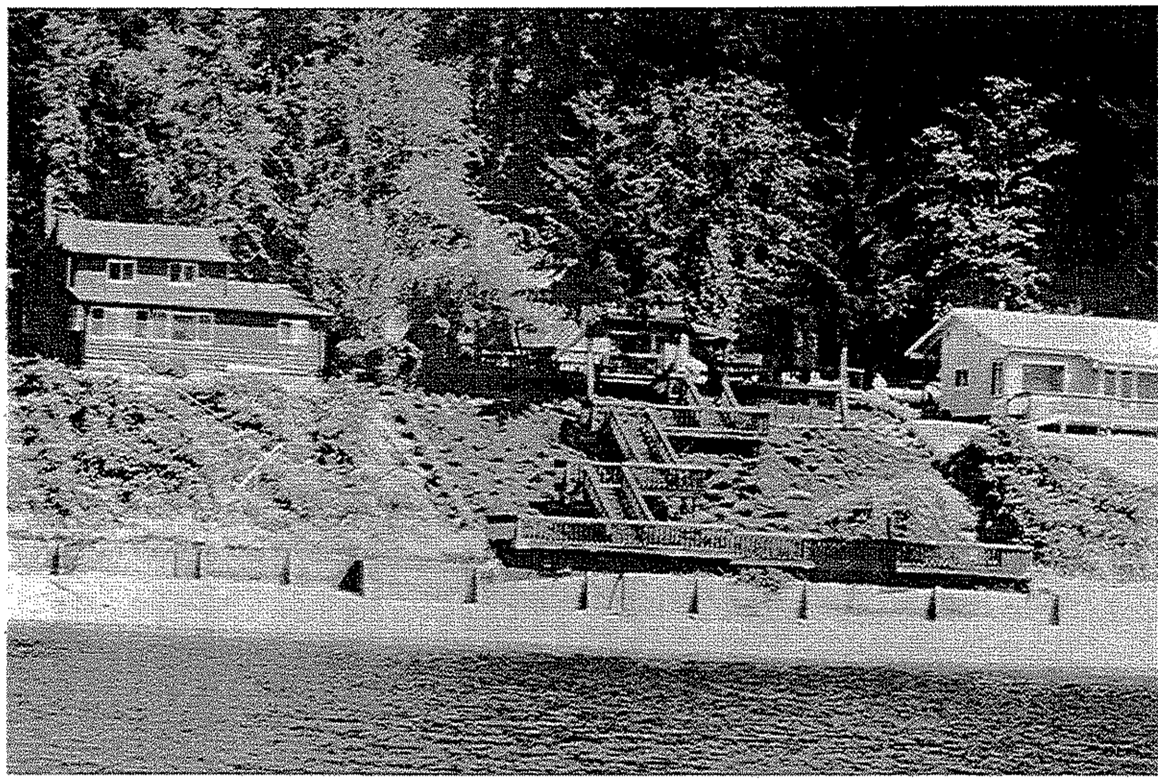


Thurston County: Upslope debris slides have removed vegetation and overtopped bulkheads.

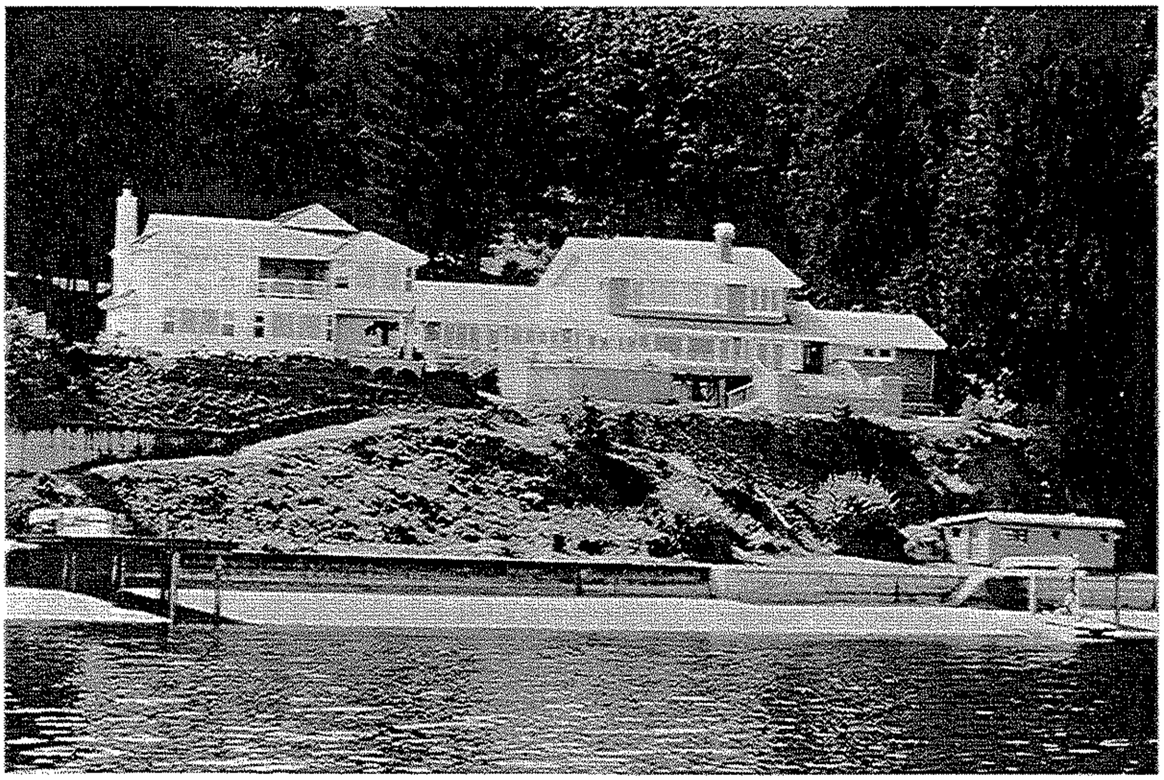
Green Point, Pierce County: Partially vegetated bluff with small slides.



Eld Inlet, Thurston County: Vertical, unvegetated bluff. Note staircases to the left.



Thurston County: Developed, armored shoreline. Note "clean" beach, absence of overhanging vegetation and large organic debris.



Thurston County: Developed, armored shoreline. Note "clean" beach, absence of overhanging vegetation and large organic debris.

3.0 Types of Slope Failure

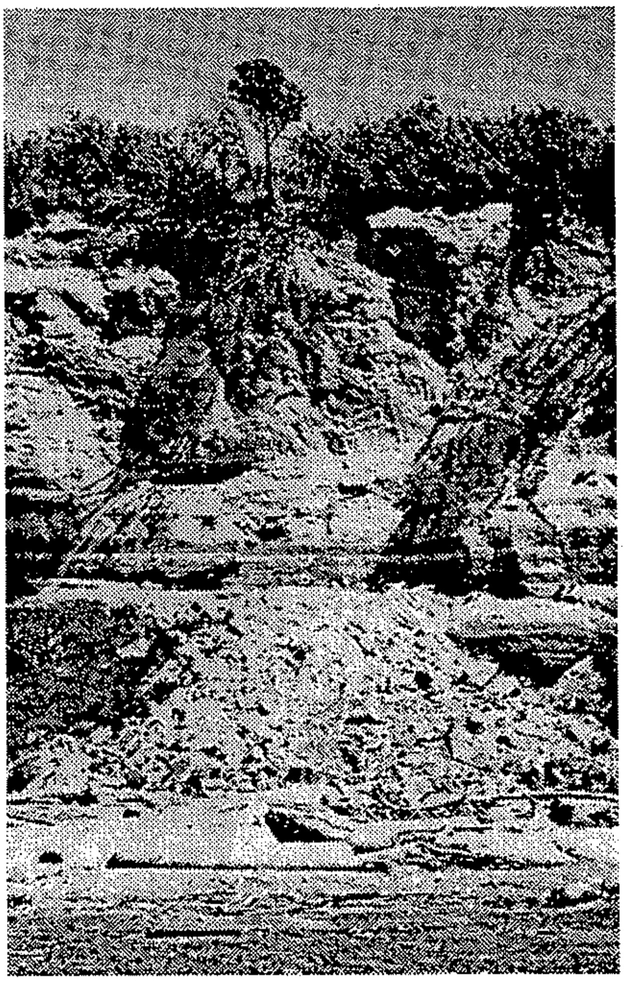
Slope failures along Puget Sound shorelines result from a combination of various factors including steep (glaciated) slopes, high seasonal rainfall amounts, and variability in the permeability of the exposed glacial sediments. Typical types of slope failures which occur in the Puget Sound area include soil and rock falls, shallow slides and flows, and deep-seated slumps and flows. Some Puget Sound shorelines are also the sites of ancient slides and slumps. Most slope failures reflect some combination of these various processes and events. Descriptions of the following types of slope failures along Puget Sound shorelines come from Thorsen (1989), Canning (1991), Tubbs (1975), and Varnes (1978).

3.1 Soil and Rock Falls

Falls involve a mass of any size which is detached from a steep slope along a surface on which little or no shearing takes place. The material descends mostly through the air by free fall, leaping, bounding, or rolling, with movement occurring at very rapid to extremely rapid rates. This movement may occur suddenly or may be preceded by minor movements which result from the progressive separation of the mass from its source (Varnes, 1978).

Soil or earth falls involve predominantly fine grained material which is characterized by very rapid movement. Fine grained materials present along the bluffs of Puget Sound include glacial till and lacustrine or lake-bed deposits. Soil falls are often precipitated by undercutting of the banks/bluffs which typically occurs along Puget Sound due to shoreline wave erosion (Figure 3-1).

Rock falls involve a newly detached mass from an area of bedrock. As in soil falls, the "toe support" at the base of a bluff can be removed by erosion, with the resulting failure of the mass. As a result of glaciation, ice scour locally caused steepening of bedrock slopes.



South Bluff, Discovery Park, Seattle
Olympia Interglacial Sediments Overlain by Vashon Till

Source: Tubbs and Dunne (1977)

Figure 3-1
Soil Fall

Rock falls occur from the weathering face and build up a pile of rock debris or talus at the base of the slope (Figure 3-2). Rock falls are limited to the relatively few areas around Puget Sound were bedrock outcrops occur, principally, in portions of the San Juan, Whatcom, and Skagit Counties. Local examples are described in the following Coastal Zone Atlas (Vol. 3, San Juan County, 1978) quote:

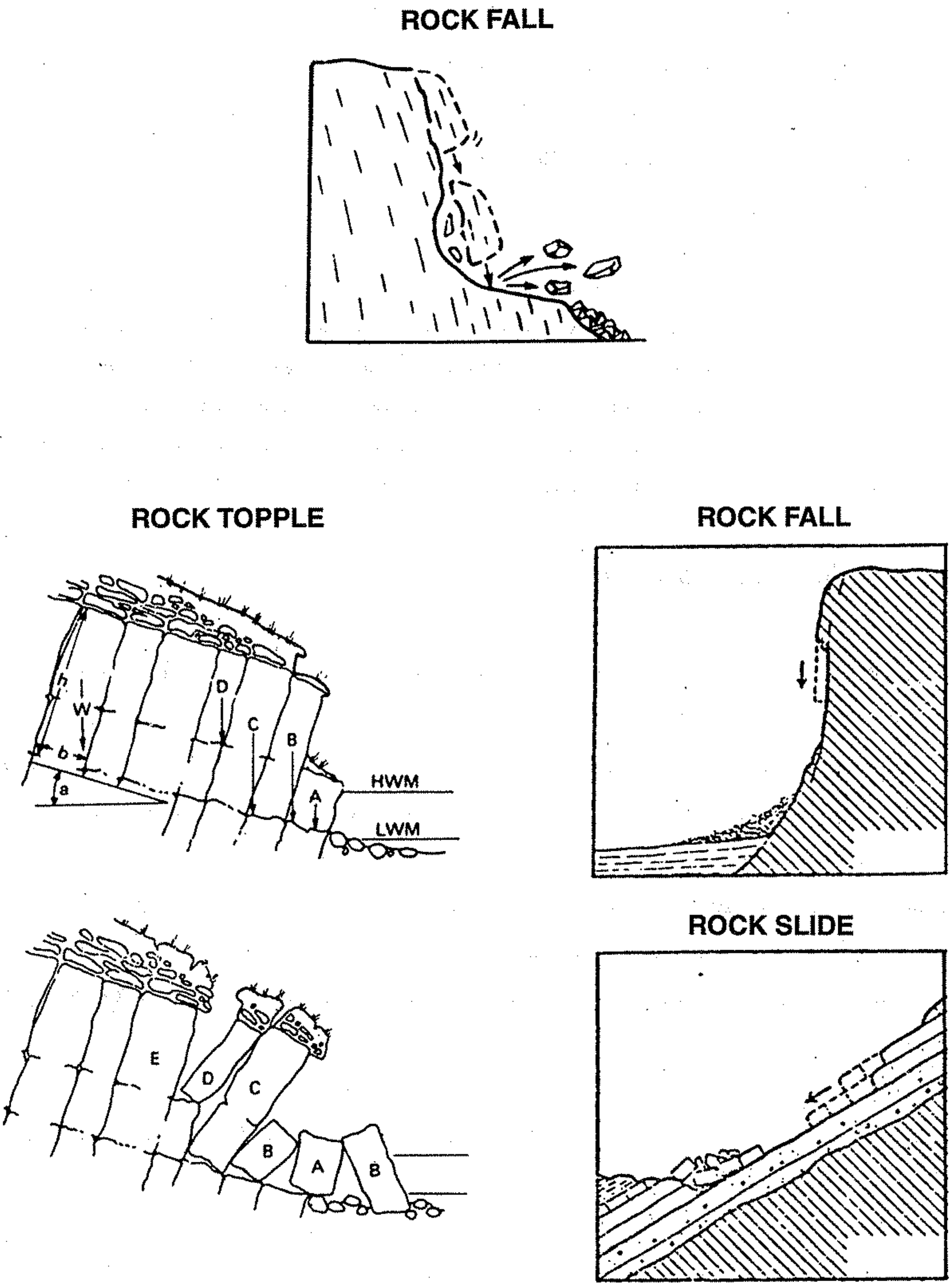
> "During glaciation of the area, ice scour caused extreme steepening of bedrock slopes in some places. Rockfalls from the weathering rock faces occur nearly continually, and form a continually thickening pile of rock debris (talus) at the base of the slope. Because of the steepness of the slopes, hazards from rockfall, and the tendency of talus to flow when disturbed, such areas should receive critical slope stability considerations. The southwest coastline of Lummi Island and the steep slopes near the north end of Deepwater Bay, Cypress Island, are examples of hazardous rockfall areas."

3.2 Shallow Slides and Flows

Shallow slides and flows involve only the upper few feet of material on a slope. This blanket of weathered surficial material, often held together by plant roots, and overlying more consolidated sediments, is called the regolith (Figure 3-3). When a slope fails by sliding, the movement involves shear displacement along one or several surfaces, or within a relatively narrow zone which is visible or may be inferred. Flows in soil involve a displaced mass where the distribution of velocities and displacements resemble viscous fluids. There is a gradation from debris slides to debris flows which is dependent on increases in water content and mobility, as well as type and rate of movement (Varnes, 1978).

The Coastal Zone Atlas (Vol. 3, San Juan County, 1978) provides the following description of the process:

> "Most of the Whatcom County seacliffs and many seacliffs in Skagit County contain silty, clayey glaciomarine drift. This material is hard when dry, but becomes soft and weak when saturated with water. In addition, it shrinks and swells. These properties render it unstable



Sources: Sharpe (1938), Varnes (1978)

Figure 3-2
Rock Fall, Topple and Slide

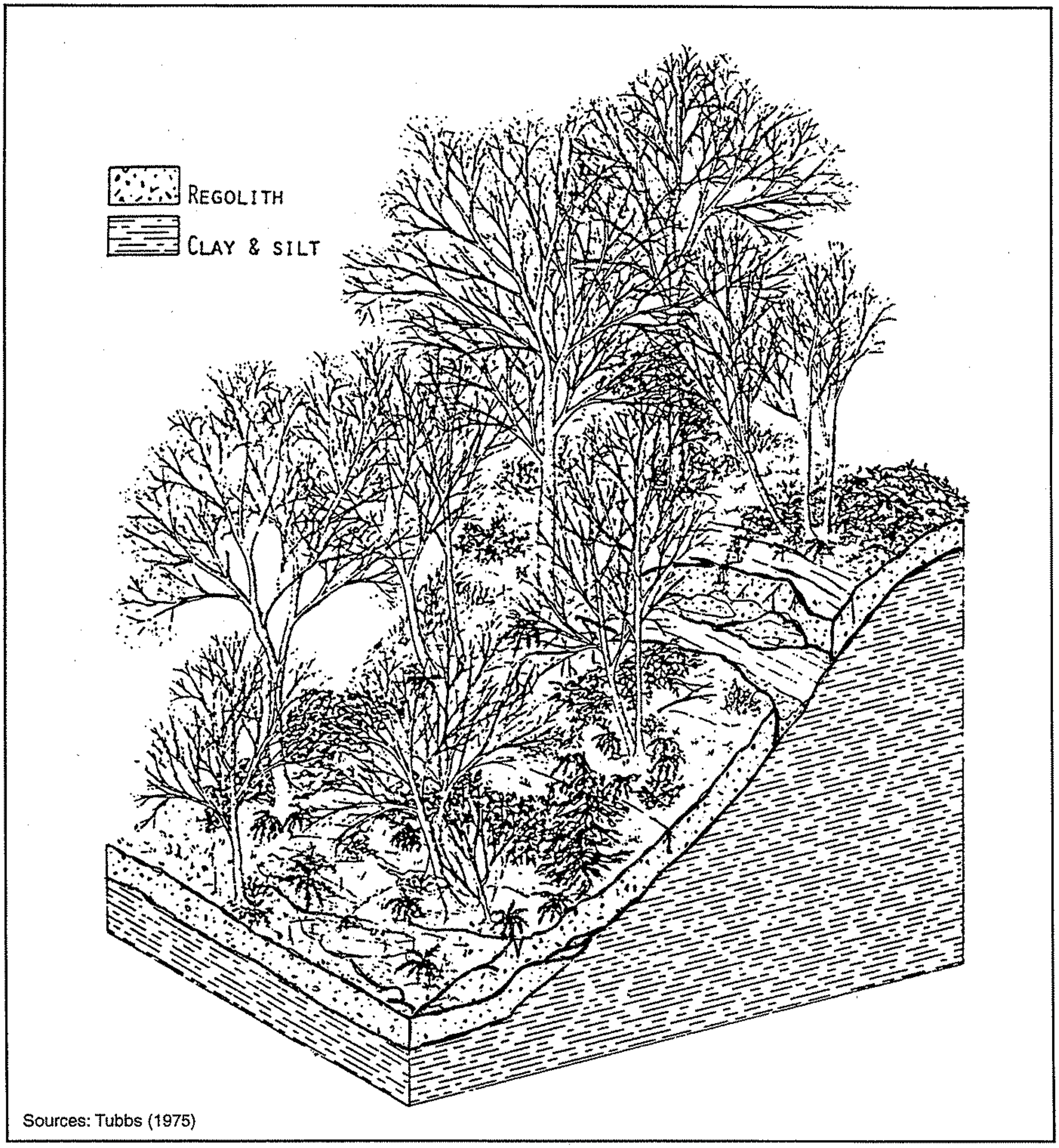


Figure 3-3
Debris Slide

when exposed in steep slopes. Failure of the glaciomarine drift may begin by small scale slumping, but is typified by mud and debris flows. The flows often empty an amphitheater-like hollow at the top of the cliff. Such features may be the site of frequent mudflows for many years ... It was noted during the field work that many of the sites of these landslides had associated with them some type of artificial drain. Typically, the opening of a drain-pipe coincided with the head of a landslide. This fact suggests that artificial drains along seacliffs are locally increasing saturation of the glaciomarine drift, and accelerating the landslide process."

Debris slides and debris avalanches are a shallow form of failure which involve only the upper few feet of soil (regolith) and are typically only tens of feet wide. When debris slides occur on slopes of sufficient steepness and height, they can develop into debris avalanches (Figure 3-4; Tubbs, 1975). Debris slides and avalanches can occur when the upper few of soil has been loosened by weathering, freeze-thaw, or the action of roots; and this loosened layer of soil overlies an impermeable layer, such as a rock layer, till or a glaciolacustrine unit consisting of silt or clay (e.g., Lawton Clay). In periods of heavy precipitation, this upper soil layer becomes saturated and the contact between this saturated material and the underlying impermeable material becomes a zone of weakness where the debris avalanche failure is initiated. Although debris avalanches typically involve small amounts of material, they can travel at high speeds and present risks for structures located below them. In cases where the debris avalanche or debris slide intercepts additional water and becomes more mobile, it will become a **debris flow** incorporating more material and affecting a correspondingly larger area.

Soil creep involves the slow, imperceptible movement of the upper few feet of soil down-slope due to gravitational forces (Figure 3-5). It is typically seen in steeply sloping materials, however, due to the slow rate of movement, it does not pose a threat to the safety to structures located upslope of the movement. Heavy rainfall and increased soil saturation tend to increase the rate of soil creep.

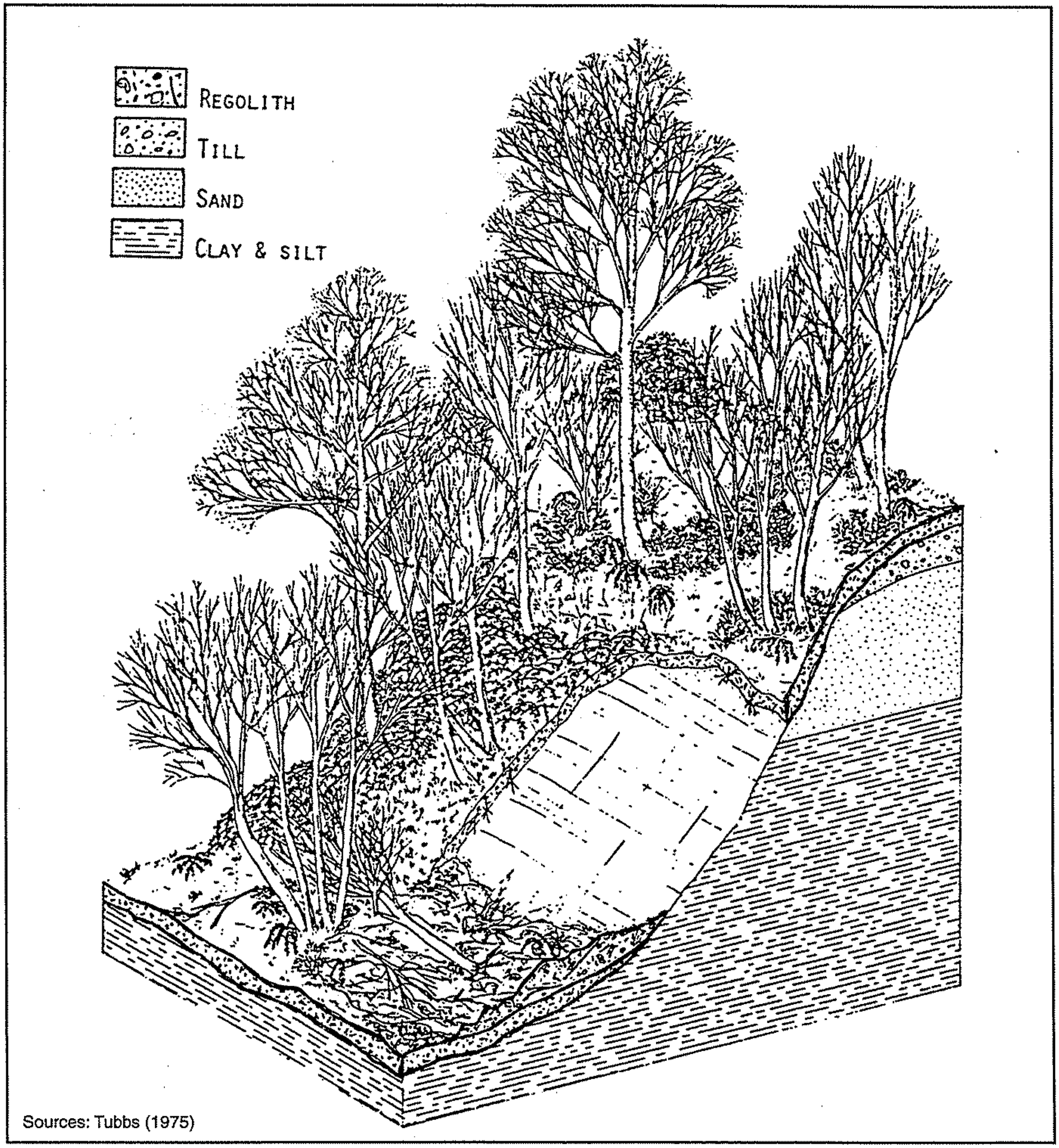
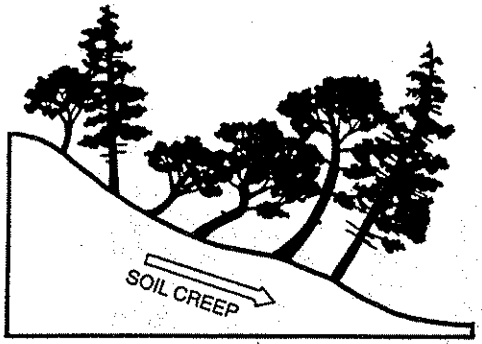
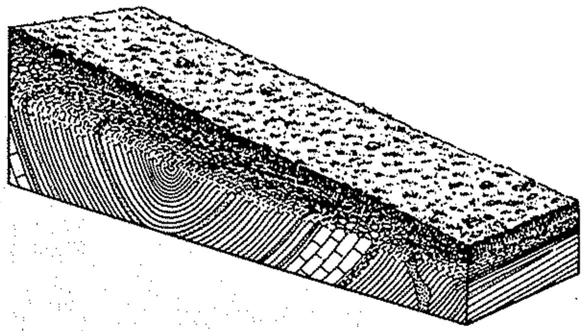


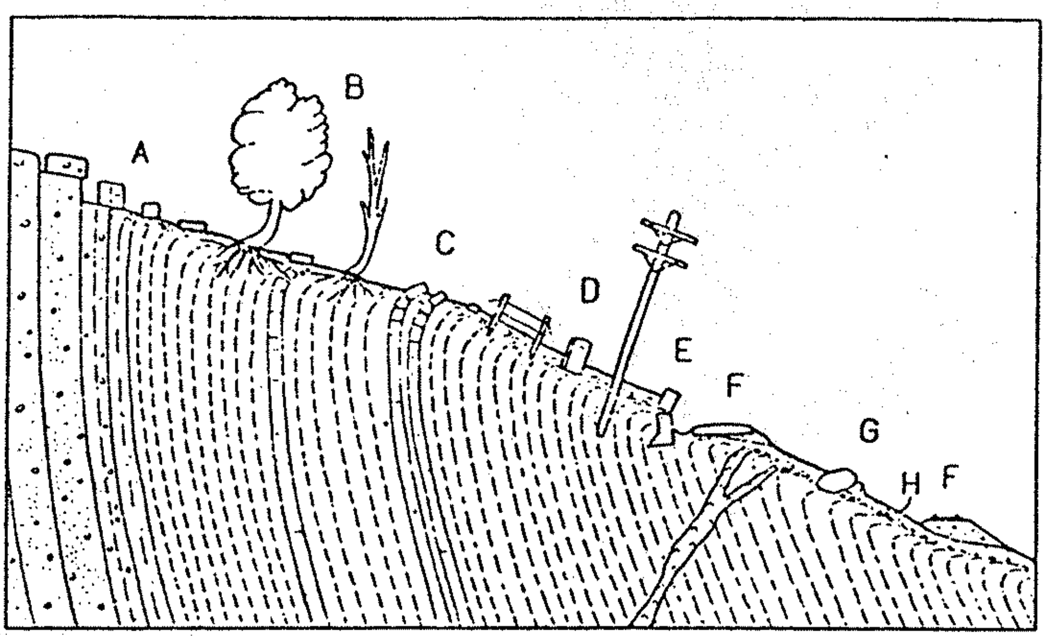
Figure 3-4
Debris Slide - Debris Avalanche

EVIDENCE OF SOIL CREEP



Soil creep causes districtive curved form of tree trunks over time.





(A) Moved joint blocks. (B) Trees with curved trunks concave upslope. (C) Downslope bending and dragging of bedrock. (D) Displaced posts, poles, monuments (E) Broken or displaced retaining walls and foundations. (F) Roads and railroads moved out of alignment. (G) Turf rolls downhill from creeping boulders. (H) Line of stones at base of creeping soil.

Sources: Sharpe (1938), Varnes (1978), Manashe (1993)

Figure 3-5
Soil Creep

Rock slides (contrasted with rock falls) occur when blocks of rock slide downslope along existing fracture planes, or zones of structural weakness (Figure 3-2). This is especially common in areas where the orientation of the structural weakness is steeper than the existing slope. The action of glaciers has oversteepened many of the bedrock slopes bordering Puget Sound making them more susceptible to rock slides. Water infiltration into fractures in the rocks can often weaken the rock and increase the instability.

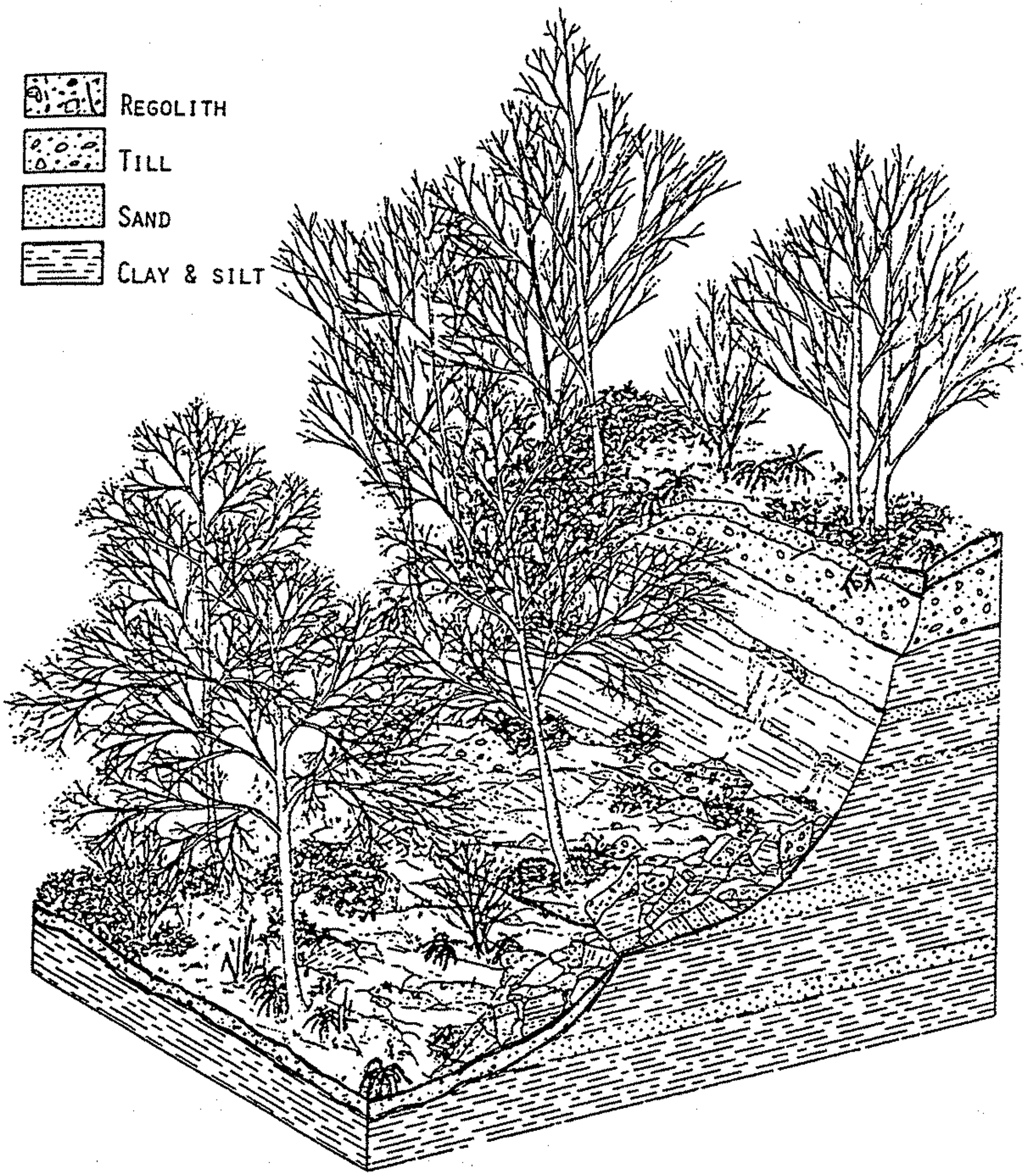
Again the Coastal Zone Atlas (Vol. 3, San Juan County, 1978) provides local examples:

> "Chuckanut Drive exhibits intermediate and unstable slope conditions that are in part due to rock slide potential. South of Larrabee State Park, the rocks of the Chuckanut Formation have been steepened by glacier ice scour or plucking. In several places, the steep slopes are nearly parallel to the dip of a prominent fracture plane within the rocks. In some cases, blocks of rock have slid downslope along these fracture planes."

3.3 Deep-seated Slides and Flows

An important factor responsible for many **deep-seated slides and flow failures** is the pronounced change in physical properties between geologic units present in the slope. The principal properties responsible for many of the deep-seated slumps and associated flows are the permeability and shear strength of slope sediments under saturated conditions (Coastal Zone Atlas, 1978).

Rotational slumps and earth flows are a common form of deep-seated failure on slopes around Puget Sound (Figures 3-6 and 3-7). The surface of rupture of the slump is concave and cuts through various units, leaving a characteristic scarp face at the top of the bluff (Figure 3-8). The initiating force for this type of movement is usually high groundwater levels and will typically be found in interbedded units where high groundwater levels are present, or at the contact of saturated units—such as outwash—with underlying impermeable units—such as till or lacustrine deposits. After the initial slump failure, the disturbed material at the toe of the slump will often continue to flow down the slope as an **earthflow**.



Sources: Tubbs (1975)

Figure 3-6
Slump

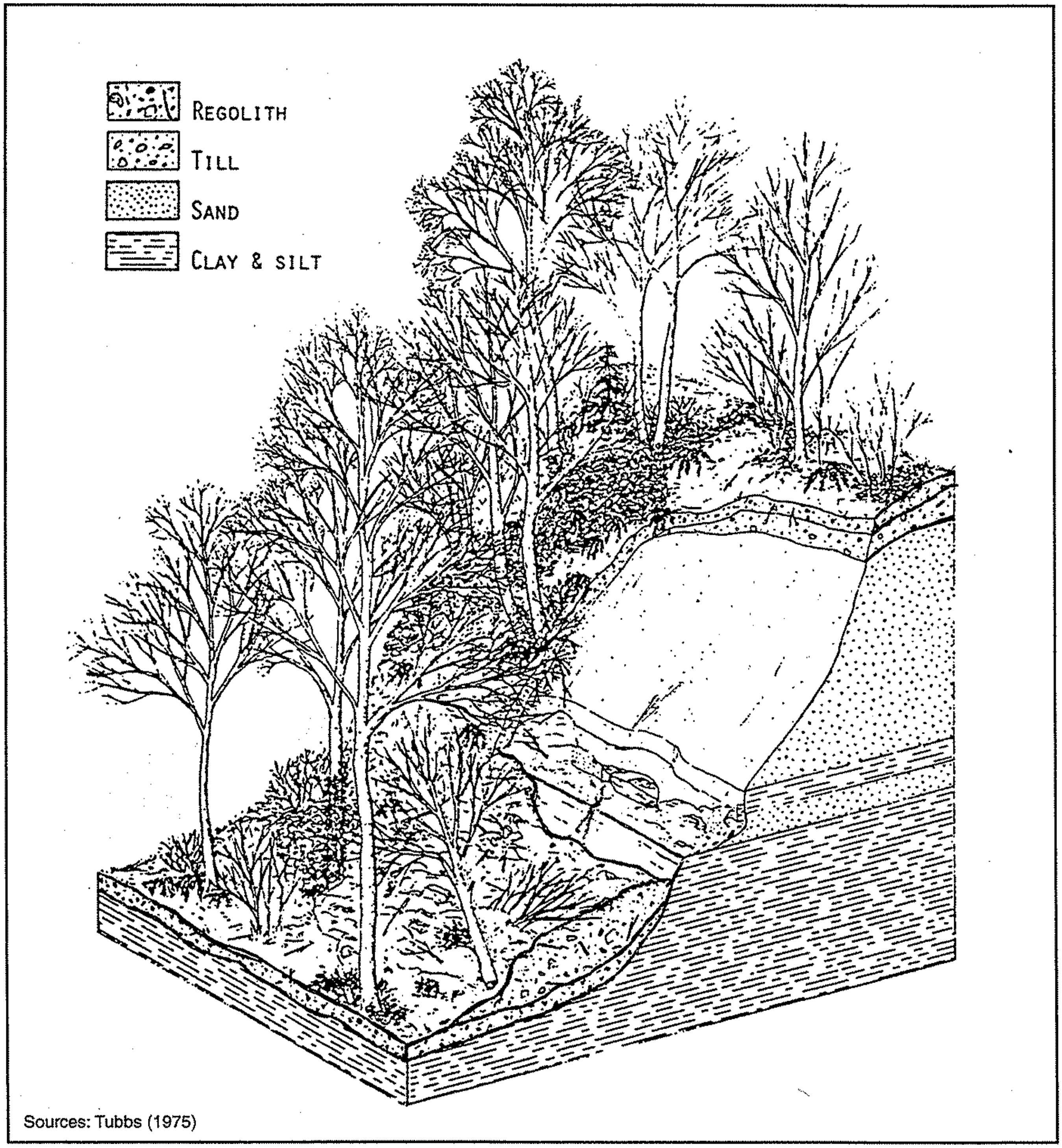
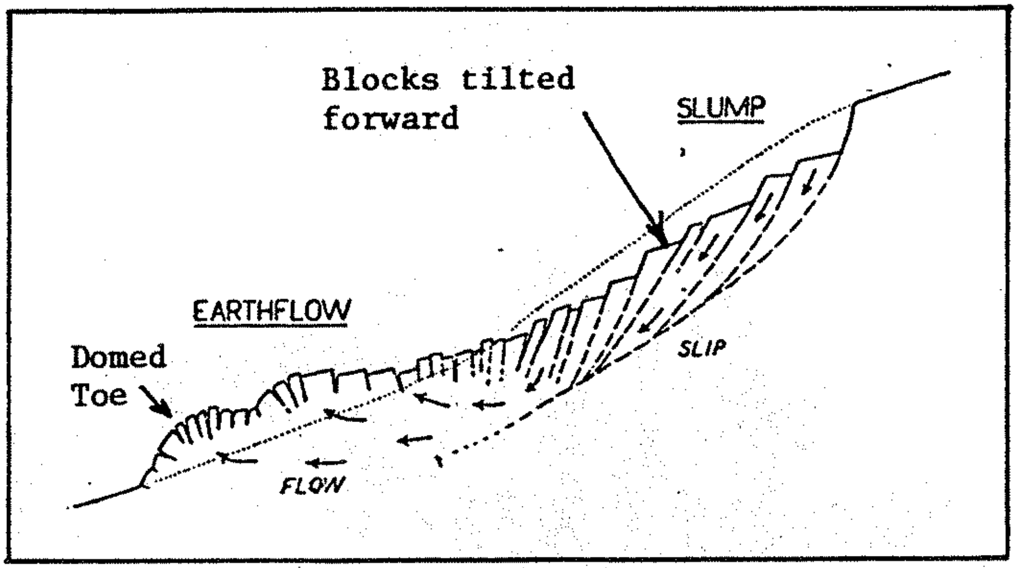
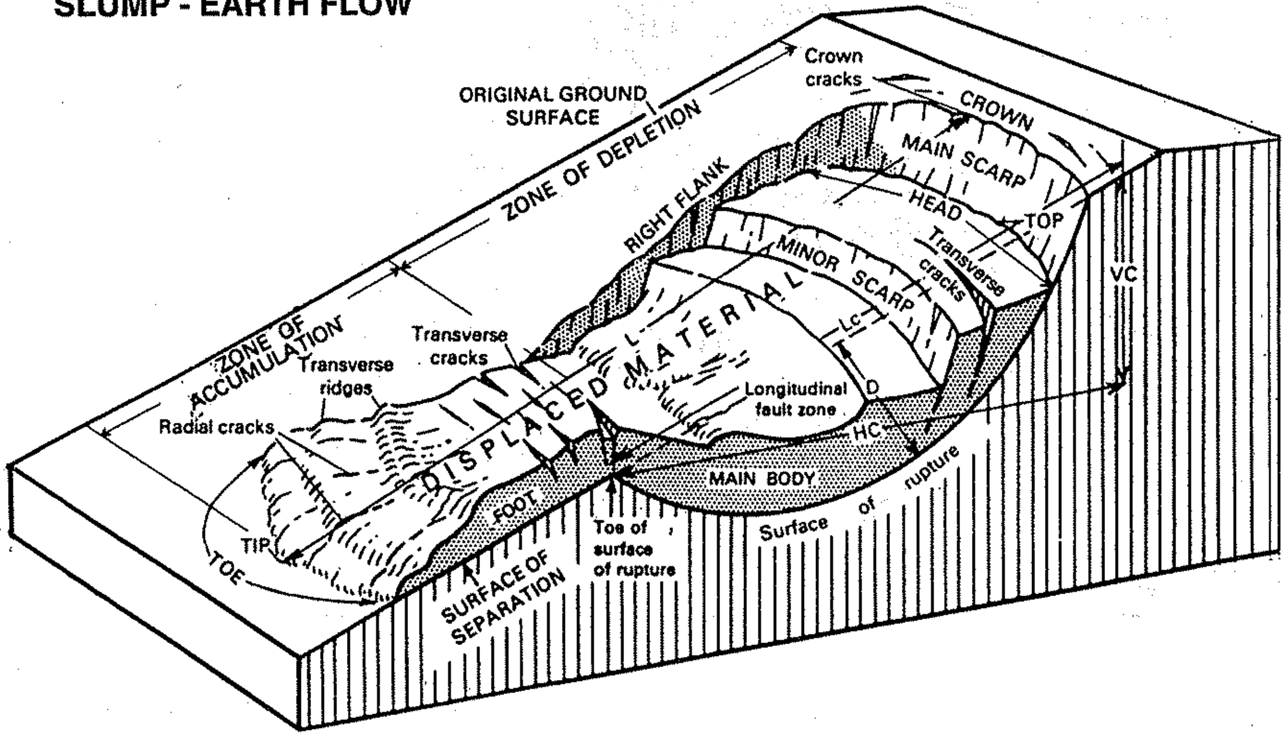


Figure 3-7
Slump - Debris Avalance Involving Intercalated Sand and Clay

CROSS-SECTION OF AN EARTHFLOW



SLUMP - EARTH FLOW



Sources: Sharpe (1938), Varnes (1978)

Figure 3-8
Nomenclature of Slumps and Earth Flows

In areas of Puget Sound were coastal banks and bluffs consist predominantly of glacial sedimentary deposits, debris slides (Figure 3-3)—leading to debris avalanches (Figure 3-4)—are the most common forms of slope failure. In a comprehensive study (Tubbs, 1975) of 47 landslides documented in the Seattle area during the unusually wet winter of 1972-72, 37 began as debris slides, of which 22 evolved into debris avalanches. The remaining 10 landslides all began as slumps (Figure 3-6) and five of these also evolved into debris avalanches.

3.4 Ancient Landslides

Ancient landslides are present along many of the bedrock and soil slopes bordering Puget Sound (Coastal Zone Atlas of Washington, Volumes 1-12, 1977-80; Thorsen, 1987). As the glaciers receded, bluffs bordering Puget Sound were steeply cut because of the erosive action of the glaciers. Often, groundwater levels present in the glacial deposits were high and were reflective of a wetter time period. As a result of oversteepening and the high water levels, many landslides occurred in these areas when the glaciers receded, especially in those deposits where the strength of the material was exceeded by the existing conditions, namely, the steep slopes and high water levels. In some cases, these ancient landslides reached a flatter, more stable configuration after the original landslide movement; however, modifications of these slopes can re-initiate slope movement. Generally, old landslide deposits are prone to renewed future activity because the strength of the existing material has been modified and weakened by the past movement.

Thorsen (1987) notes additional characteristics of ancient landslides, as follows:

> "Ancient slides and slide complexes are areas not only of broken, disturbed, and weakened soil, but also of disrupted groundwater flow. The resulting erratic distribution of soil conditions make drainage or other stabilization techniques all the more difficult and expensive. Such difficulties are compounded by the slide's large size. Ownership of land parcels on such large slides is commonly divided, especially in high-value coastal residential areas. In such instances, some kind of group effort, such as formation of a "Natural Hazard

> Abatement District" (Kockelman, 1986) may be a solution to slide control. Piecemeal or lot-by-lot stabilization efforts are usually doomed from the start."

Thorsen (1987) further indicates that:

> "Landslide recognition is an art based on training, experience, and careful attention to detail. Recognition is important because...almost all natural slides and most construction- and drainage-related slides occur in areas where slides have previously occurred."

Table 3-1 provides a list of some of the field characteristics and clues that might help in recognizing the location of an ancient slide area.

sea10028407.wp5

Table 3-1 Some Characteristic Features of Landslides
Geomorphic Characteristics • Amphitheaters or scallops in an otherwise straight bluff line • Low bank areas in an area of bluffs (ancient slides) • Local reversal in slope direction (slumps) hummocky topography, especially with undrained depressions • Ground cracks (most slide forms) stair-step topography (multiple-slice slumps) • Slopes that steepen downward (very viscous flows)
Vegetation clues: • Distribution of water-loving plants on slopes, suggesting groundwater concentrations • Tilted or jackstrawed conifers (slumps, earthflows) • Patches of dead trees (suggesting sheared roots) • Linear groups of alder trees of the same age on a hillside (any active slide) • Bare soil patches, especially their slope and distribution (debris avalanches) • Buried logs and other vegetation (flows, debris avalanches) • Vegetation out of place (trees in ponds, etc.) • Split trees and/or stumps
Structural indications: • Buckled or crooked fence lines • Broken underground plumbing • Powerlines unusually taut or loose • Excessive foundation or driveway cracking • New gaps between parts of structures (e.g., between deck and house) • Vertical elements out of plumb, tilted poles, or walls • Sticking doors and windows
Other clues: • Aggregates of delicate fine-grained sediment in a high-energy environment (e.g., silt "pebbles" in a gravel) • Tilted sediments, such as lake bed silts that were deposited horizontally (slumps) • Muddy springs or muddy spring deposits • Water emerging or disappearing in a new area
Note: Few, if any these alone are certain indicators of landslides, but several in combination suggest that a landslide may be present. Source: Thorsen (1987).

sea1002840B.wp5

4.0 Causes of Slope Instability

The stability of slopes is controlled by topographic, geologic, and climatic variables that influence both the shear stress and shear resistance in a slope (Gray and Leiser, 1982). Soil movement and slope failures occur when shear stresses exceed the shear strength or resistance of the slope materials. The "failure surface" between stable ground below and moving ground above occurs where the ratio of shear strength to shear stress is the lowest. Varnes (1958) tabulates variables that cause slope instability by either increasing shear stress or decreasing shear strength (Table 4-1). Identification of the relative roles of these variables at a particular site is the key to prevention and control of slope movements.

Recent commercial and residential developments on the bluffs surrounding Puget Sound are increasingly directed towards those areas which are marginally stable as the more stable locations have already been developed (Canning, 1991, Thorsen, 1989). There are three primary reasons slopes fail:

- Removal of lateral support at the toe or along the side of the slope
- Surcharging (top loading) or adding materials to the head of the slope
- Changes in the moisture content or drainage pattern of the slope material

Typically, all three of these factors accompany shoreline development. Lateral support at the toe of the slope can be removed by grading or development of neighboring properties, or by natural forces, such as wave action, which undercut the slope. In order to create a suitable building pad for a proposed structure, site grading can result in fills at the top of the slope. These fills load the top of the slope (surcharging/top loading), which increases the instability of the slope. Finally, changes in the moisture content of the natural slope material often accompany development. Surface drainage typically is altered or diverted because of construction grading. Subsurface drainage is usually increased as a result of a septic system installation and seasonal irrigation requirements of newly landscaped areas with vegetation that may have higher water demands. These changes in drainage patterns

Table 4-1
Factors Contributing to Unstable Slopes

FACTORS THAT CONTRIBUTE TO *High Shear Stress*	FACTORS THAT CONTRIBUTE TO *Low Shear Strength*
A. Removal of lateral support 1. Erosion—bank cutting by streams and rivers 2. Human agencies—cuts, canals, pits, etc.	A. Initial state 1. Composition—inherently weak materials 2. Texture—loose soils, metastable grain structures 3. Gross structure—faults, jointing, bedding, planes, varving, etc.
B. Surcharge 1. Natural agencies—weight of snow, ice, and rainwater 2. Human agencies, fills, buildings, etc.	B. Changes due to weathering and other physico-Chemical reactions 1. Frost action and thermal expansion 2. Hydration of clay minerals 3. Drying and cracking 4. Leaching
C. Transitory earth stresses—earthquakes	
D. Regional tilting	
E. Removal of underlying support 1. Subaerial weathering—solutioning by groundwater 2. Subterranean erosion—piping 3. Human agencies—mining	C. Changes in intergrannular forces due to pore water 1. Buoyancy in saturated state 2. Loss in capillary tension upon saturation 3. Seepage pressure of percolating groundwater
F. Lateral pressures 1. Water in vertical cracks 2. Freezing water in cracks 3. Swelling 4. Root wedging	D. Changes in structure 1. Fissuring of preconsolidated clays due to release of lateral restraint 2. Grain structure collapse upon disturbance

Source: Gray and Leiser (1982) after Varnes (1958) load the top of the slope because of the increase in saturated soil mass (weight) and pore water pressure. In addition, this increase in pore water pressure reduces frictional forces (grain to grain contact) and lubricates the material in the deposit. This, in turn, decreases cohesion and can result in slope failure (Varnes, 1978).

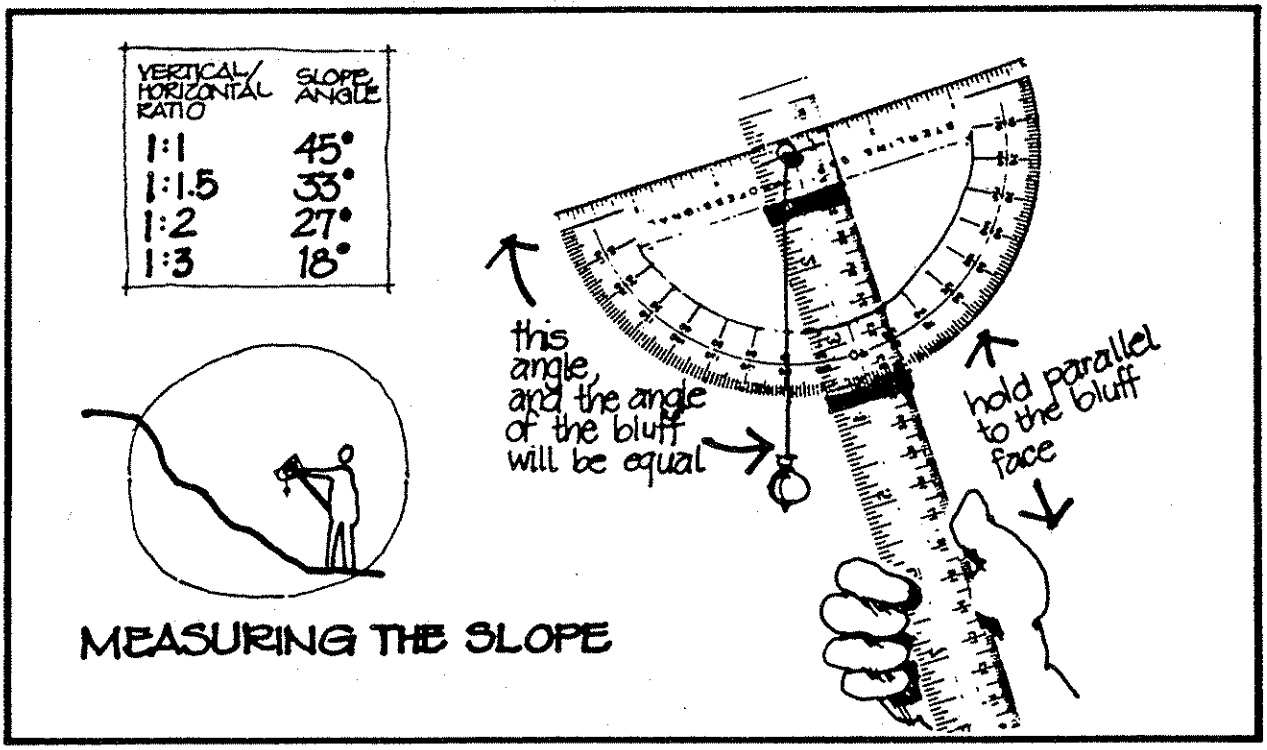
Additional forces that are not discussed in this report but which are also responsible for negatively impacting the stability of a coastal slope include seismic shaking and vibrations from man made sources.

4.1 Height and Slope Angle (Gravity)

The height of a coastal bank or bluff, together with the slope angle[1] (Figure 4-1) of the bank or bluff face, might initially appear to be the most important variables determining slope stability. Certainly, higher, steeper bluff faces are more prone to gravitational collapse than lower, more gently sloping ones—particularly when the bank or bluff is composed of unconsolidated sedimentary materials. The relationship is not always a simple one, however. Rock or sediment type, groundwater relationships, and the presence or absence of vegetation, all play a significant role in determining slope stability.

Herdendorf (1984) describing Ohio's Lake Erie glacial till bluffs (much like those of Puget Sound) notes that natural slopes in areas unaffected by erosion are stable at a 34-degree (1.5:1) slope. When fully vegetated and well drained, the till can remain stable on slopes as steep as 60 degrees (0.6:1). In the absence of vegetation cover, dry till can remain stable on 45-degree (1:1) slopes—but when saturated, unvegetated till becomes unstable on slopes as low as 15 degrees (2.25:1).

[1]The inclination of the land surface from the horizontal. Percentage of slope is the vertical distance divided by the horizontal distance, multiplied by 100. Slope is also measured in degrees (90 degrees being vertical) or as a ratio. A 100 percent slope would be 45 degrees or 1:1.



Source: Tainter (1982)

Figure 4-1
Measuring Bluff Slope Angles

Within Puget Sound, tall faces of solid bedrock in the San Juan Islands can be stable at very steep slope angles, depending on the nature and angle of local rock jointing patterns. Glacial deposits, however, exhibit a broad range of "friction angles" (the angle at which a cut slope in a given material will stand; see Section 4.3.1). A dense, consolidated till is stable on 35- to 45-degree slopes, while fine-grained lacustrine deposits may fail on slopes above 15 to 35 degrees.

Tubbs' (1975, and included references) extensive studies of landsliding in Seattle provide the most detailed understanding, to date, of slope failure mechanisms in the banks and bluffs around Puget Sound. In the winter of 1971 to 1972, widespread flooding and land-sliding in western Washington caused extensive property damage and resulted in part of the Puget Lowland being declared a natural disaster area. Federal disaster assistance records documented 47 landslides in Seattle during February and March, 1972. Tubbs (1974a) examined each of these slides, relating their occurrence to certain geologic and climatic factors. Subsequent studies at Discovery Park, Seattle (Tubbs, et al. 1974), confirmed a relationship between slope failure and specific stratigraphic units, while an analysis of slide frequency between 1932 and 1972 (Tubbs 1975) revealed a clear linkage to soil saturation and short-term rainfall patterns.

Located near the center of Puget Lowland, Seattle's glacial geology and climate are generally representative of conditions throughout much of Puget Sound. Tubbs' studies of the causal mechanisms of landsliding in Seattle thus provide an excellent model for application to shoreline banks and bluffs throughout the Sound. (An obvious already noted exception are coastal bluffs dominated by bedrock outcrops rather than glacial deposits—e.g., parts of the north Sound and San Juan Islands.)

Of the 47 Seattle landslides examined by Tubbs, 37 began as debris slides (Figure 3-3)—and 22 of which evolved into debris avalanches (Figure 3-4). These debris slides involved movement of a relative shallow layer—usually only a few feet thick—of weathered soil material (or regolith) that slid over the substantially more consolidated deposits beneath. The remaining 10 landslides all originated as slumps (Figure 3-6), where the failure surface cut into the underlying consolidated deposits and both these deposits and the overlying regolith were included in the slide mass. Five of the slumps also evolved into debris avalanches. The debris avalanches occurred on taller, steeper slopes, moved downhill quite rapidly (more than 1 foot per minute), and extended to the base of the slope or to a less steep break in slope. They were typically elongated in a downslope direction and about the same width as the original failure scar. The avalanche debris caused relatively little scour of the slope surface as it moved downhill.

Tubbs concluded that most slides originating as debris slides could be satisfactorily modeled as "infinite slope failures" (Taylor, 1948; see also Edil and Vallejo, 1980). They occur on slopes of nearly constant inclination, are shallow relative to their aerial extent, and involve a fairly uniform thickness of regolith. Assuming uniform soil properties within the regolith, the stability analysis of a potential slide mass is reduced to an analysis of the stresses in a column of soil extending from the ground surface to the consolidated substrate beneath (Figure 4-2).

Shear strength on the potential failure surface at the base of the regolith is related to the effective cohesion of the soil, the effective angle of internal friction, and the pore water pressure at the base of the soil column.

In subsequent stratigraphic analyses, Tubbs et al. (1974) demonstrated that local debris slides were generally underlain by sedimentary units with very low permeability, such as the Lawton Clay or most pre-Vashon sediments (Section 4.3, Figure 4-12). This causes groundwater moving through the regolith to flow parallel with the surface of the slope. As the total amount of groundwater rises within the regolith both the mass (weight) of the soil column and the pore water pressure also increase. The increased weight of saturated soils on the slope enhances the risk of failure, while the increased pore pressure effectively "lubricates" the potential failure surface.

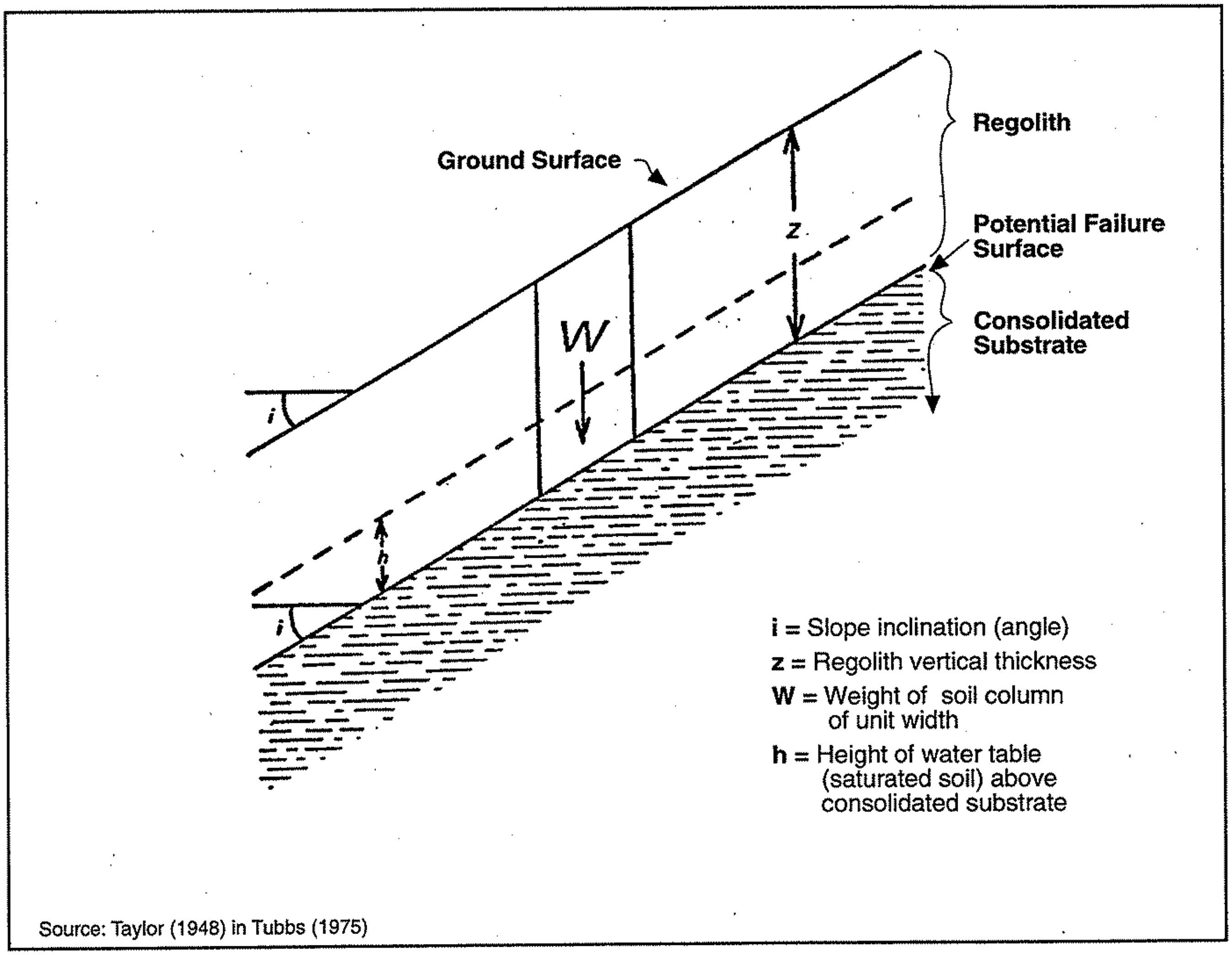


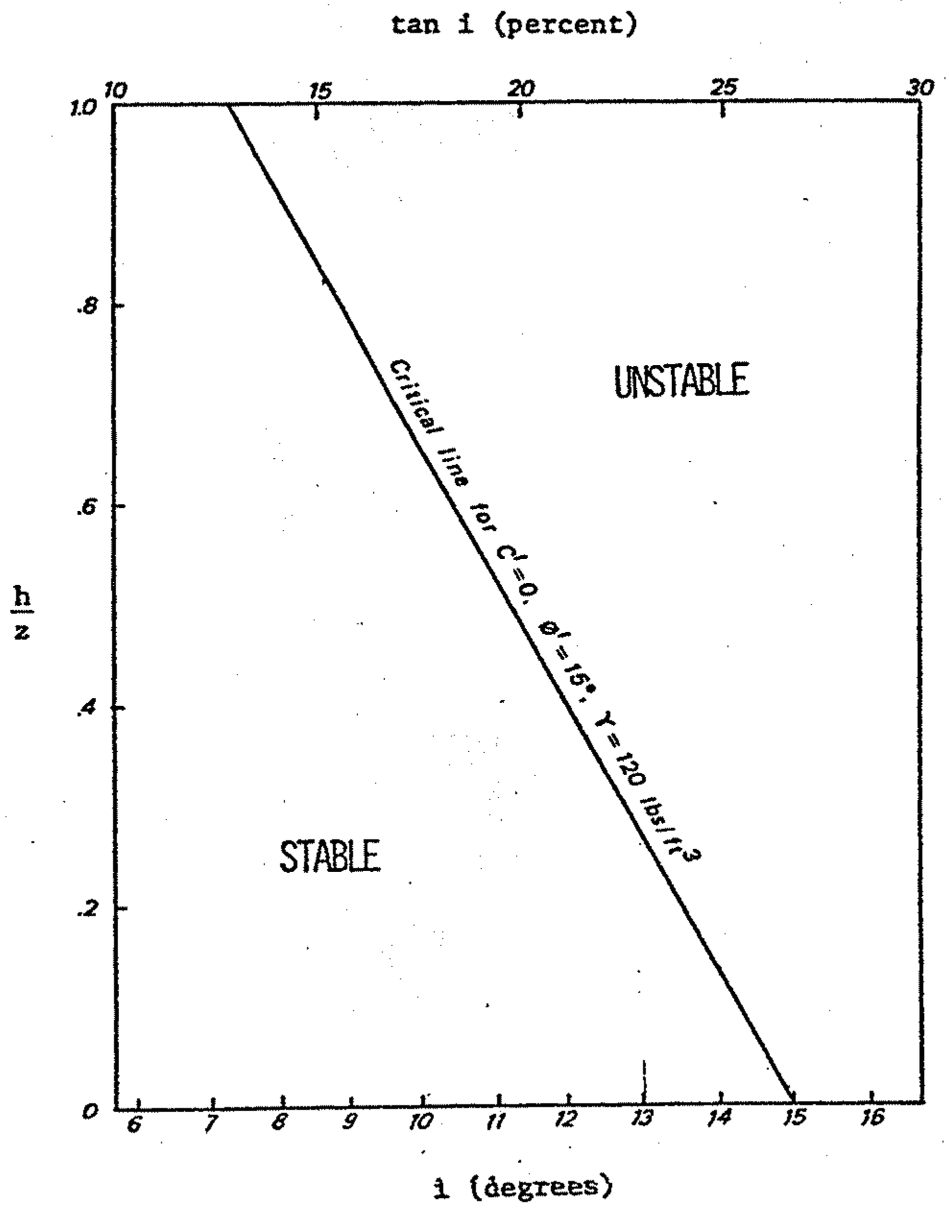
Figure 4-2
Infinite-Slope Failure Model Key Components

Theoretical calculations based on actual field measurements of Lawton Clay properties indicate that the amount the watertable must rise within the regolith (i.e., the degree of saturation of the potential slide mass) to induce a debris slide is a function of the slope angle (Figure 4-3). Figure 4-3 suggests that debris slides should **not** occur on bluff slopes of less than approximately 13 percent that are underlain by a consolidated substrate with physical properties similar to or exceeding those of the Lawton Clay. This theoretical prediction gains support from the empirical data presented in Figure 4-4. The histogram shows how the 47 Seattle landslides examined by Tubbs were distributed by slope angle (plotted as percent slope). Only three of the landslides originating as debris slides occurred on slopes of less than 15 percent inclination.

Figure 4-4 also shows a departure from the theoretical model. The model indicates that significant quantities of regolith cannot accumulate on slopes of greater than approximately 27 percent—yet accumulation of significant quantities of this surficial, weathered regolith material is a prerequisite for debris slides. Actual field data, however, show that numerous debris slides occurred on slopes of greater than 30 percent. Obviously, the regolith must be present for the debris slide to occur. Tubbs (1975) explained the discrepancy by noting that many slides were actually underlain by material stronger than the Lawton Clay, which was better able to accumulate the regolith. Tubbs also noted the probable anchoring role of plant roots in allowing accumulation of a greater thickness of regolith material than could be supported by the strength of the soil alone.

Analysis of the slumps, while more difficult than that of the debris slides, also showed a close association with stratigraphically controlled groundwater conditions. Tubbs (1975) work on the relationship of Seattle landslides to soil saturation and short-term rainfall events is described in Section 4.5 of this report.

Miller (1973), studying west-central King County, south of Seattle, identified slope angle, local stratigraphy and land modification by human activity as major components determining local slope stability. Areas sloping less than 15 percent were considered relatively



C' = Effective cohesion of soil

Φ' = Effective angle of internal friction

γ = Unit weight of soil

i = Slope inclination (angle)

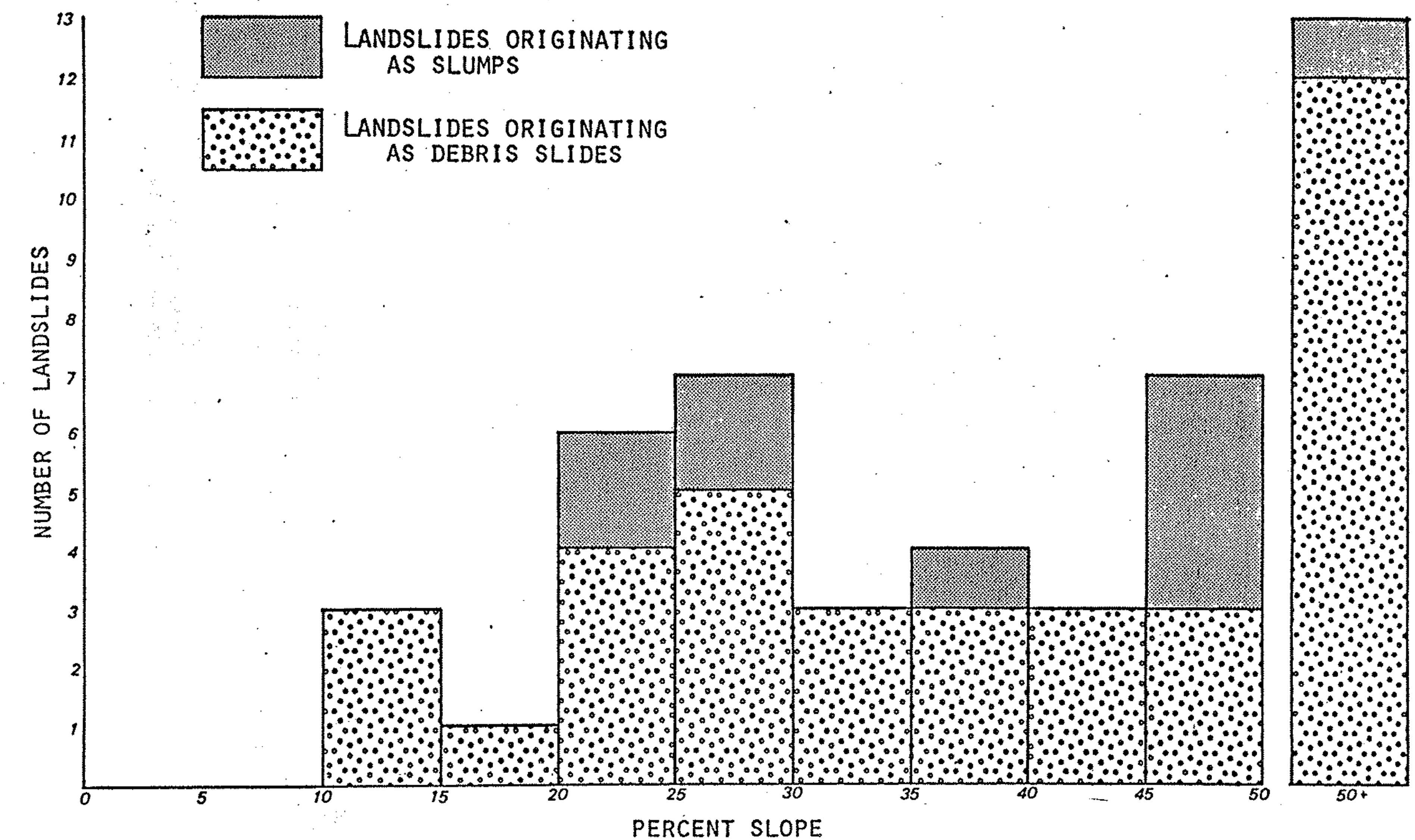
h = Height of water table above consolidated substrate

z = Regolith vertical thickness

Source: Tubbs (1975)

Figure 4-3

Seattle Landslides: Separation of Stable vs Unstable Slope Conditions Based on Slope Angle and Fraction of Regolith Below Water Table



Source: Tubbs (1975)

Figure 4-4
Seattle Landslides as a Function of Slope Inclination, 1971-72

stable, while areas with steeper than 15 percent slopes and underlain by "tight silt or clay" units were considered relatively unstable. Areas with slopes steeper than 15 percent but underlain by other stratigraphic units were described as having intermediate stability. These criteria closely parallel those subsequently described by Tubbs (1974a, 1975).

Edil and Vallejo (1980) describe the mechanics of coastal landslides along the Great Lakes shoreline and the influence of slope parameters. They note that landslides and slope recession triggered by wave-generated toe erosion involve some unique and complex features that are very hard to model (see also Kamphuis, 1987; Wilcock, Miller and Kerhin, 1992, 1993). While they present a more complex slope-stability analysis than that of Tubbs (1975) their study conclusions, quoted below, are strikingly similar:

> "The influence of slope parameters, namely, geometry (slope height and inclination), material properties (strength parameters and unit weight), and the relative position of the groundwater table on the limiting stability conditions of uniform slopes is presented based on such a limit equilibrium analysis. The relative influence of some of these parameters varies with slope height and the slopes can be viewed as low and high slopes with a height of 25 m as an appropriate demarcation between the two groups. (Edil and Vellejo, 1980)."

The conclusion that "low" (less than 25 m) and "high" (greater than 25 m) slopes behave differently at similar slope angles does not appear to have been examined for Puget Sound coastal bluffs. Edil and Vallejo (1980) conclude that for unconsolidated till slopes around the Great Lakes, high slopes can reach an unstable condition—with respect to deep slips—faster than low slopes as the slope inclinations change by an equal amount. (Steeper slopes can reach an unstable condition faster than flatter slopes as their heights change by an equal amount.)

4.2 Beach Processes and Toe Erosion

It is extremely important to understand that all of the apparently distinct features of the shore-zone—the shallow subtidal; the beach, banks, and bluffs behind the beach; and the coastal uplands bordering the bluffs—are part of a closely integrated system. Further, this is true for a whole variety of interrelated physical and biological processes or "landscape linkages" (Forman and Gedron, 1986) that operate across the shore-zone. Modification of any part of this system is thus likely to have repercussions on other parts of the system—some rapid and obvious, while other effects may occur more slowly and be easily missed.

Recent studies of seacliff erosion along the Oregon Coast (Shih, 1992) provide an excellent overview of the wide array of factors that influence shoreline erosion (Figure 4-5). The focus here is on **toe erosion**—wave action at the base of a bank or bluff, that results in a sequence of undercutting and oversteepening, slope failure, removal of the collapsed sedimentary material (talus), and re-exposure of the bank or bluff face to renewed wave attack (Figure 4-6; see also Kamphuis, 1987). Shih (1992) provides an excellent diagrammatic summary of this cliff (or bluff) erosion "system," identifying key interactions and feedback loops that operate among the different processes (Figure 4-7). **An obvious but not always adequately appreciated element of this overall erosion system is the central role of the beach as a buffer that can protect the adjacent bank or bluff from wave erosion.**

Laboratory experiments designed to simulate wave erosion at the base of coastal cliffs (Sunamura, 1992, 1993, in Shih, 1992) show the importance of beach elevation in controlling cliff erosion. Plunging waves (Komar, 1976; Downing, 1983) produce relatively high dynamic pressures and create a vortex containing sand grains that can "sandblast" the bluff toe and accelerate erosion rates. Kamphuis (1987), modelling recession rates of glacial till bluffs bordering the Great Lakes, notes that wave action alone is insufficient to erode the foreshore material. The presence of granual material in the water column as bed load or saltation load, however, acts as an abrasive and *can* cause foreshore erosion.

Figure 4-8 shows a plot of (laboratory) cliff erosion rate versus the relative beach elevation (h/d). The optimal condition for the formation of plunging waves, and thus maximum toe erosion, occurs when the cliff-beach junction (h) is at about sea level (d). Toe erosion rates diminish as the height of the beach increases toward to limit of wave run-up. This clearly demonstrates the practical importance of beach protection in buffering wave attack at the toe of coastal banks and bluffs. If the beach is sufficiently developed to absorb

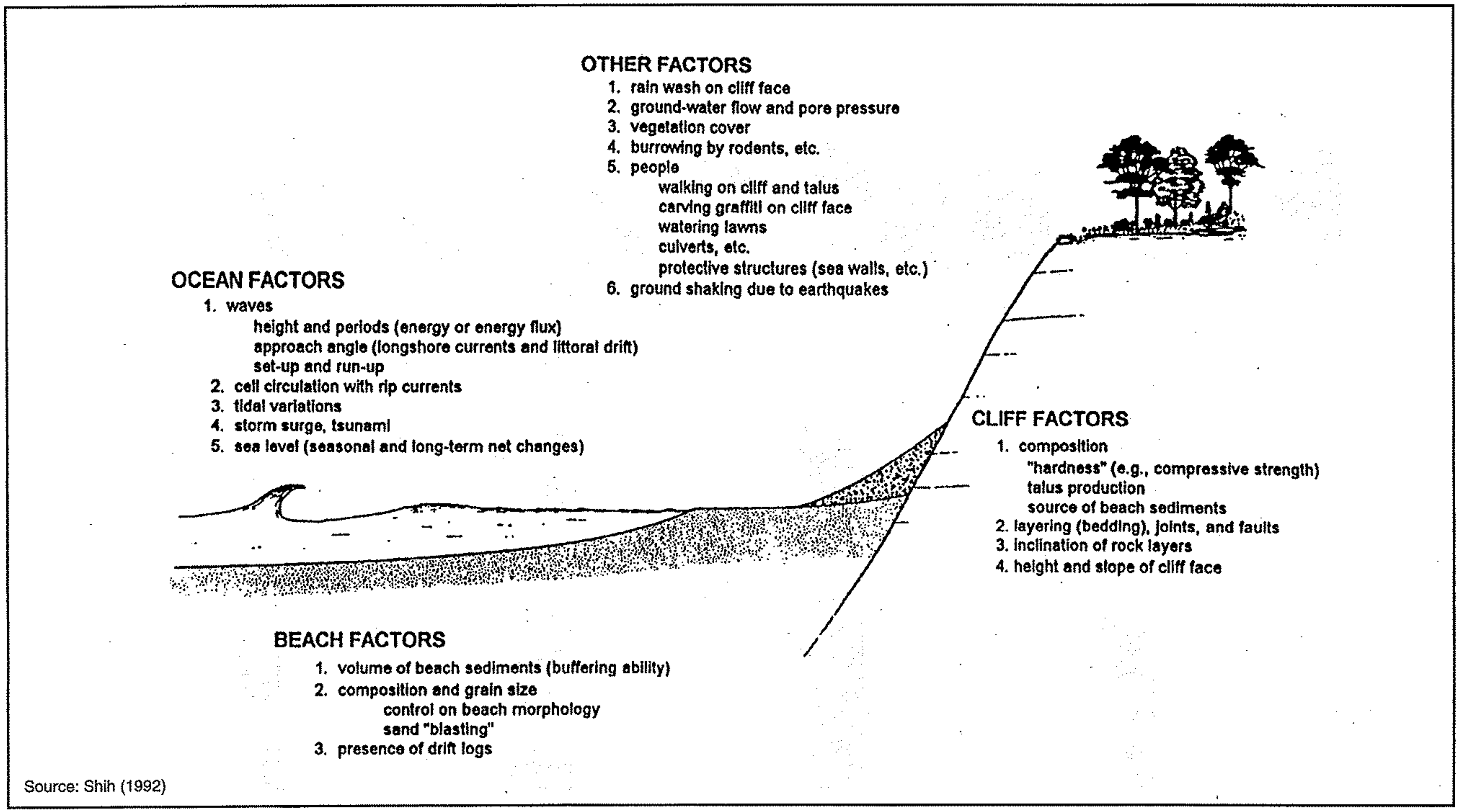


Figure 4-5
Factors Involved in Sea Cliff Erosion

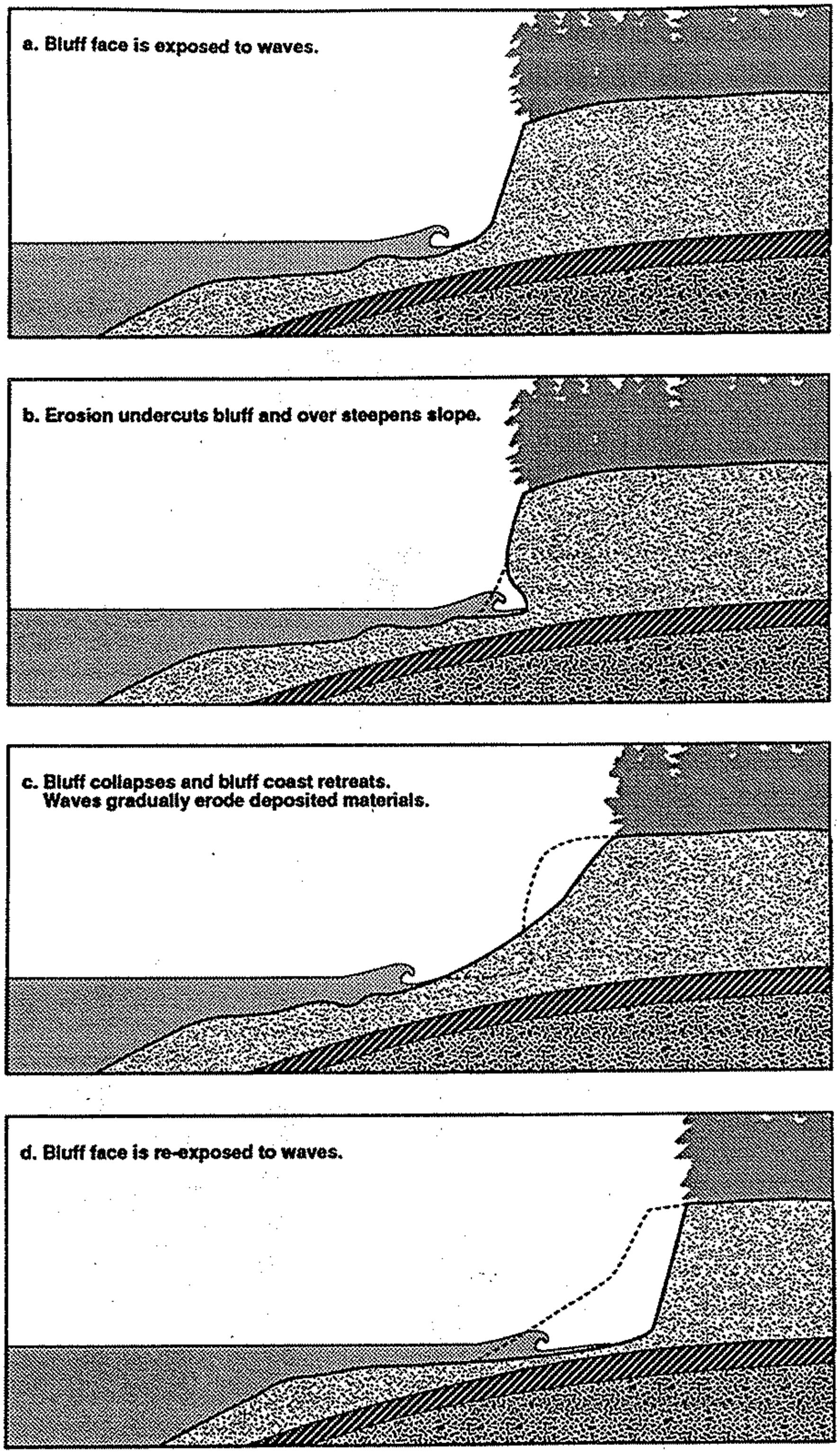


Figure 4-6
Wave Erosion Influences Bluff Stability

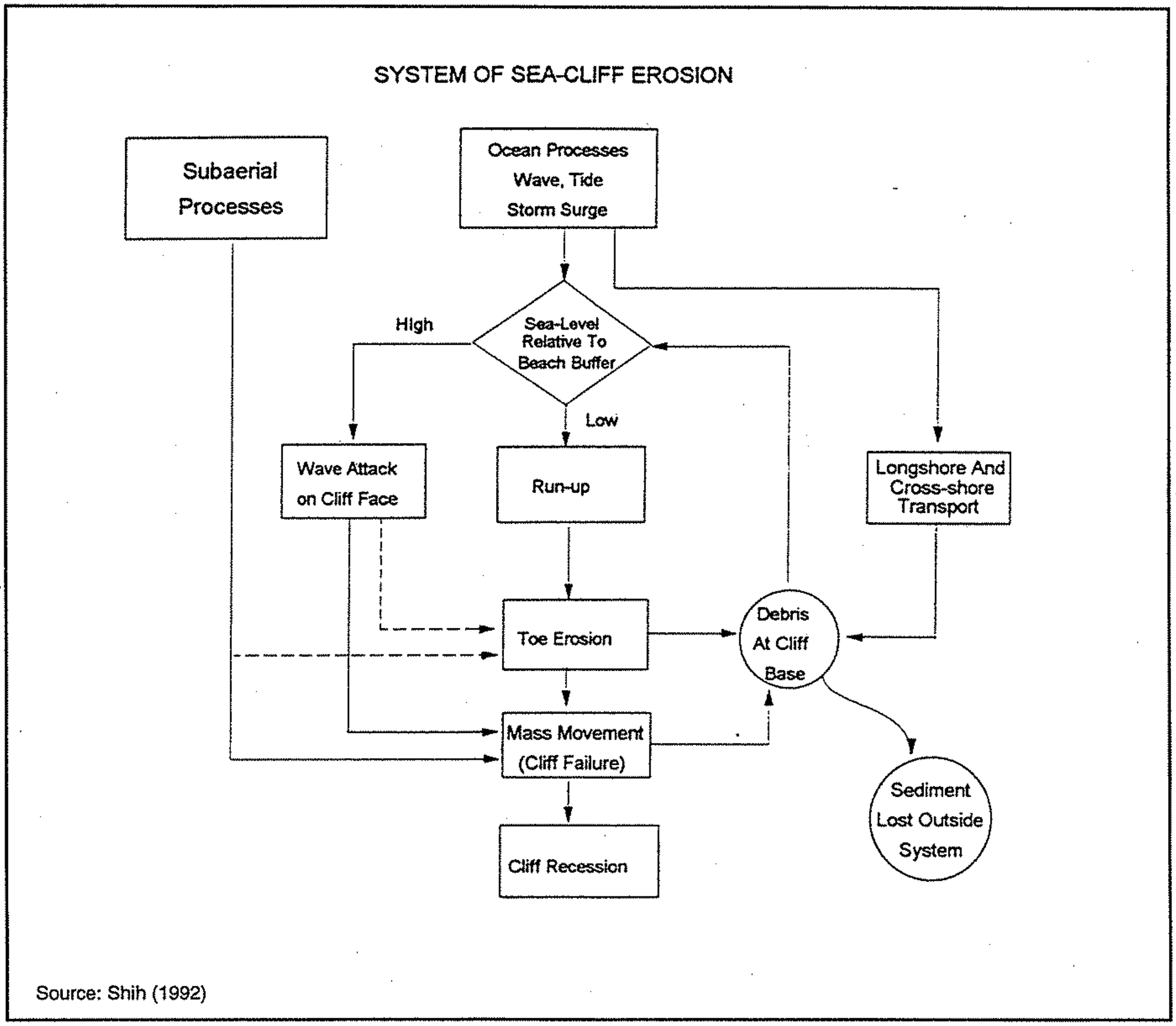


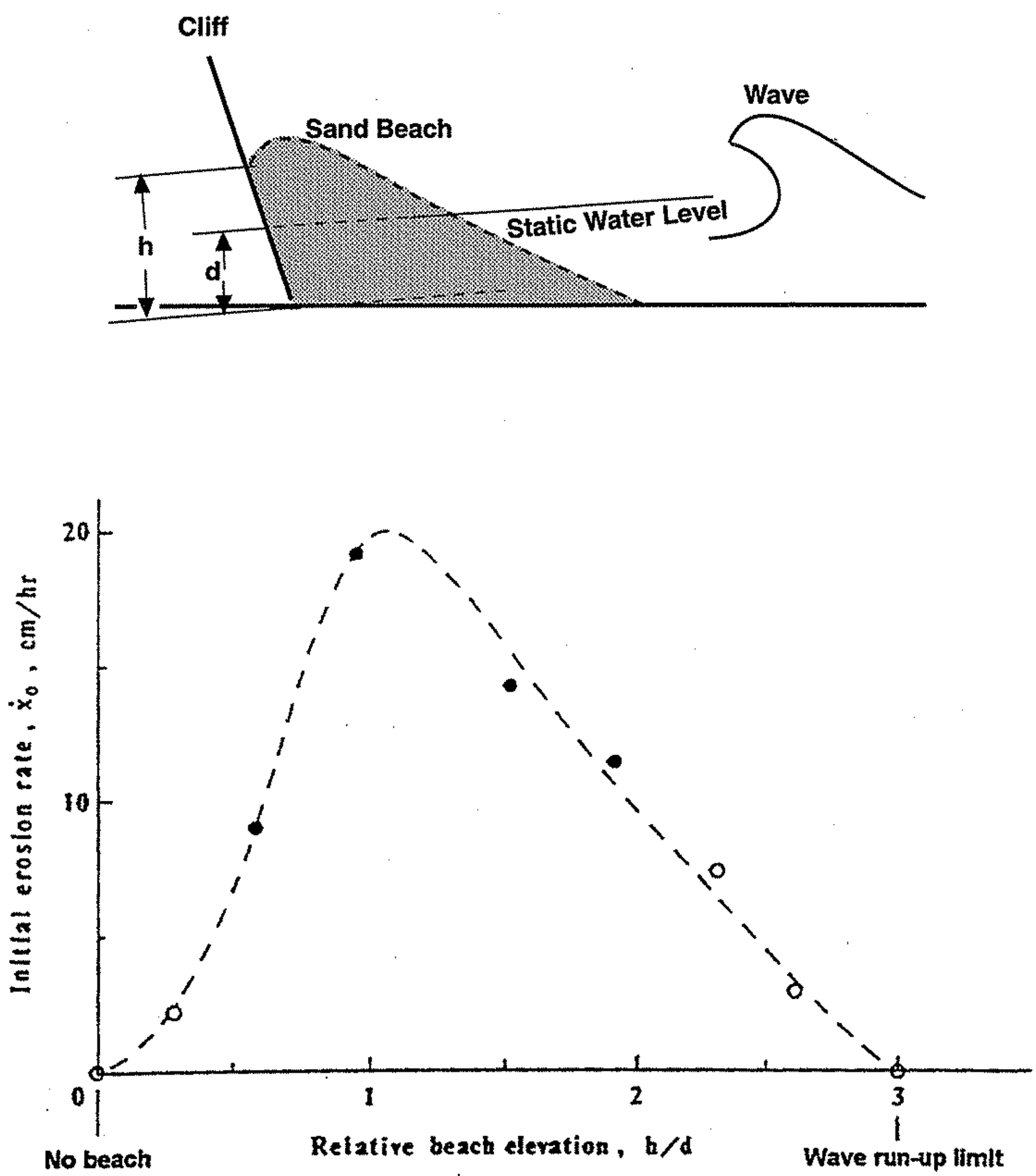
Figure 4-7
Sea-Cliff/Bluff Erosion System

normal wave run-up then the waves do not reach the toe of the bluff and the bluff is buffered from erosion, except under severe storm conditions. Conversely, if the beach is low and narrow, waves can readily reach the bluff and cause active toe erosion. Different rates of toe erosion—working in concert with local stratigraphic and erosional characteristics—can result in distinctly different and characteristic slope forms in coastal bluffs (Hutchinson, 1973, in Wilcock, Miller and Kerhin, 1993).

Beach sediments in Puget Sound are largely derived from river input and erosion of coastal bluffs. An estimated 3.2 million metric tons of sediment enters the Sound each year from major rivers. Ninety percent of this river input consists of fine-grained sediments that do not accumulate as beach deposits. Another estimated 2.7 million metric tons of sediment enter the Sound each year from erosion of coastal beaches, banks, and bluffs (Downing, 1983). The fact that Puget Sound's coastal bluffs provide the principle source, over 90 percent, of local beach materials illustrates a critical feedback loop within the coastal erosion system (Figure 4-7). Bluff erosion generates the material that forms the beaches—which then, in turn, protect the bluffs from further erosion.

The intricate coastline of Puget Sound is divided among large numbers of relatively short littoral cells or "coastal drift sectors" (Schwartz and Wallace, 1986; Terich, 1987). Each drift sector includes three elements: (1) a feeder bluff or source of new beach sediments; (2) a transport sector or driftway, in which newly deposited sediments are sorted, winnowed and carried downdrift by the wave-generated alongshore drift circulation system; and (3) a sediment "sink," often an accreating beach, where sediment moving downdrift accumulates. This is, of course, an idealized model that changes from sector to sector reflecting local conditions and may also change seasonally to reflect different wave and current regimes. While the bluff erosion/beach protection interaction noted above is real, in most drift sectors actively eroding bluffs tend to be *spatially separated* from the depositional beaches that buffer bluffs from wave attack.

Understanding these dynamic spatial interrelationships has important consequences for developing appropriate bluff protection strategies. The nature of "the problem" is clearly different in each segment of a drift sector. Toe erosion may be a concern at the foot of a



Cliff erosion rate versus relative beach elevation (h/d), where h is the height of the cliff-base junction, and d is the water level at the base of the cliff. Vortex formation (•) results from plunging waves that produce high dyamic pressures and contain sand grains as "blasting agents."

Source: Sunamura (1982) in Shih (1992)

Figure 4-8
Beaches Buffer Wave Attack Dissipating Wave Energy Further Offshore

feeder bluff but is of no consequence behind an accreating beach. If a seawall is installed to halt toe erosion at the feeder bluff, however, sediment input from the bluffs will be cut off from the beach and over time, downdrift sections of the beach will experience increased erosion and beach loss. A classic example of one property owner's "solution" becoming a nearby property owner's problem!

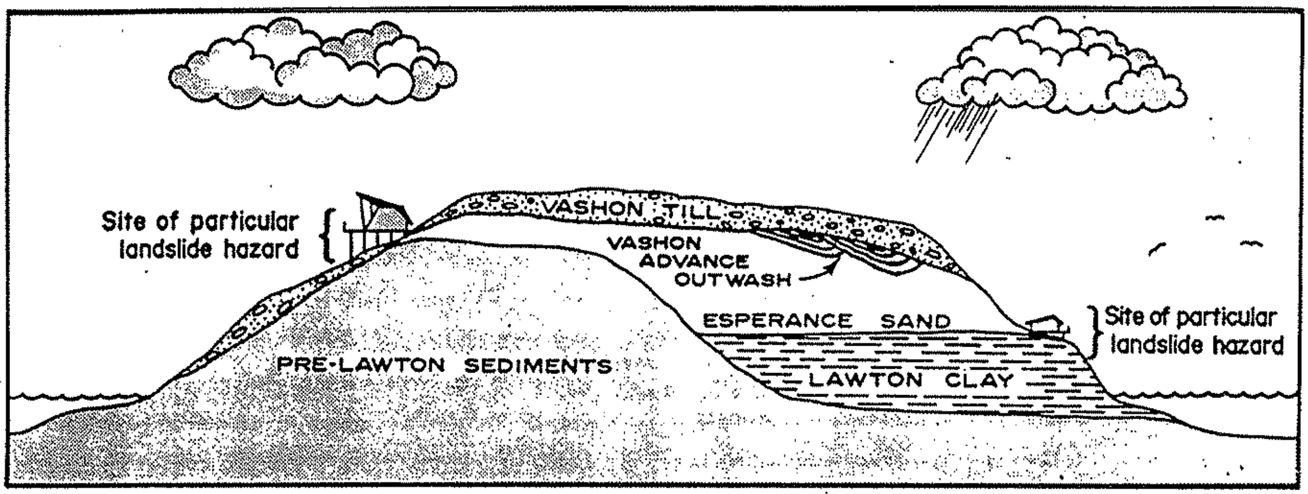
Other reports in this series describe a broad range of specific solutions for shore protection (**Task 2**: Engineering and Geotechnical Techniques for Shoreline Protection in Puget Sound), as well as the potential physical (**Task 3**: Shoreline Armoring Effects on Physical Coastal Processes in Puget Sound) and biological (**Task 5**: Shoreline Armoring Effects on Coastal Ecology and Biological Resources in Puget Sound) consequences of such protection.

4.3 Local Geology

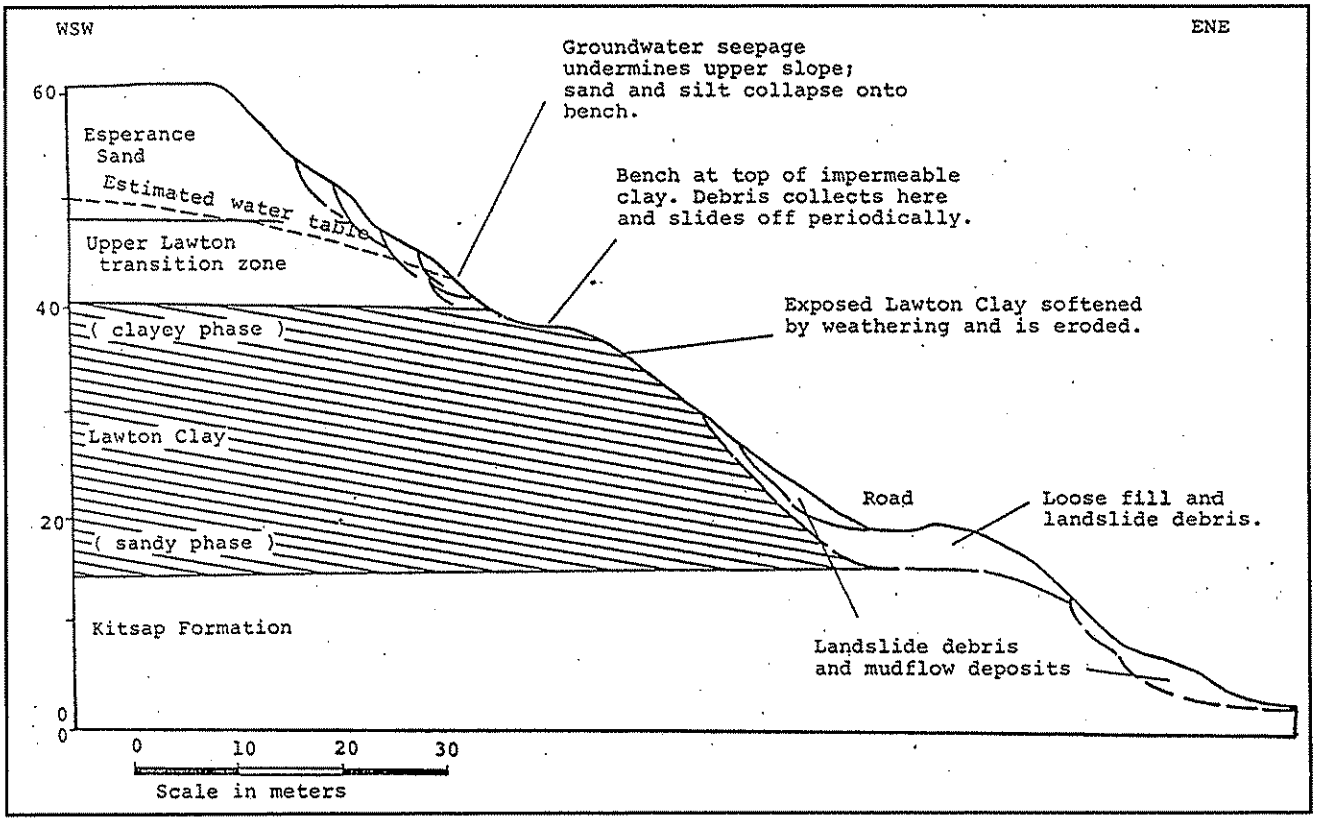
> "Quaternary events in the Puget Lowland have produced materials and landforms that are highly susceptible to landsliding (Tubbs, 1975)."

4.3.1 Stratigraphy and Landsliding

Tubbs' (1975; Tubbs et al., 1974; Tubbs and Dunne, 1977) studies of landsliding in Seattle (see also Sections 4.1 and 4.5) documented a close relationship between slope stability and stratigraphic factors (Figure 4-9). Thirty-seven of the 47 landslides he examined in the winter of 1971-72 involved either the Lawton Clay (12 debris slides, 3 slumps) or pre-Vashon sediments (15 debris slides, 7 slumps; Figure 4-9). Taken together, these stratigraphic units underlie less than 10 percent of Seattle yet they were present beneath nearly 80 percent of the landslides.



Cross-section of Typical Seattle Hill
Landslide Hazard Locations



Stratigraphy and Landslide Processes
California Way S.E., Seattle

Source: Tubbs (1974), Tubbs and Dunne (1977)

Figure 4-9
Local Geology Influences Bluff Stability

The distinguishing characteristic of both the Lawton Clay and pre-Vashon sediments is their very low permeability relative to other local stratigraphic units. This encourages the build-up of groundwater in overlying units, a factor Tubbs (1975) clearly demonstrated is critical to slope stability in the Seattle area.

Tubbs (1975) also noted that 21 of the 47 landslides examined occurred at locations were contacts between the Esperance Sand (Figure 4-12) and either the Lawton Clay (14 sites) or pre-Vashon sediments (7 sites) were present. The high permeability of the Esperance Sand relative to both lower units results in extensive groundwater seepage at their stratigraphic contact. This contributes to saturation of the regolith along the contact, increasing pore water pressures and thus decreasing the stability of the overlying Esperance Sand unit. Tubbs found evidence of similar effects at locations were sand beds were intercalated within the Lawton Clay.

The importance of Puget Sound's unique glacial history and sediments to understanding regional bluff stability issues is clearly demonstrated by Tubbs (1975) Seattle landsliding studies. The following subsections therefore briefly summarize recent glacial events with the Puget Lowland, glacial sediment characteristics, and the availability of geologic maps and reference materials covering the Puget Sound coastline.

4.3.2 Regional Glacial History and Sediments

Glaciation has been a dominant force in the recent history of Puget Sound shorelines—both the erosive action of glaciers as they alternately advanced and receded from the area, and the unique sediment types deposited by these glaciers. General discussions of the glacial geology of Puget Sound can be found in *Cascadia* (McKee, 1972, pp. 290-304) and *Landforms of Washington* (Easterbrook, 1970, pp. 42-72). The following discussion will familiarize readers with the glacial geologic processes responsible for much of the present topography and sedimentary deposits of Puget Sound's coastal banks and bluffs.

In Puget Sound, there is evidence for four different glacial advances and retreats, as shown in the stratigraphic table (Table 4-2 from Easterbrook (1970). Many of the older glacial deposits have either been completely or partially eroded away by the more recent glacial advances, or in some locations, were never deposited. This creates a complex glacial stratigraphic sequence that varies both laterally and vertically, often within short distances (see Fact Sheets).

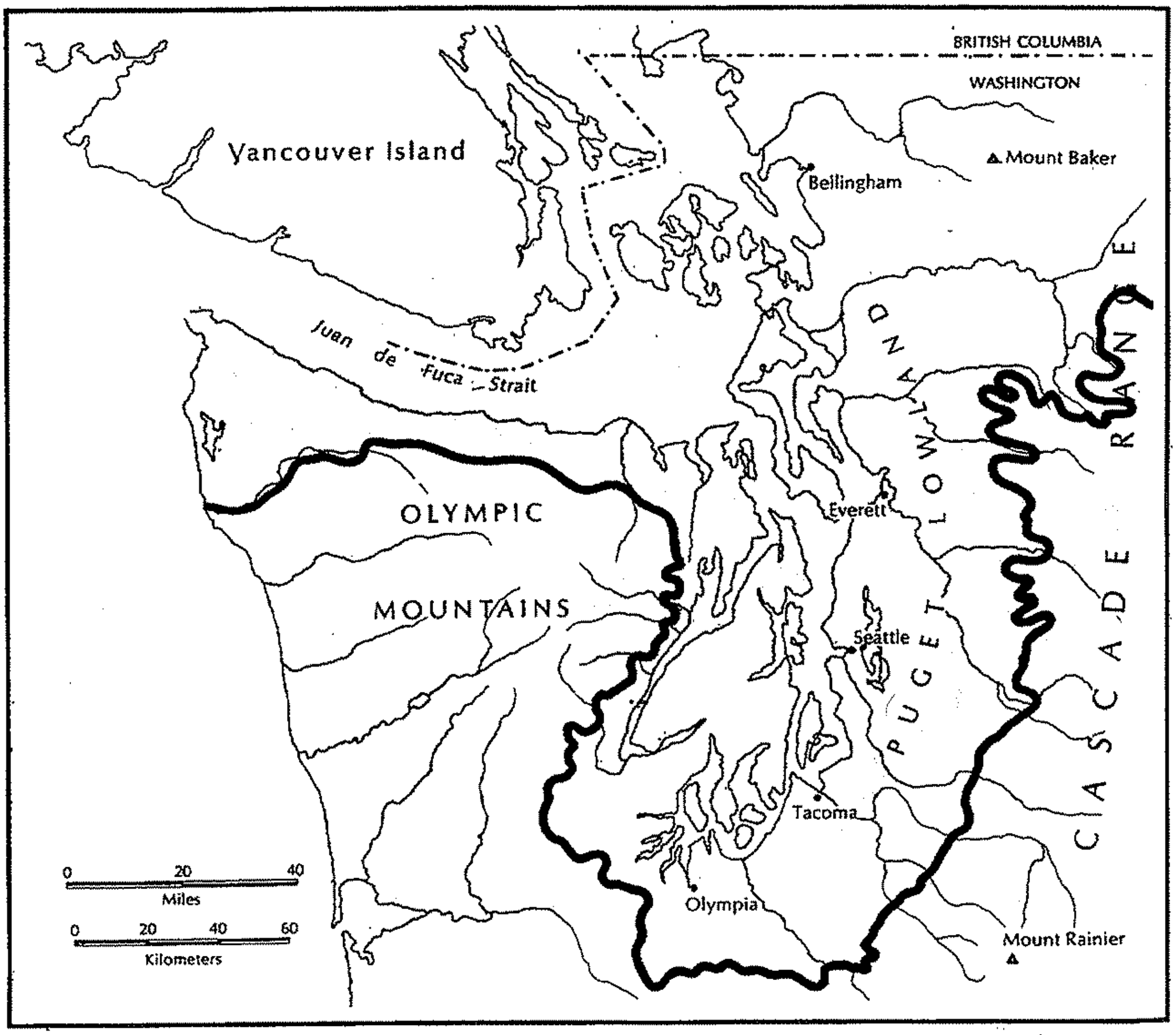
Much of the topography and glacial deposits that crop out on the bluffs bordering Puget Sound are the result of the most recent glacial episode—the Vashon glaciation—which advanced into the Seattle area about 15,000 years ago. The older glacial deposits are usually buried beneath those of the Vashon glaciation and are often exposed by wave erosion at the toe of coastal bluffs. The thickness of the ice during the Vashon Glaciation varied from about 5,700 feet near the Canadian border, to about 3,000 to 4,000 feet in the Seattle area, and decreased to about 1,800 feet in Tacoma. The maximum extent of the glacial advance in the Puget Lowland was in Tenino, about 15 miles south of Olympia (Figure 4-10; Easterbrook, 1970).

As a glacier advances into an area, meltwater streams are present at the front of the glacier and deposit a variety of coarse grained materials ranging in size from sand to coarse gravel. These deposits are referred to as **advance outwash**. The Esperance Sand is an advance outwash deposit that preceded the deposition of the Vashon till. In looking at a stratigraphic section of glacial deposits, the advance outwash typically coarsens upward as the source of the material moves closer to where it is being deposited (Figure 4-11, McKee, 1972). In other areas, at a greater distance from the glacial ice front, or where drainages are blocked by glacial ice, glacial lakes are formed in which fine grained sediments such as silt and clay are deposited. In the Seattle area, the Lawton Clay is a **glacial lake deposit**, which preceded the deposition of the Esperance Sand (Figure 4-12). As the glacier advances, these lake deposits are typically overridden and consolidated by the weight of the glacial ice and as a result are extremely dense and compact. They possess higher strength than a water deposited sand, silt, or clay that has not been overlain by glacial ice, and typically are more stable in steeper natural or cut slopes and are more

Table 4-2
Pleistocene Sequence in the Puget Lowland

Geologic Climate Units		Stratigraphic Units	C^{14} Age
Fraser Glaciation	Sumas Stade	Sumas Drift	11,000
	Everson Interstade	Everson Glaciomarine Drift	13,000
	Vashon Stade	Vashon Drift	
	Evans Creek Stade	Evans Creek Drift	18,000
Olympia Interglaciation		Quadra Sediments	23,000
		Kitsap Formation	27,000
Salmon Springs Glaciation		Salmon Springs Drift	35,000
		Possession Drift	47,000
Puyallup Interglaciation		Puyallup Formation	50,000
		Whidbey Formation	Older than 50,000
Stuck Glaciation		Stuck Drift	
		Double Bluff Drift	
Alderton Interglaciation			
Orting Glaciation		Orting Drift	

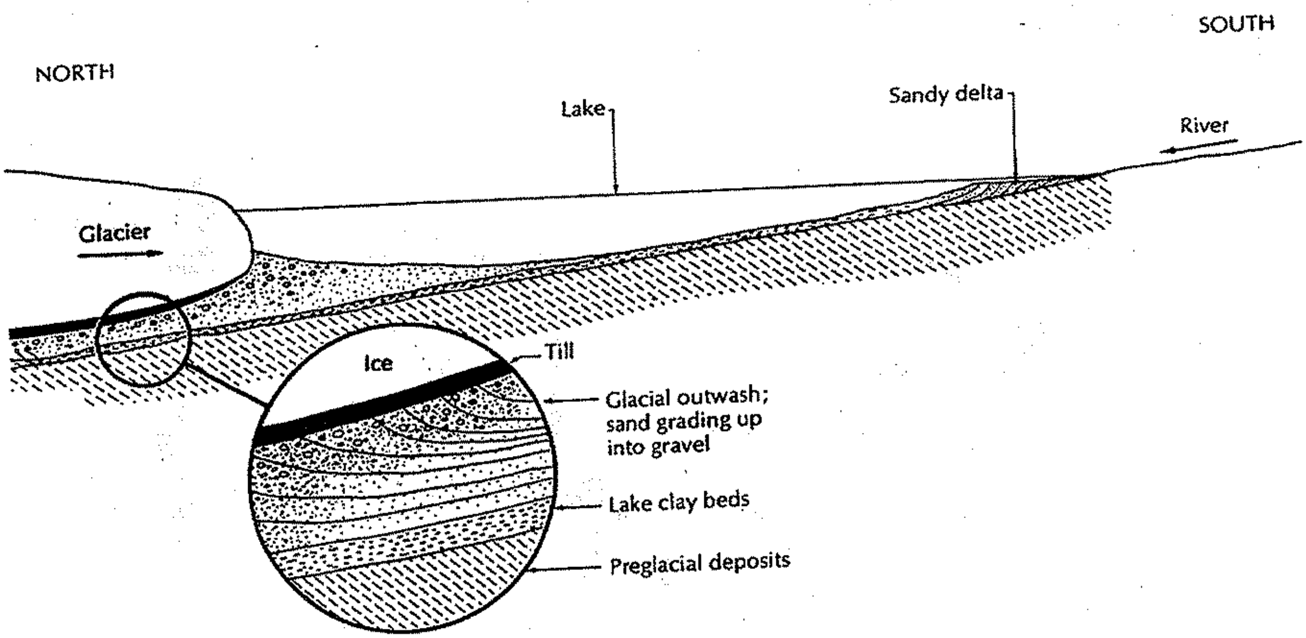
Source: Easterbrook (1970).



Source: McKee (1972)

Figure 4-10

Maximum Extent of the Vashon Glaciation in Puget Sound



Source: McKee (1972)

Figure 4-11
Generalized Sedimentation Patterns in the Puget Lowland Glacial Lake

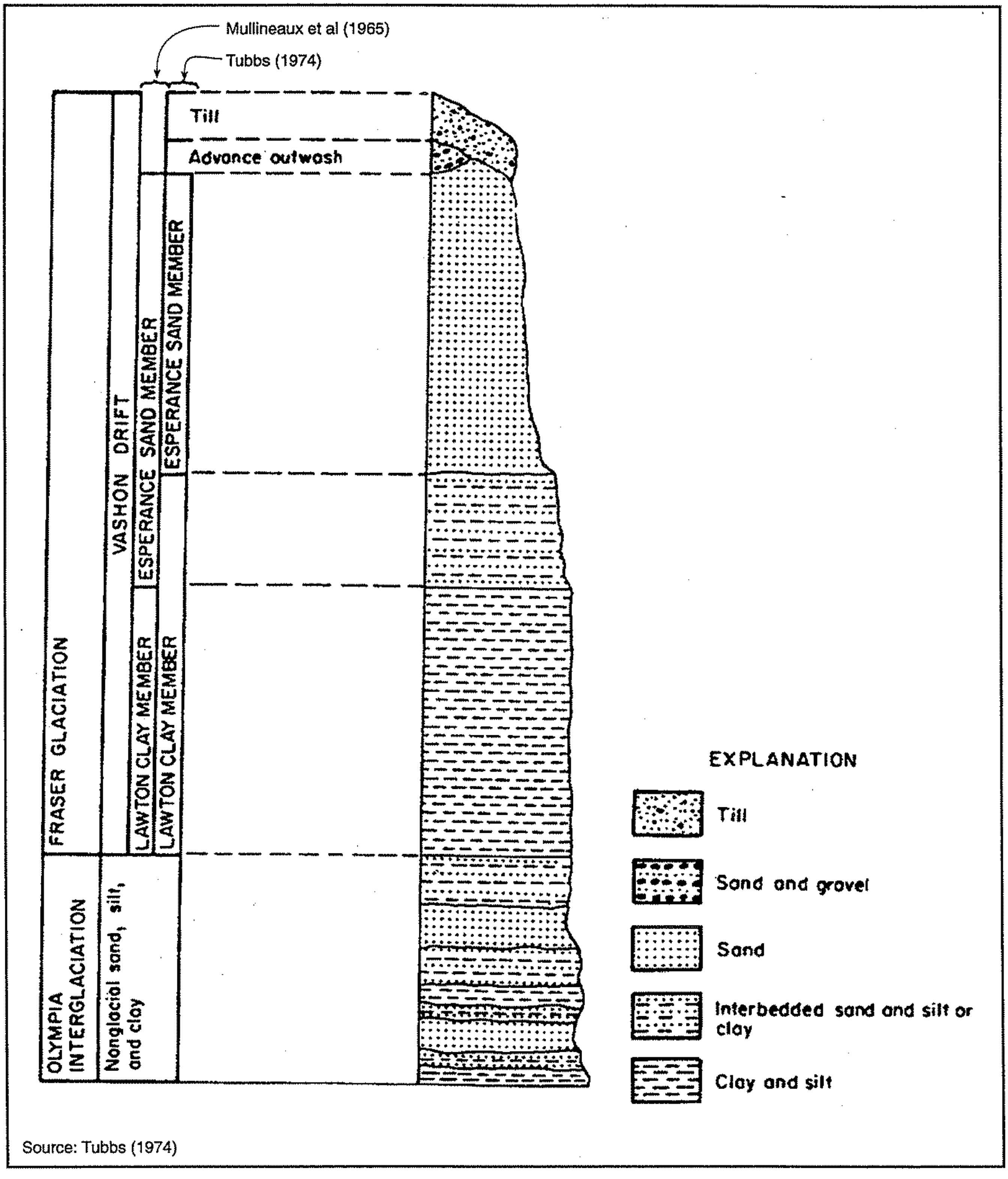


Figure 4-12
Typical Vashon Stratigraphic Section in Seattle Area

resistant to erosion. Because the material is granular, it is generally very permeable to the flow of water. High water levels are not typically found in outwash except where the outwash is underlain by finer grained till or lake deposits.

As a glacier progresses into an area, material is picked up at the base of a glacier. This unsorted mixture of clay, silt, sand, gravel and boulders is referred to as **till.** Most of the till deposits covering the Puget Lowland are the result of the last glacial advance in the area and are referred to as the Vashon till. The Vashon till on some geologic maps has been broken out into two units, lodgement and ablation till. Till that has been overridden by the weight of the glacial ice is **lodgement till** and is typically highly overconsolidated and impermeable, and forms a barrier to the vertical movement of groundwater. **Ablation till** is material trapped or carried *within* the ice that is deposited as the glaciers melt and recede from the area. It tends to be less dense and more permeable than the underlying lodgement till. Groundwater is generally present at the contact between the overlying ablation till and the lodgement till, or at the contact of the upper weathered portion of the till and the unweathered till. Because glaciers are dynamic systems, local ice fronts can move back and forth many times within each respective major advance or recession and sandy outwash lenses are common within most till units. Groundwater may also be present within these sandy lenses and may lead to unstable conditions on the slopes if water levels within the sand lens are high.

Recessional outwash consists of coarse grained material that was deposited from meltwater of the glacier as it receded from the area. Since recessional outwash has not been overridden by the weight of the glacial ice, it is generally not as dense as the underlying till or advance outwash sediments. As a result, it is only stable on shallower slopes and is more susceptible to the effects of water erosion.

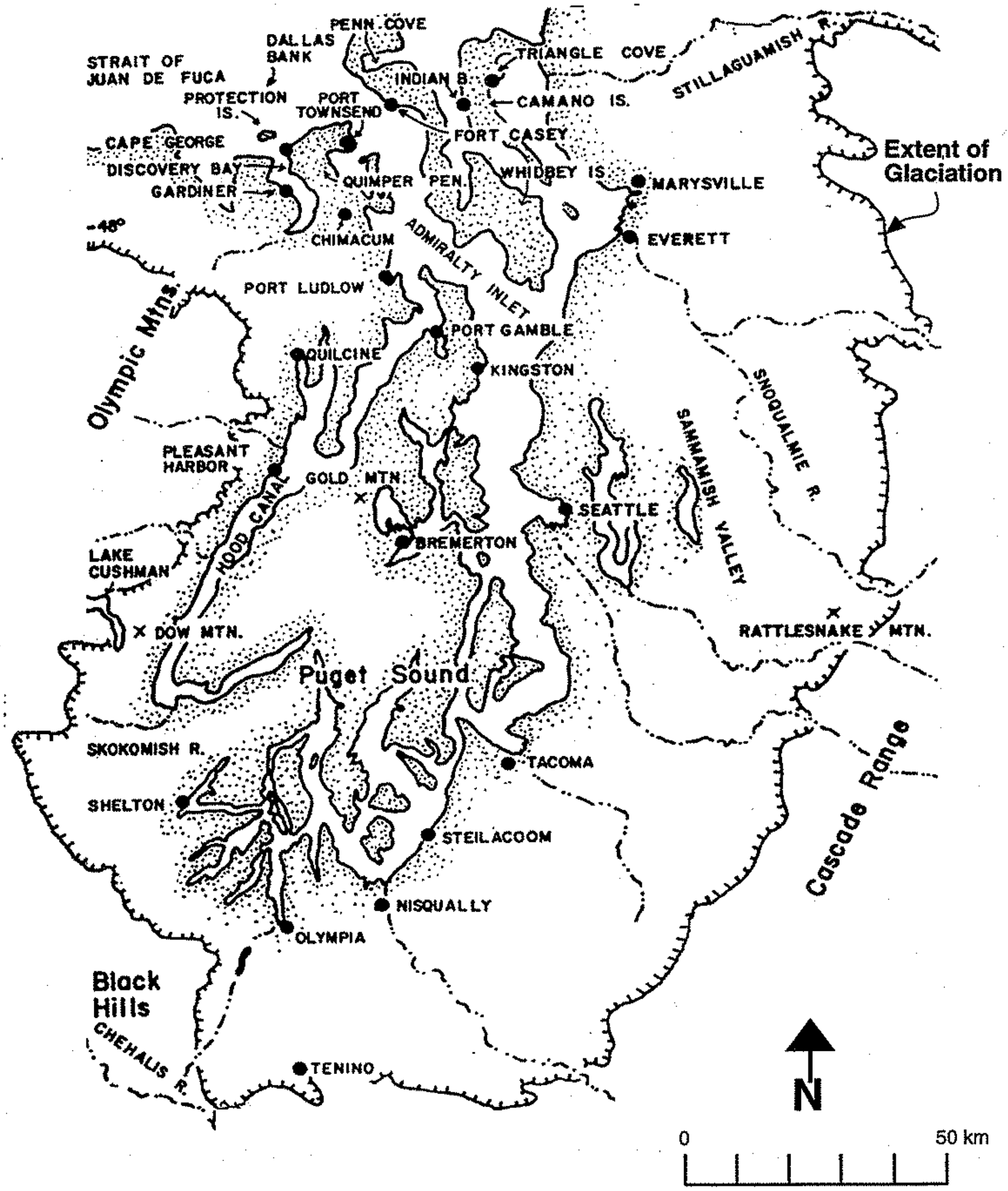
The composition of both recessional and advance outwash varies depending on the location of the ice front. Deposits near the front of the ice tend to be coarser grained, reflecting a higher energy environment. As the glacier advances or recedes, local drainages can be dammed by glacial ice, thus forming lakes where fine grained silt and clay are deposited.

Abrupt changes between sediment types often occur both laterally and horizontally. Recessional outwash typically has finer sediment near the top of the unit as the source of the material recedes from the area, and as a result, silty materials may be present near the surface. Figures 4-13 and 4-14 (Thorson, 1980) illustrate the generalized distribution of various glacial deposits present within the Puget Sound Lowland.

As the Vashon glaciers receded, bluffs bordering Puget Sound were steeply cut because of the erosive action of the ice. Often, groundwater levels present in the glacial deposits were high, reflective of the earlier, wetter time period. As a result of oversteepening and the high groundwater water levels, many landslides occurred along the bluffs when the glaciers receded. This was especially true for those deposits where the strength of the material was exceeded by the existing conditions, namely, the steep slopes and high water levels. These areas are mapped as the "ancient landslides" present on many regional geologic maps. In many cases, these ancient landslides reached a more stable, flatter configuration after their original movement—however, modifications of these slopes can re-initiate slope movement (Thorsen, 1987).

4.3.1 Strength of Glacial Materials

The strength of natural deposits is a combination of friction and cohesion. **Friction** is a resisting force between two surfaces and is influenced by the shape of the mineral grains as well as the type of mineral components which make up a soil unit. Friction is a direct function of the normal force. **Cohesion** is related to the bonding between sediment particles resulting from electrochemical or other forces, and is not related to the normal force. **Strength** is not a constant value for a given material but rather is dependent upon many forces, including material properties, the magnitude and direction of the applied force and the rate of application, drainage conditions in the material, and the magnitude of the confining pressure (Hunt, 1986). When speaking of a friction angle or a cohesion value for a given material, a range of values is typically listed to account for the variety of natural conditions which are likely to be present in a given area. The following discussion gives values of friction angles and cohesion for various glacial deposits; these values are intended



Source: Tubbs (1980)

Figure 4-13
Puget Lowland Locations

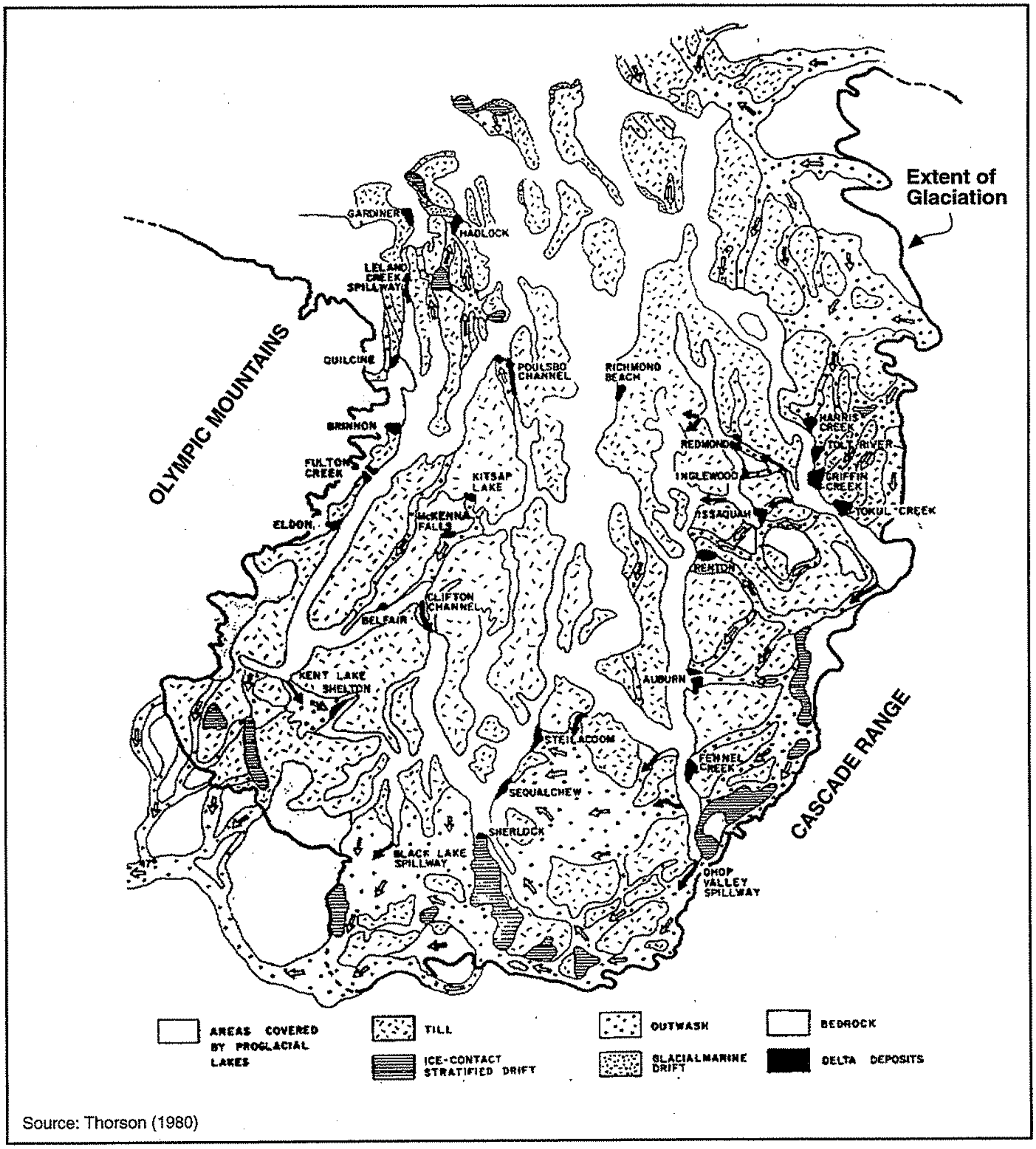


Figure 4-14
Generalized Glacial Geology Map of Puget Lowland

for general guidance only. The **friction angle** can be commonly taken as the angle at which a slope cut in a given material will stand. This value can be increased or decreased by a series of variables that are not always obvious because of the variable nature of the deposit. These variables include position of the groundwater table, cohesion, stratigraphic anomalies within the deposit, and the natural and man-made forces that are applied to the deposit.

In those areas where till outcrops, existing slopes are typically steep because of the dense, hard, overconsolidated nature of the material. A friction angle in till typically ranges from 35 to 45 degrees, but may be less depending on stratigraphic interbeds, such as sand lenses or high groundwater levels. Cohesion values are high and can vary from 1,000 to 4,000 pounds per square foot (psf; Koloski et al., 1989). Failures in till usually occur for two reasons: (1) surficial weathering and loosening of the exposed material that causes the till to slough down the slope (e.g., debris slide), and (2) freeze-thaw cycles and stress cracking that tend to loosen blocks of material from the slope, resulting in failure of large intact blocks of till (e.g., slump). Stress cracking occurs when soil that was previously subjected to a heavy load (such as that of a glacier)—is relieved of the load (as when the glaciers receded from the area). The soil rebounds to an open surface which in this case is the existing slope or ground surface, accompanied by cracking. Foundations for structures founded on till can support loads from about 1,500 to 5,000 psf (Koloski et al., 1989). The lower values are likely reflective of conditions on weathered or ablation till, while the higher values are more applicable to unweathered material.

Areas that are underlain by outwash deposits have friction angles ranging from 30 to 40 degrees. Cohesion values vary from 0 to 1,000 psf depending on the amount of fine grained sediment in the deposit (Koloski et al., 1989). The presence of a high groundwater table or a steeply dipping impermeable layer within the deposit, will also decrease the natural angle at which the slope is stable. Advance outwash that has been overridden by the glacier and is thus more consolidated, tends to be stable at steeper angles than those areas underlain by recessional (unconsolidated) outwash. Foundation loading for structures on advance outwash vary from 1,500 to 3,000 psf (Koloski et al, 1989).

Finer grained lake, or lacustrine deposits which have been overridden by glaciers have friction angles ranging from 15 to 35 degrees, and cohesion values of 0 to 3,000 psf (Koloski et al., 1989). Because of their fine grained nature, these deposits typically act as barriers to groundwater movement allowing water to collect at the interface between these and other, more permeable units. When these deposits are interbedded with other units, and outcrop on a slope, water tends to flow along the contact and exit on the slope face as a seep or spring, saturating the overlying material. These areas are zones of weakness where slope failures commonly occur (Figure 4-9; Tubbs, 1975).

4.3.2 Available Coastal Mapping

The Coastal Zone Atlas of Washington (Washington Department of Ecology, 1977- 1980), was published to alert owners of property bordering Puget Sound to the concerns and hazards associated with coastal development. Maps of the geology and relative stability of coastal slopes are included in the Atlas.

The map scale used results in features narrower than 200 feet being difficult to portray accurately. Small and/or ancient landslides that were difficult to identify because landslide features were masked by dense vegetation are not shown. In addition, new slides have occurred since Atlas publication. Thus, the Atlas maps likely *underestimate* the total number of landslides that are present on Puget Sound bluffs. The intent of the maps, however, is to alert the public of potential hazards, but not to be *the* definitive resource as to whether the hazard exists on a specific property parcel.

The slope stability classification used in the Coastal Zone Atlas is presented in Table 4-3. This classification identifies which combinations of geologic units, slope angles, and groundwater conditions present the most likely conditions for slope failure. This classification—or one closely similar—is used on many published slope stability maps.

Table 4-3
Slope Stability Class Definitions

CLASS 1; S, Stable Slopes: Believed to be stable. Slopes are generally less than 15%, but may be greater than 15% in local areas of low relief and low ground water concentration. Includes mostly rolling uplands underlain by very stable material, such as young glacial till, covered in places by a thin layer of sandy gravel or other permeable material; also included are flood plains, deltas, alluvial fans, and some beach deposits. Normal, proper engineering practices generally are adequate to ensure continued stability

CLASS 2; I, Intermediate Slopes: Believed to be stable under natural conditions; may become unstable if disturbed. Slopes generally greater than 15%, but may be less than 15% in areas with less stable geologic materials. Includes areas underlain by: (1) well-drained sand and gravel, mostly in valley sides; (2) glacial till on slopes greater than 15%; and (3) bedrock. Destabilization may be caused by man's activities, oversteepening by erosion, or strong seismic shaking. Local minor modifications in slope for small buildings and narrow roads will probably result in little or no hazard unless proper engineering practices are ignored. Geologic engineering studies should precede significant development.

CLASS 3; U, Unstable Slopes: Inferred to be unstable. Slopes generally are greater than 15%, in areas underlain by weak, unstable materials in which old or recently active landslides have occurred. Includes areas of sand and gravel on top of impermeable till, silt, or clay, mostly along steep valley sides and Puget Sound shorelines. Most of these slides occur during periods of heavy rains. These slope failures include a few landslides of moderate size, but the most common occurrences are of slumping, slicing, and falling of relatively small amounts of earth materials. Thorough geologic engineering investigations imperative for safe development.

CLASS 4; Uos, Unstable Old Slides: Former landslide areas. Generally located within Class 3 areas. Includes relatively large slumps, flows, and slides of soil, rock, and debris that have occurred since the retreat of glaciers from the region. Present stability unknown, but sliding may be reactivated by excavations, slope modifications, or strong seismic shaking. These areas should be considered unstable land unless and until proven otherwise by thorough geologic engineering investigations.

CLASS 5; Urs, Unstable Recent Slides: Recent landslide areas. Known areas of recently active rapid downslope movement (probably within the past 50 years) generally within Class 2 and 3 areas. Includes relatively large- to moderate-sized landslides, but most commonly only slumping, sliding, and falling of relatively small amounts of earth material, usually occurring during periods of heavy rains. Presently stability considered very poor.

UNCLASSIFIED; M, Modified Slopes: Areas highly modified by human activities. Slope responses to a combination of natural processes and man's activities may be unpredictable. (Coastal Zone Atlas mapping only.)

1. As defined by the US Geological Survey and Washington Department of Natural Resources for Washington. Numerical classes are USGS and WDNR designations. Letter codes are Washington Department of Ecology Coastal Zone Atlas designations.

Source: Canning (1991)

Four **Fact Sheets** are included in this report to illustrate how local geological data and the accompanying slope stability maps in the Coastal Zone Atlas can be interpreted. The four examples include a range of different coastal types located from Chuckanut Bay, Whatcom County, to Budd Inlet in Thurston County.

Appendix B

Appendix B of this report provides a general bibliography on landslides of shore areas in Puget Sound, as well as **slope stability maps** and publications for each of the counties bordering the Sound. These bibliographies supplement the Washington Coastal Zone Atlas and include geologic and slope stability maps that may provide additional information relating to the causes of potential stability problems on a local bluff. Also included are citations for **soil surveys** for each county, which are published by the United States Department of Agriculture, Soil Conservation Service. These soil surveys generally provide more detailed mapping of the soils present at a given site, however, their descriptions are limited to the top 5 feet of surface material. These publications typically include descriptions of the erosion potential of the soil and in some specific cases, the report will note whether the material is subject to slippage. The determination for these classifications are based primarily on slope angle, soil type, and water levels. Soil maps are presented at a scale of 1:24,000, with the soil types superimposed on an aerial photograph of the area. Springs, seeps, wet areas, and slides are also mapped. Because of the mapping scale, areas denoted as "stable" but located next to unstable areas should be considered suspect, as movement in one area can have deleterious effects on the neighboring parcels.

If after checking the existing literature there appears to be a stability problem at a particular site, the assistance of a geologist or geotechnical engineer specializing in slope stability issues is recommended. These professionals can search for more definitive evidence to substantiate or refute the presence of a landslide and can recommend remedial measures to minimize the impacts of the slope stability hazard on the proposed construction or development.

4.4 Vegetation Management

The shores and bluffs of Puget Sound support a wide variety of trees and shrubs, herbaceous plants and grasses, mosses and lichens all adapted to local site conditions (Franklin and Dyrness, 1988; Kruckeberg, 1991). Many environmental factors influence local vegetation including steepness of the slope, soil type and development, hydrology (soil moisture conditions), aspect (orientation of a slope face relative to the sun), microclimate, microhabitat, and site disturbance—whether caused by natural processes (erosion, fire, extreme climate events, seismic activity) or human impacts (logging, clearing, road building, grading, construction). Menashe (1993) discusses how these various factors influence shoreland vegetation and provides a listing of plants commonly found on Puget Sound shorelands.

4.4.1 Vegetation Indicators

Menashe (1993) also cites examples of how species composition and other vegetation characteristics can provide valuable clues or indicators of the history and stability of coastal slopes. For example, alder (*Alnus* sp.), willow (*Salix* sp.), and fireweed (*Epilobium angustifolium*) are all relatively short-lived pioneer species that readily colonize recently disturbed bare soil. A predominantly single-species, even-aged stand of red alder (*Alnus rubra*) or willow along with an understory of stinging nettle (*Urtica* sp.) and bracken fern (*Pteridium aquilimum*) can indicate a fairly recent, large-scale slump or earth flow. Alternatively, healthy vegetation composed of a variety of deciduous and evergreen trees, shrubs and groundcovers—all of various ages—usually indicates the site has not been recently disturbed and that vegetation cover has stabilized local soil movements.

A line of moisture-loving red alders or willows growing across a slope might reflect colonization of bare ground following a recent slide—or a zone of groundwater seepage marking the junction between an impervious clay layer and overlying sandy soils. In either case, there is a potential for unstable slope conditions that should be investigated further.

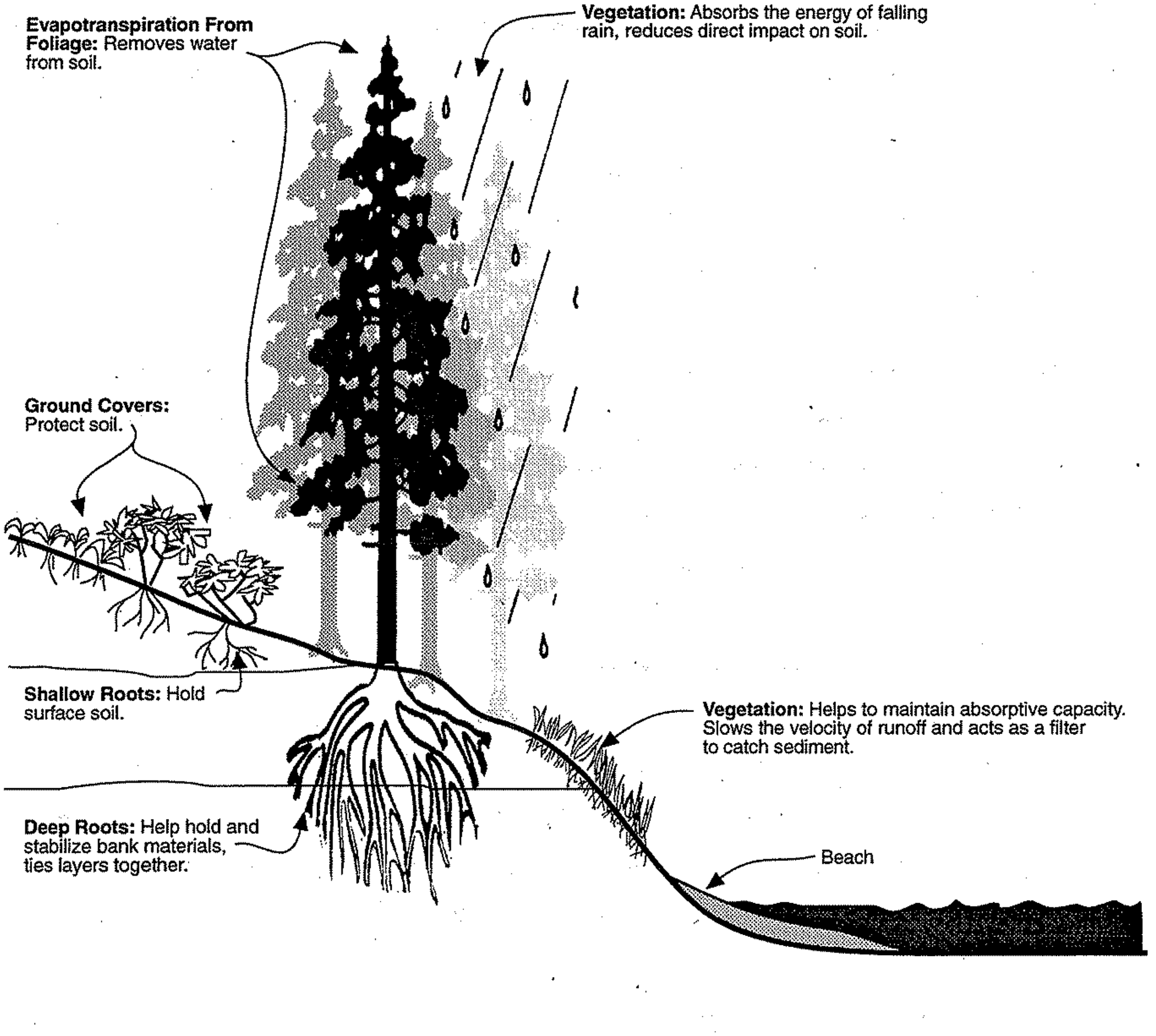
Downed trees may reflect diseases such as root rot, shallow rooting and wind-caused blow down, poorly planned tree removal that exposes previously stable trees to new wind stresses, or slope disturbances that undermine the trees' root mass. Curved tree trunks such as shown in Figure 3-5 usually reflect slow, gradual soil creep, while the jumbled appearance of "jackstrawed" trees often results from a slump or earth flow. Dead trees in the latter situation probably indicate the roots were sheared or broken loose during the earth movement.

Banks or bluffs devoid of vegetation typically suggest the site is either too steep to support vegetation (near vertical bluff faces of glacial till, for example), or that recurrent erosion and slumping preclude plant establishment (retreating sandy bluffs, for example). Bare bluffs can also indicate recent or ongoing slope failure due to wave-related toe erosion and upslope slumping (e.g., feeder bluffs).

4.4.2 Vegetation and Slope Stability

The presence or absence of vegetation on the shoreline banks and bluffs of Puget Sound—and how that vegetation is managed during and after site development—usually plays a crucial role in determining local slope stability. Some of the ways in which vegetation cover influences slope stability are illustrated in Figure 4-15.

The presence of vegetation reduces the potential for slope erosion in at least three different ways. First, plant roots, large and small, provide a fibrous web that stabilizes and anchors the soil. Second, plant cover intercepts the falling rain, reducing the direct impact of raindrops on the ground surface and protecting the soil from surface runoff and erosion. Dense groundcovers, especially grasses, reduce runoff velocity and act as filters trapping soil particles that would otherwise be washed downslope. Thirdly, vegetation, and associated plant litter, the partially decomposed remains of roots, stems and leaves, moderate critical soil moisture relationships. By slowing runoff, vegetation enhances infiltration; associated litter acts like a sponge, holding the moisture and releasing it slowly over an extended period. Plants can also play an important role in dewatering unstable slopes.



Source: After Tainter (1982) and Menashe (1993)

Figure 4-15
Vegetation Cover Influences Bluff Stability

Soil moisture is drawn up through roots and stems, trunks and branches, into plant leaves where transpiration releases it back into the atmosphere. This reduction in soil moisture can contribute significantly to soil stability.

Gray and Leiser (1982) in their classic text, *Biotechnical Slope Protection and Erosion*[2], summarize an extensive body of quantitative laboratory and field research that documents the role of vegetation in the stability and protection of slopes. Defining the "hydro-mechanical" influences of vegetation they distinguish between the role of shallow-rooted grasses and forbs in preventing surficial erosion on slopes, from that of deeper-rooted shrubs and trees that help prevent mass movement—particularly shallow sliding in slopes.

Major effects of herbaceous plants in controlling erosion include:

Interception—Foliage and plant litter absorb the energy of falling raindrops and reduce direct impacts on soil.

Restraint—Root systems physically bind soil particles and above-ground plant parts filter sediment out of runoff.

Retardation—Above-ground plant parts and litter increase surface roughness and reduce runoff velocity.

Infiltration—Roots and plant litter help maintain soil porosity and permeability.

Transpiration—Depletion of soil moisture by plants delays the onset of soil saturation and surface runoff.

---

[2]Regrettably, this excellent text, published by Van Nostrand Reinhold Company, Inc., New York, is presently out of print. It is well worth obtaining a copy from a college or public library.

The role of vegetation in controlling rainfall erosion is well known and other effects such as slowing runoff and filtering sediment (suspended solids) have been successfully incorporated into stormwater biofiltration systems (SWPCD 1992, Ecology 1992, EPA 1993).

The influences of woody plants on mass movement (shallow sliding) are less well documented but probably include the following:

Root Reinforcement—Roots mechanically reinforce soil by transferring shear stresses in the soil to tensile resistance in the roots.

Soil Moisture Depletion—Interception of raindrops by foliage as well as evapotranspiration limit buildup of soil moisture.

Buttressing and Arching—Tree trunks can act as buttress piles or arch abutments in a slope, counteracting shear stresses.

Surcharge—The weight of vegetation on a slope exerts a destabilizing downslope stress and a stress component perpendicular to the slope that increases resistance to sliding.

Root Wedging—Roots invade cracks and fissures in soil or rock causing local instability by wedging action.

Windthrowing—Strong downslope winds exert an overturning movement on trees causing blowdowns (usually of aged, diseased, or undermined trees) that disturb slope soils.

The first three effects—root reinforcement, soil moisture depletion, and buttressing—enhance slope stability. Surcharge may have either beneficial or adverse impacts depending on local soil or slope conditions. The last two effects—root wedging and windthrowing—are likely to decrease slope stability. While a full discussion of experimental data supporting each of these effects is beyond the scope of this report, some representative examples are outlined below.

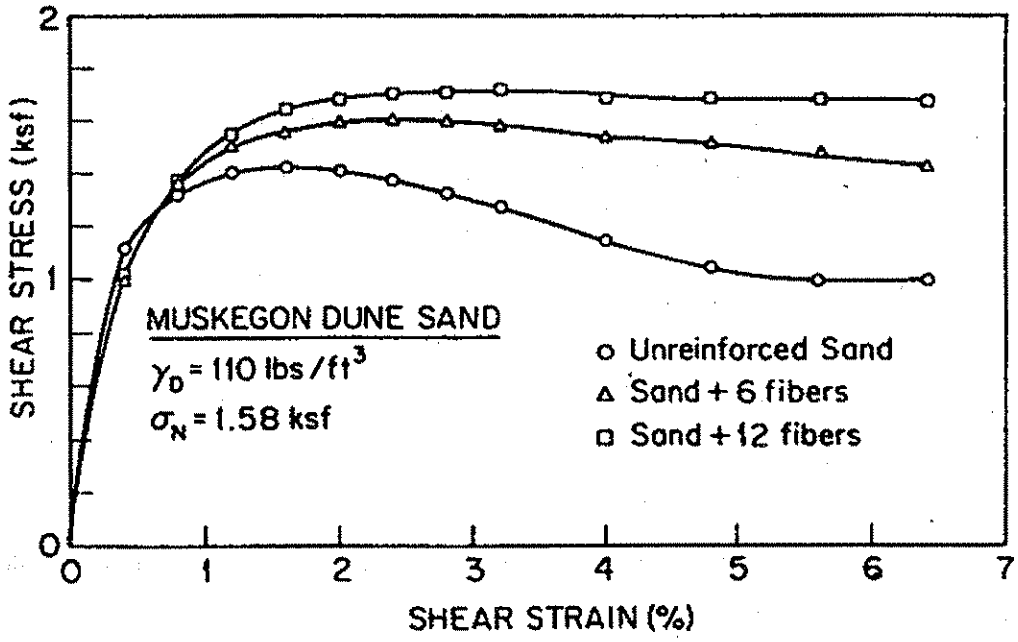
4.4.3 Roof Reinforcement

Root reinforcement is the most obvious way in which woody vegetation stabilizes soils. The intermingled lateral roots of plants bind the soil together into a monolithic mass. Soil reinforced with either artificial fibers or roots behaves as a composite material with high tensile strength elastic fibers embedded in a plastic soil matrix. Shear stresses in the soil mobilize tensile resistance in the fibers (roots), thus imparting greater strength to the soil. Some soils are also made tougher, better able to resist continued deformation without loss of residual strength.

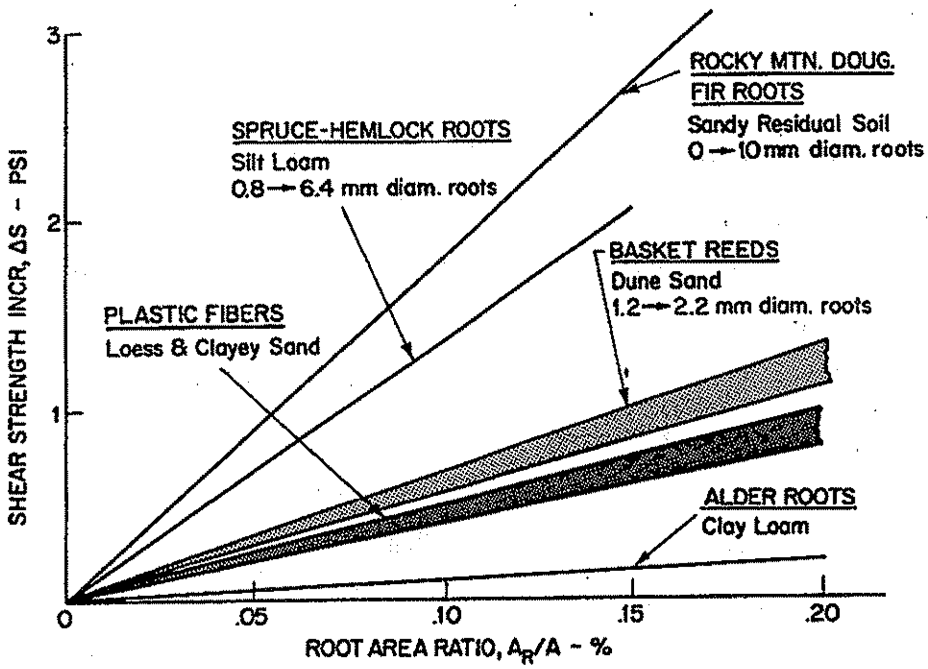
Figure 4-16 (top) illustrates the results of a test in which 1.75mm-diameter reed fibers were added to otherwise unreinforced clean dune sand. The addition of more fibers clearly increases the shear strength of the dune sand over a range of shear strain values. Additional experiments demonstrated that several fiber properties and parameters—e.g., fiber length, length/diameter ratio, tensile strength, skin friction—can all influence the level of increased shear strength.

Figure 4-16 (bottom) illustrates the results of a broad group of root and fiber reinforcement studies that show a general increase in soil shear strength with an increase in total cross-sectional area of roots (i.e., more roots result in greater shear strength). Endo and Tsuruta (1969, in Gray and Leiser, 1982) studying the reinforcing effect of young European alder tree roots on clay loam soils confirmed a similar finding: soil shear strength increased directly with the bulk weight of roots per unit volume of soil. A variety of theoretical root reinforcement models have been developed that help to both explain and predict these relationships (Gray and Leiser, 1982). Clearly, the depth and extent of root branching are important in choosing plants for soil stabilization. Theoretical root reinforcement models indicate that a high concentration of long, flexible roots per unit volume of soil and roots with relatively high tensile strength will maximize soil rooting strength.

Figure 4-17 (left) shows the typical root morphology of a 60-year-old pine tree. The majority of roots, 80 to 90 percent, are laterals, concentrated in the top few feet of soil.



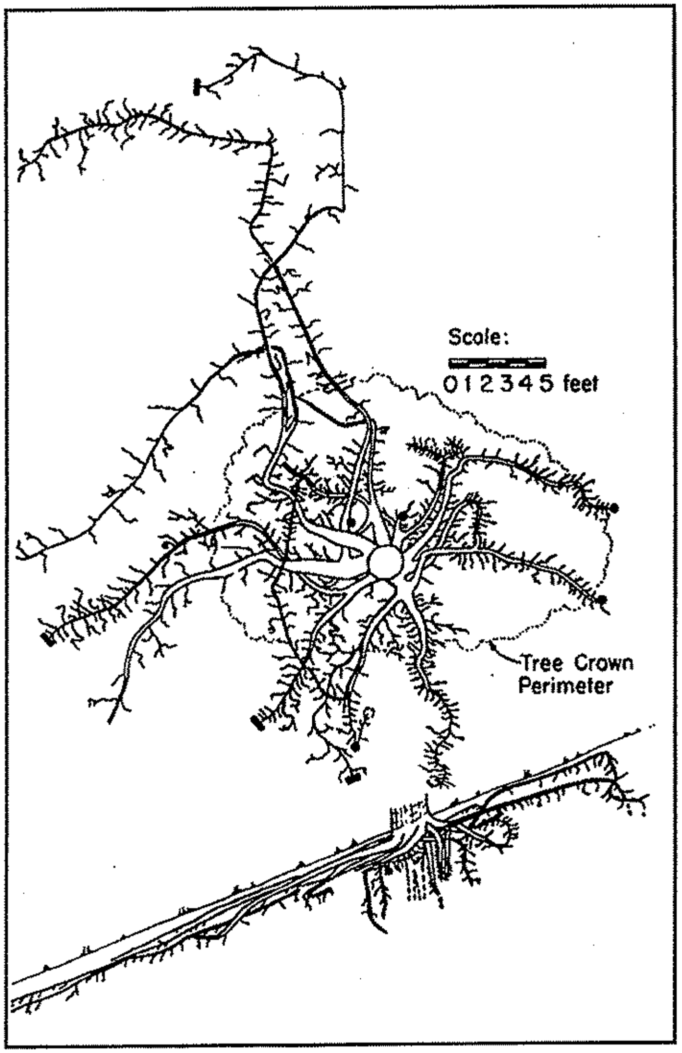
Reed Fibers Increase Shear Strength of Dune Sands



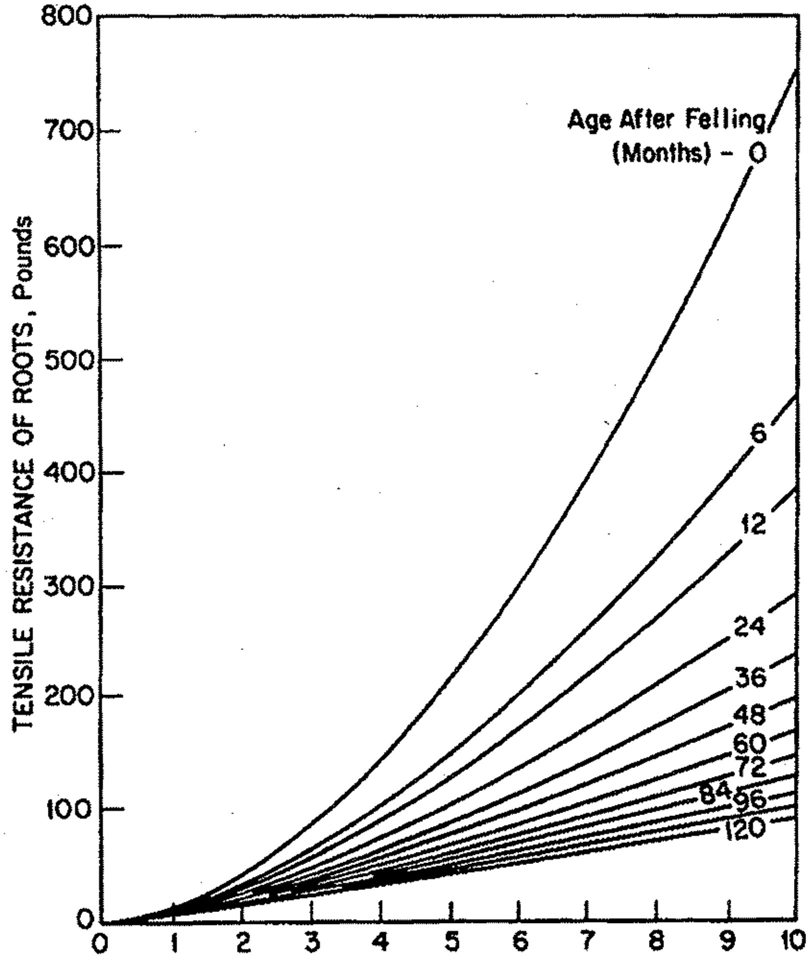
Root or Fiber Reinforcement Increases Soil Shear Strength

Source: Gray and Leiser (1982)

Figure 4-16
Root Reinforcement



Root Structure of 60-year old Ponderosa Pine Tree



Pacific Coast Douglas Fir Tensile Resistance of Roots as Function of Root Size and Age

Source: Curtis (1964), Burroughs and Thomas (1977)

Figure 4-17
Root Structure and Tensile Resistance

Additional downward penetrating central roots and semivertical "sinkers," growing out of the laterals, penetrate deeper substrata and anchor the tree more firmly. The regionally important Douglas fir (*Pseudotsuga menziesii*) exhibits a similar pattern, with vertical roots becoming more pronounced in older trees.

The tensile strength of live roots and the decline in strength of roots with time after cutting have each been extensively investigated (Gray and Reiser, 1982). Several studies indicate that tensile strength decreases with increasing root size for diameters up to 15 mm. Species differences are pronounced: Pacific Coast Douglas fir roots yielded an average tensile strength of 510 kg/cm^2 (2-10 mm root diameter), more than five times the average recorded for Sitka spruce and Western hemlock roots (99 kg/cm^2, 2-6 mm root diameter).

Figure 4-17 (right) illustrates a typical pattern of declining root strength, as a function of root size and age, after a tree is felled. Fir roots lose 50 percent of their strength after one year and five years after felling a 1-cm diameter root has lost 75 percent of its fresh strength. This information, along with the root reinforcement models referenced earlier, has been used to evaluate the impact of cutting woody vegetation on soil shear strength and slope stability over time. While root strength decline after tree cutting is clearly both species and site dependent, several studies suggest a common general pattern. Landslide hazards increase with the loss of root strength and are generally greatest 4 or 5 years after tree removal. The hazard remains high for up to 10 years after removal, but by the end of 20 years is likely to have returned to predisturbance levels.

4.4.4 Soil Moisture Modification

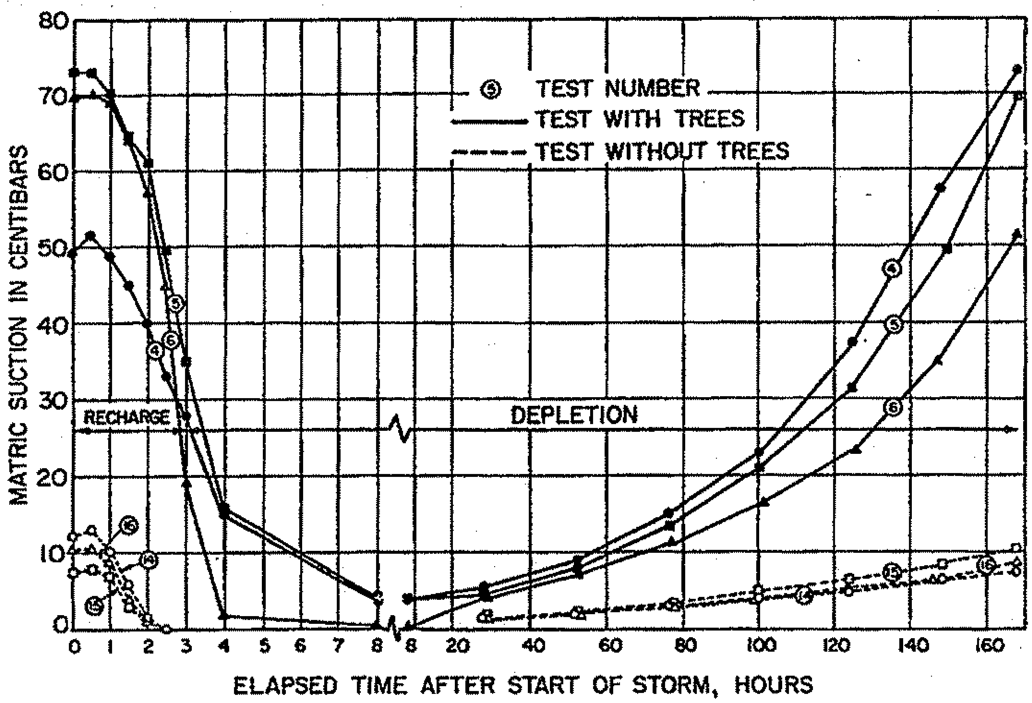
The ability of vegetation and especially trees to deplete soil moisture to considerable depths and develop large moisture deficits in soils is well established (Brenner, 1973; Gray and Leiser, 1982 and included references). Since rates of soil creep and the risk of landslides increase with periods of higher or prolonged soil moisture stress (Tubbs, 1975), the degree to which slope vegetation can reduce soil moisture stress will also reduce the risk of mass movement. **Because rooting depths are limited, the presence of vegetation alone, or its**

potential effects on soil moisture, cannot prevent deeper-seated structural or rotational slides.

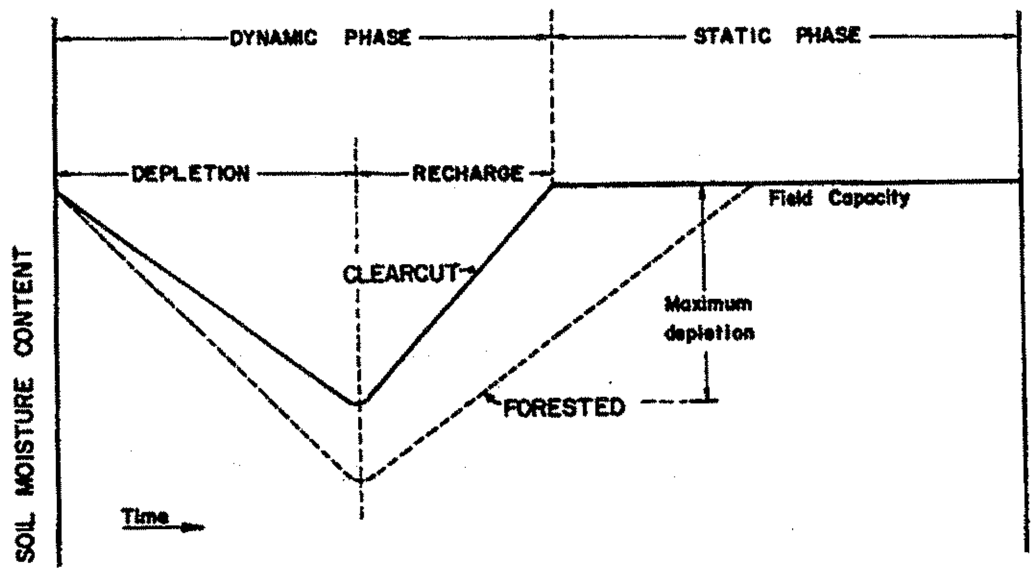
Plants transpire water through their leaves and thus deplete soil moisture. Bluff vegetation can also intercept and adsorb rainfall in the tops of trees and bushes, as well as in the plant litter below. This combination of interception and evapotranspiration tends to maintain drier bluff soils and delay the onset of saturated or waterlogged conditions. Conversely, removal of trees and/or other vegetation from coastal bluff slopes tends to result in wetter soils and faster groundwater recharge times following heavy rains (Figure 4-18, bottom).

Figure 4-18 (top) illustrates typical results from an experimental and modeling study by Brenner (1973), who examined differences in soil moisture patterns between forested and clear-cut slopes. A matric suction value (i.e., tensiometer measurement of suction required to draw water out of the soil) of zero indicates saturated soils. In this example, on a 20-degree slope, soils on the clear-cut slope become saturated (fully recharged) after less than 3 hours of simulated storm rainfall, while at least 8 hours are required to saturate soils on the comparable forested slope. Depletion of soil moisture, reflected by an increase in matric suction, begins on both the clear-cut and forested slopes almost immediately after rainfall ceases. While both slopes return to pre-storm conditions within 170 hours, the degree of moisture removal is five to seven times greater for the forested slope than the clear-cut.

Field studies in clear-cut versus adjacent forested plots in a virgin Douglas fir-Hemlock forest in the Oregon Cascades generally support Brenner's experimental results. Within 3 years of the clear-cut, however, herbs and shrubs invading the cutover site were nearly as effective as old-growth timber in depleting soil moisture (Gray and Leiser, 1982). This confirms the importance of vegetation cover in moderating soil moisture on unstable slopes and also suggests that the first year after cutting is likely to be the most critical for moisture-related (versus root reinforcement) landslide hazards.



Soil Moisture Regime in Forested vs Cut Slope



Forest cover Accelerates Soil Moisture Depletion

Source: Gray and Leiser (1982)

Figure 4-18
Slope Vegetation Influences Hydrologic Regime

Once soils are fully saturated then the significance of vegetation in "holding" a slope becomes one of root reinforcement or buttressing rather than soil moisture control. Under drier conditions, however, the vegetation-related decrease in soil moisture can increase shear resistance, slow soil creep movement, and provide a slope stabilizing influence.

4.4.5 Slope Buttressing

In addition to root reinforcement, firmly anchored, rigid tree trunks growing in slopes provide buttressing and "soil arching" action against shallow slope movement (Gray and Leiser, 1982). Figure 4-19 shows a good example of a tree trunk buttressing an upslope earth mass.

Arching occurs in slopes when the soil attempts to move around or between a row of piles (trees) firmly anchored in an unyielding layer. Under the right circumstances, the trees act as both cantilever piles and abutments to "soil arches" that form in the ground upslope of the trees. Theoretical models incorporating variables such as the spacing and diameter of tree trunks, slope angle and thickness of the yielding soil profile, and soil shear strength properties, have been developed to predict the potential magnitude and effectiveness of such buttressing and soil arching. The "critical distance" between adjacent tree trunks to achieve effective arching is very sensitive to soil cohesion, especially along the basal sliding surface between the surficial soil layer (regolith) and unyielding deeper slope material. Assuming zero soil cohesion, arching might require the critical distance between adjacent tree trunks to be as little as 4 feet, but with even minimal soil cohesion (e.g., 50 psf) this distance could increase to over 20 feet.

The examples outlined above, along with other theoretical and experimental studies, clearly demonstrate that woody vegetation increases the soil shear resistance through root reinforcement, soil moisture depletion, and soil arching. All of these effects can enhance the stability of Puget Sound's coastal bank and bluff slopes. Gray and Leiser (1982) cite additional evidence from numerous studies of forest clear-cuts on watershed slopes in the Oregon western Cascades and elsewhere. Loss of rooting strength and increased soil moisture

Slope buttressing by ponderosa pine, Mendocino National Forest,California
Unbuttressed slope to the left has failed

Source: Gray and Leiser (1982)

Figure 4-19
Slope Buttressing

levels frequently result in a cause-and-effect relationship between tree cutting and slope instability. An analysis of nearly 400 slides (debris-avalanches) from four different forested regions of the Oregon Cascades, the Olympic Peninsula, and the British Columbia Coast Ranges showed a 2- to 4-fold increase in debris-avalanche erosion (as $m^3/km^2/year$) as a direct result of clear-cuts.

4.5 Surface and Groundwater Management

Longterm recession of coastal slopes is ultimately triggered by wave erosion at the toe of the slope; however, a variety of complex "face degradational processes"—sheet or surface wash, seepage effects such as piping and sapping, frost and ice action (solifluction), and weathering—can all influence slope stability above the toe (Figure 5-18); Edil and Vallejo, 1980; Menashe, 1993). Hydrogeologic erosion processes driven by seepage discharge and surface flow often determine the types and rates of slope erosion, especially of the middle and upper portions of coastal bluffs (Wilcock, Miller and Kerhin, 1992).

Raindrop erosion loosens soil particles which are carried downslope in surface flow. Topographic features such as ditches and swales concentrate sheet flow into rills and gullies which experience accelerated rates of soil erosion and transport downslope. As water moves faster down steeper slopes, its erosive capacity also increases (Menashe, 1993). As noted in Section 4.4, the presence of vegetation modifies surface runoff and erosion effects.

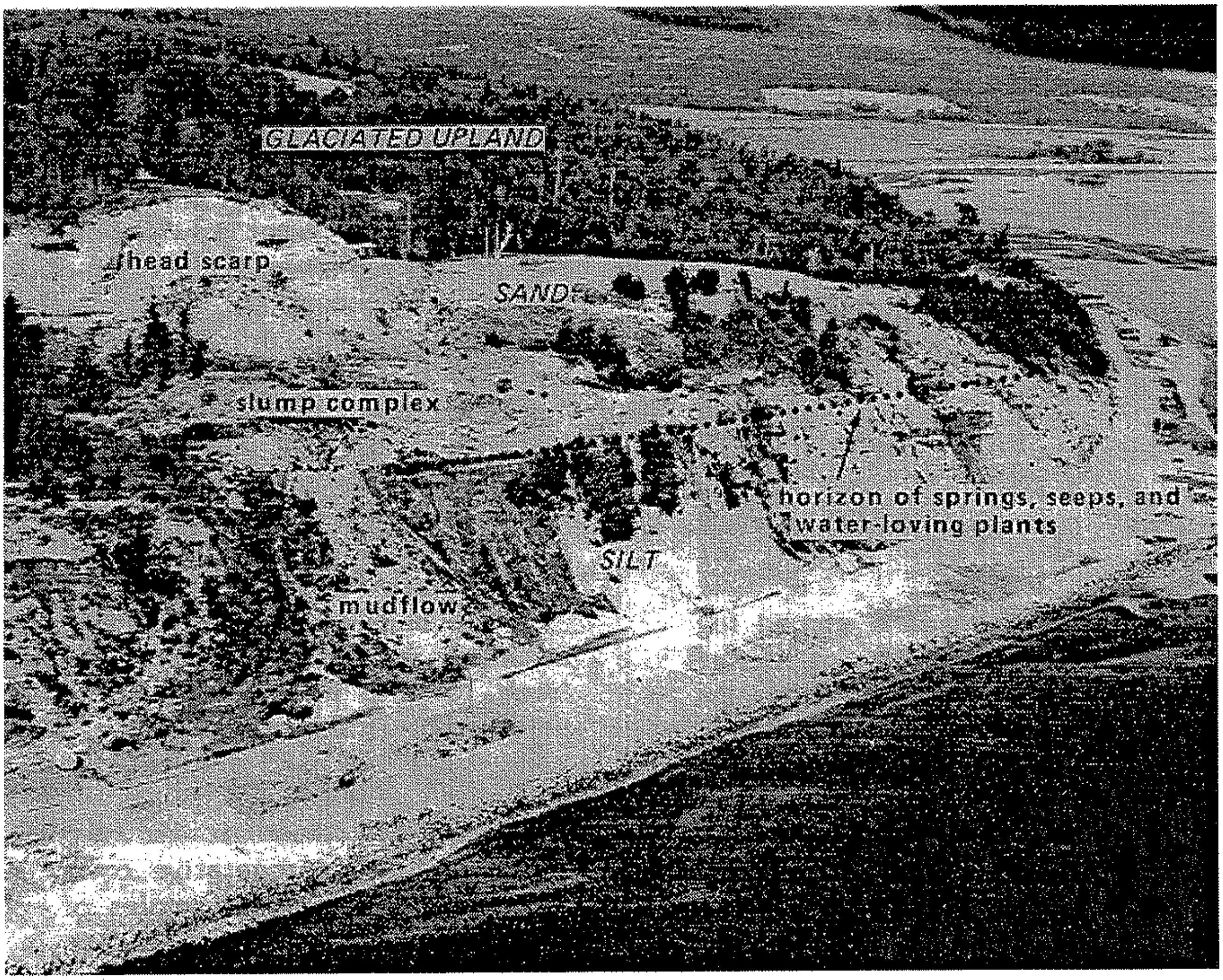
Groundwater moving through a bank or bluff may reflect local rainfall percolating through surficial layers of sands and gravels. Alternatively, the groundwater may have originated some distance away and moved laterally towards the bluff face—usually within a sandy horizon overlying an impervious till or clay layer.

Groundwater discharge from seeps and springs within the bluff face undermines overlying materials, as well as eroding the soils downslope. Increased soil saturation and pore water pressures reduce the strength of bluff sediments and increase the likelihood of landslides (Gray and Leiser, 1982; Menashe, 1993).

Seepage zones are marked by saturated sediments. Clays are maintained in a moist, plastic state, while sands are prone to piping and sapping which removes the sand and creates gaps which eventually collapse. Water oozing from the seepage zones undercuts overlying material and carries sediment and debris downslope via gullies. These gullies typically widen downward. Stormwater runoff also washes over the bluff face—especially in the absence of vegetation cover—carrying weathered loose debris to the beach below (Wilcock, Miller, and Kershin, 1993).

No quantitative studies of bluff-face degradation processes or erosion rates have been found for Puget Sound locations. Wilcock, Miller and Kershin (1992, 1993, and included references) provide an excellent example of such a study for Calvert County bluffs, that border the Maryland shore of Chesapeake Bay. They relate bluff-face erosion rates to specific erosion mechanisms, local stratigraphic/sedimentary characteristics, and the groundwater regime (monitored with piezometer records) at each of their study sites.
Many of the landslides in the Puget Sound area occur in the spring after an intense rainfall. During the spring, unlike in the fall, the ground is saturated from previous winter rainstorms, and the additional moisture builds up high groundwater pressures that contribute to slope failure. The high water levels not only load the slope with the additional weight of water, the increased pore water pressure reduces the strength of the material. Control of both surface and groundwater is thus essential in attempting to minimize impacts on the slope (Figure 4-20).

Tubbs' (1975, and included references) studies of Seattle landslides provide additional insights into the role of rainfall and groundwater in triggering both slumps and debris slides on coastal banks and bluffs (also see Sections 4.1 and 4.3). Tubbs noted the rapidity with which both slumps and debris slides responded to rainfall, suggesting that the slides were related to changes in pore water pressures within a few feet of the ground surface. He concluded that many of the slumps involved "retrogressive failure" triggered by debris slides, or by localized failures near the contact between an overlying permeable unit (e.g., Esperance Sand, Figure 4-12) and underlying impermeable unit (e.g., Lawton Clay), where a local rise in the watertable can be expected immediately following heavy rains.



South Whidbey Island. Rain readily infiltrates sandy upland until downward movement is impeded by impermeable silt layer. Saturated zone above silt interface (marked by seeps and water-loving plants) causes slumps and flows in overlying sands.

Source: Thorsen (1987)

Figure 4-20

Surface and Groundwater Flow Influence Bluff Stability

Extensive analysis of daily rainfall records and landsliding in the Seattle area for the period 1932 to 1972 (Tubbs 1975) revealed several significant positive correlations. The correlation coefficients (r) are highest for the relationships involving daily total ($r=0.95$), and two-day total (Figure 4-21, $r=0.97$) rainfall amounts (both significant at $P<0.01$ level). Slope failure and landsliding in Seattle thus appears to be commonly triggered by relatively short periods of intense rainfall (i.e., over 2 inches per day, or two successive days with over 1 inch)—a model that presumably also extends to shoreline bluffs throughout much of Puget Sound.

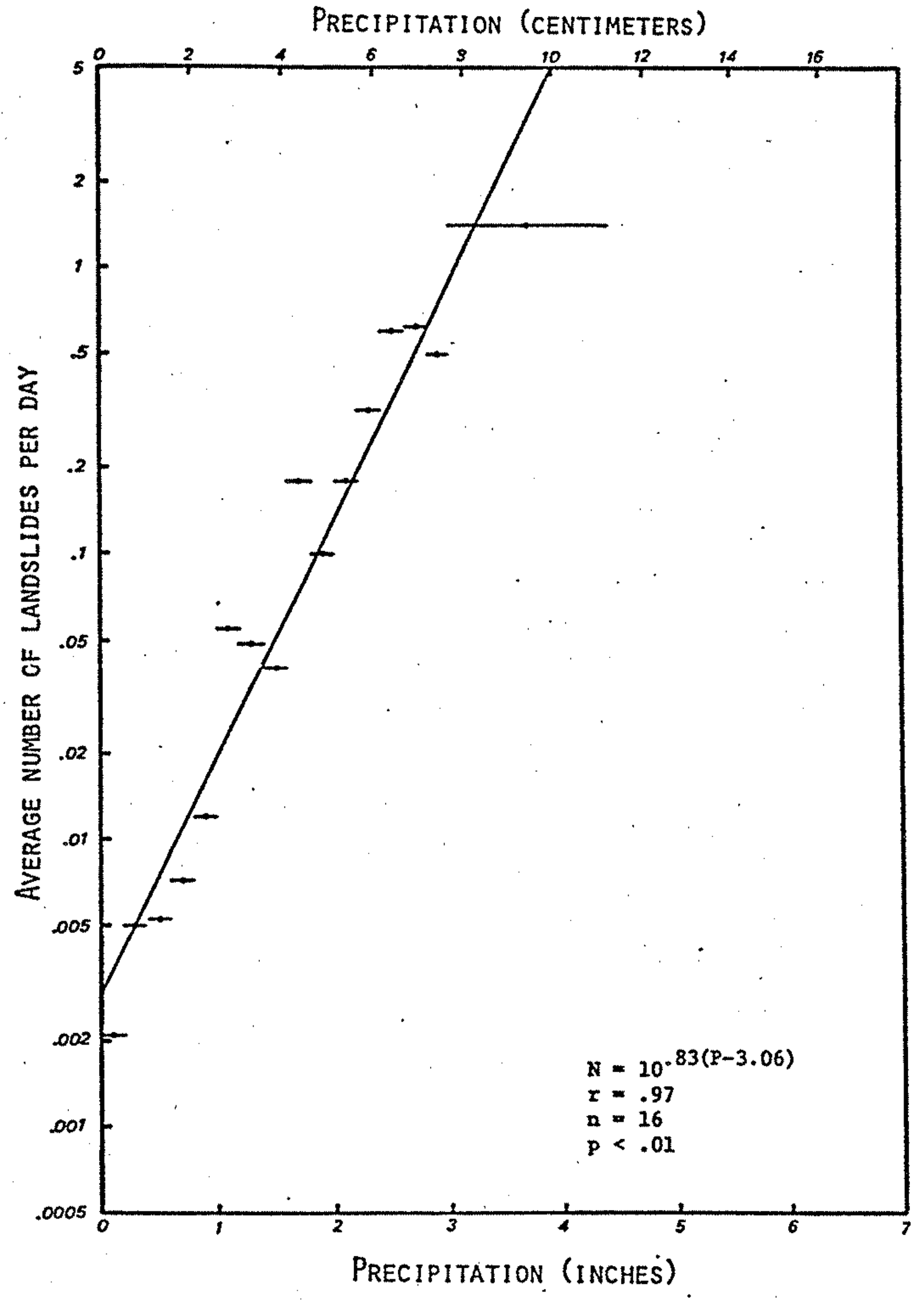
Tubbs demonstrated that landsliding on Seattle slopes typically involves failure of a relatively thin regolith—often just a few feet of weathered, surficial material. Since failure clearly relates to soil saturation of the potential slide mass, it is reasonable to expect a thin regolith to be significantly affected by short periods of intense rainfall.

Additional analyses suggest that neither longer-term cumulative rainfall amounts (i.e., up to 5 days prior to a slide), nor freeze-thaw effects are important factors affecting landsliding in the Seattle area.

4.6 Human Disturbance

Vegetation Management: A Guide for Puget Sound Bluff Property Owners (Menashe, 1993) begins with a daunting scenario of bluff development. The bluff top is cleared and graded, trees are cut to open up the view, and debris pushed over the bluff edge. The home is sited close to the bluff crest to take full advantage of the view. Utility trenches, roof and footing drains, and a septic system are all installed. Grading activities and construction traffic compact the upland soil, reducing its porosity and causing new topsoil to be brought in for landscaping. A stairway is constructed to the beach causing more vegetation to be cleared from the bluff face.

Each of these human disturbances to the natural bluff setting creates or aggravates a potential destabilizing factor that will affect longer-term slope stability. Vegetation clearing



Source: Tubbs (1975)

Figure 4-21
Seattle Landslides as a Function of Two-Day Precipation, 1932-72

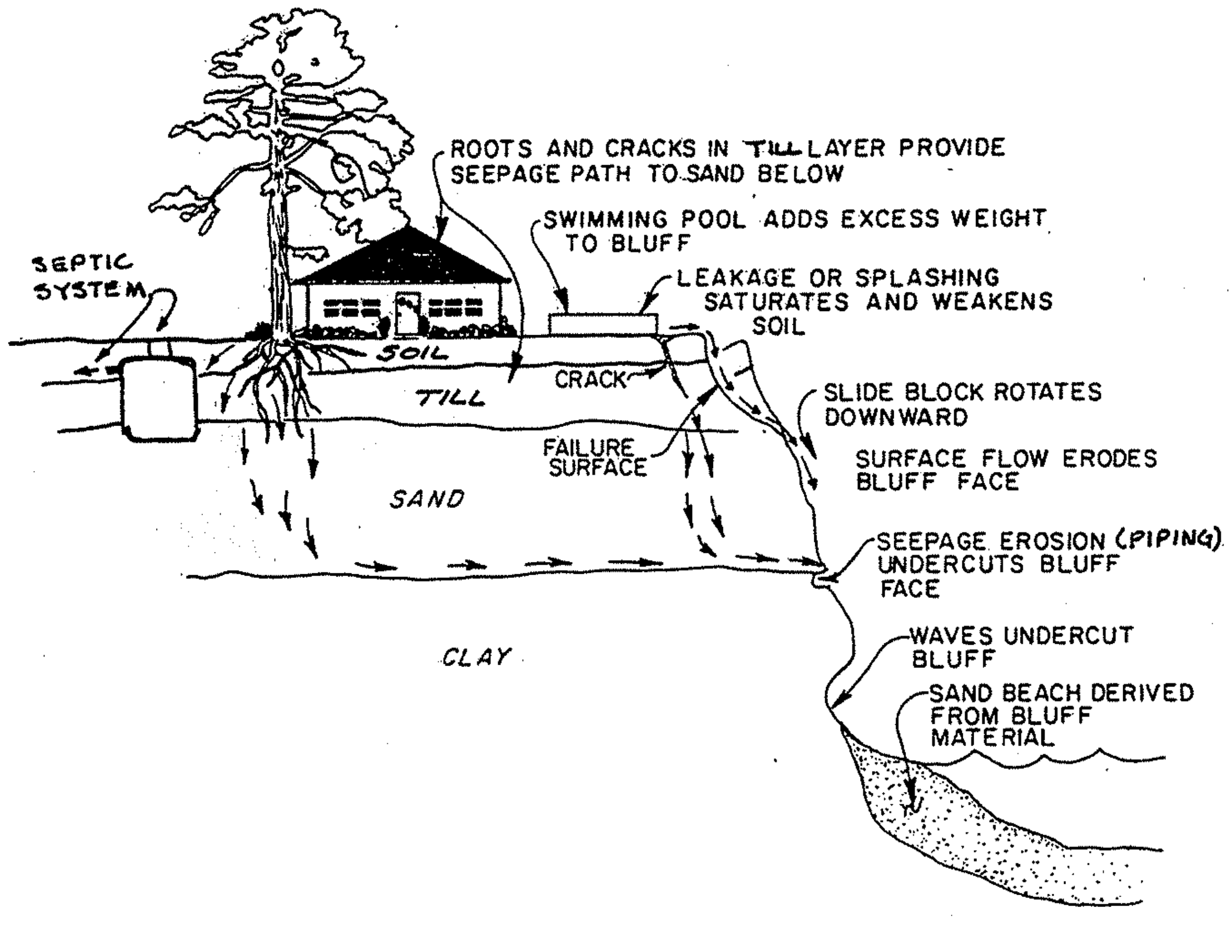
eliminates the soil binding action of plant roots. Soil compaction, trenching, and the addition of a septic system, all have the potential to alter surface water runoff and groundwater relationships. The addition of a home and new topsoil each increase the load at the top of the bluff slope. Not surprisingly, this all adds up to a recipe for increased slope erosion, soil slumping, and the potential for a serious landslide.

Figure 4-22 diagrams many of the ways in which bluff top construction can directly and indirectly influence surface and groundwater movements in coastal bluffs—as well as some other causes of bluff instability. Figure 4-23 illustrates some homeowner "solutions" to typical shoreline bluff instability concerns. Clearly, considerable time and resources have gone into protecting the homeowner's investment in shoreline property. Note, however, that property protection has been achieved at the cost of disrupting many of the "landscape linkages"—those natural processes that unite upland and offshore habitats—across the shore zone. Bluff sediments can no longer reach the beach; potential fluxes of groundwater, nutrients, and organic matter (leaf fall, LOD, insect "fallout") have all been disrupted; and with time, the beach fronting the seawall can be expected to become lower and coarser-grained (see Section 4.2; Macdonald et al., 1993; Thom et al., 1994).

Tubbs (1975) examined the role of "human factors" in his studies of Seattle area landslides. One or more of the human factors noted below may have contributed to landsliding at over 80 percent of the 47 sites he examined:

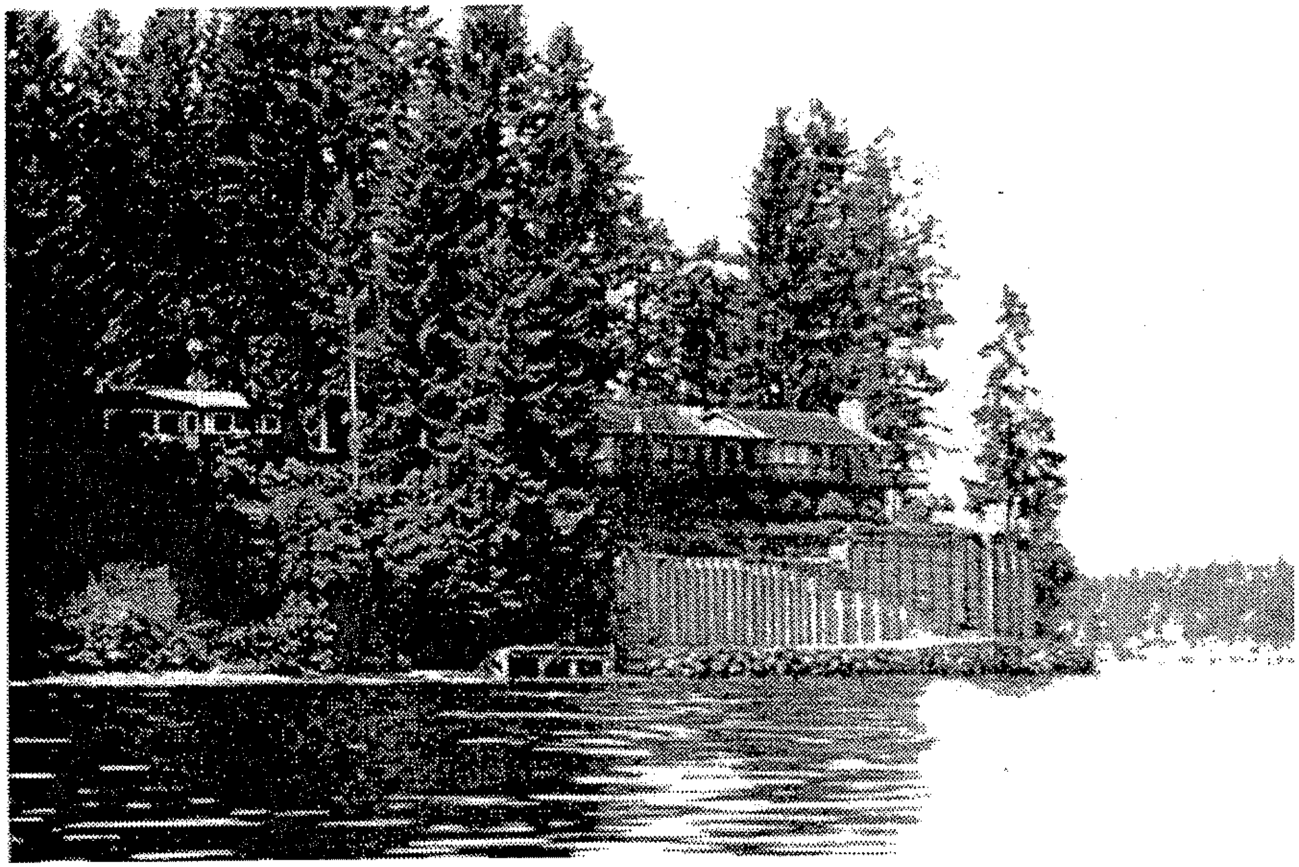
- Diversion of water onto slope—18 debris slides/3 slumps
- Steepening of slope by excavation—12 debris slides/8 slumps
- Placing of fill—13 debris slides/2 slumps
- Failure of retaining wall—4 debris slides/1 slump
- One or more of the above—29 debris slides/10 slumps

Tubbs confirms that diversion of water onto (and into) a slope was the most common contributing factor to landsliding, and was noted at over 40 percent of the 47 slide sites examined. The water source was typically runoff from roofs and paved areas. Unnaturally



Source: ACOE (1981), Canning (1991)

Figure 4-22
Development Practices Influence Bluff Stability



Fox Island, Pierce County. Tide approximately Mean High Water.Note contrast between the structurally modified shoreline (vertical rock bulkhead, plank/pile retaining wall) and adjacent more natural shoreline. The exposed, eroding bank to the left faces Mt. Rainier and correlates with major vegetation clearing.

Photo: Hugh Shipman

Figure 4-23
Bluff Impacts From Development Practices

steep excavated slopes were also noted at 40 percent of the slide sites. Over 30 percent of the landslides occurred at sites where fill had been placed on a slope, often a slope underlain by an impermeable substrate. The impacts of each of these "human factors" generally confirms the importance of topography, local stratigraphy, and rainfall in determining the occurrence of landslides. Interestingly, Tubbs' studies do not address the potentially protective role of vegetation cover in landsliding.

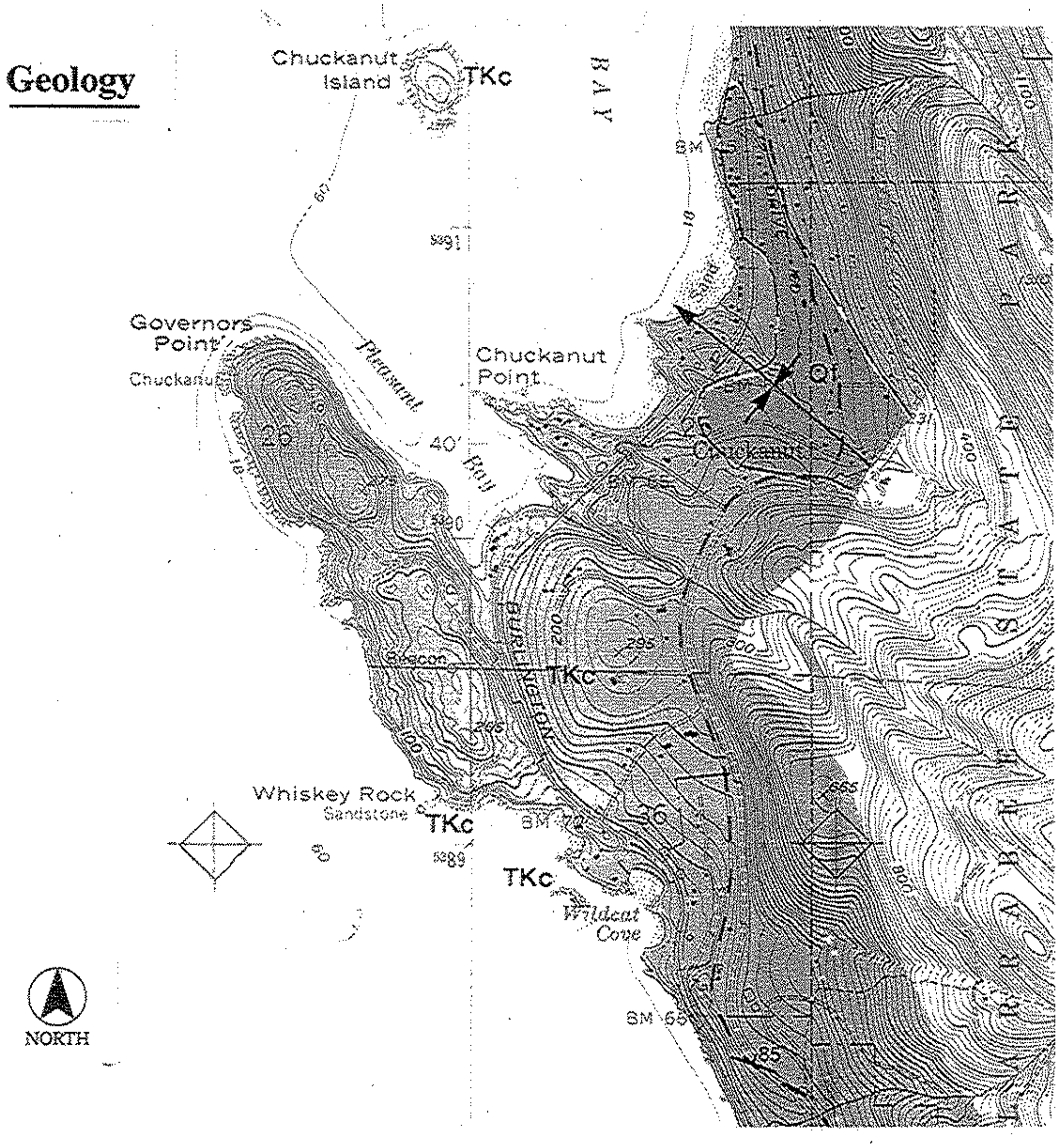
Narrative on the seacliffs of Whatcom and Skagit County (Coastal Zone Atlas Vol. 3, 1978) quoted in Section 3.2 again emphasizes the role of human disturbance on landsliding, noting that, "... many of the sites of these landslides had associated with them some type of artificial drain. Typically the opening of a drainpipe coincided with the head of a landslide."

Loads placed at the top of the slope increase the driving forces which increase the potential for landsliding. These loads can take the form of debris from grading and clearing placed at the edge of the slope or fill used for grading to construct a level pad for construction. In addition, an increase of water levels resulting from modifying the drainage patterns in an area, an increase of watering for irrigation, or installation of a septic system also function to load the top of the slope. What may appear to be a minor grading change over an area can have significant effects on the slope. Generally, Puget Sound counties monitor this by requiring a grading permit which may include a drainage and erosion control plan and/or a geotechnical/geologic report in areas having unstable slopes where grading is required (Gabriel, 1988).

Whatcom County–Chuckanut Bay

The following discussion is taken from information presented in the Coastal Zone Atlas of Washington (Volume 1, 1977). The purpose of the fact sheet is to illustrate examples of local geology and their influence on bluff stability.

The geologic unit mapped in the highlighted section of Whatcom County is part of the Chuckanut Formation, denoted by the symbol TKc. This unit is a sedimentary rock unit consisting of interbedded sandstone, conglomerate, shale and coal. In this area, the rock units which make up this formation are not horizontally bedded, but have been folded. The orientation of the bedding is shown on the map by a long line with a short hatched line in the middle where a number is located. This number indicates the angle which the rock unit dips from the horizontal. (An example of this is present just north of the Whatcom-Skagit County line on the geologic map.) Near the town of Chuckanut, the rocks have been folded towards each other into a syncline, the axis of which is noted on the map by a long arrow. The orientation of the bedding with regards to the axis of the fold is shown by the shorter arrows. A thin layer of undifferentiated glacial drift, denoted by the symbol Qf, overlies the bedrock in this area.



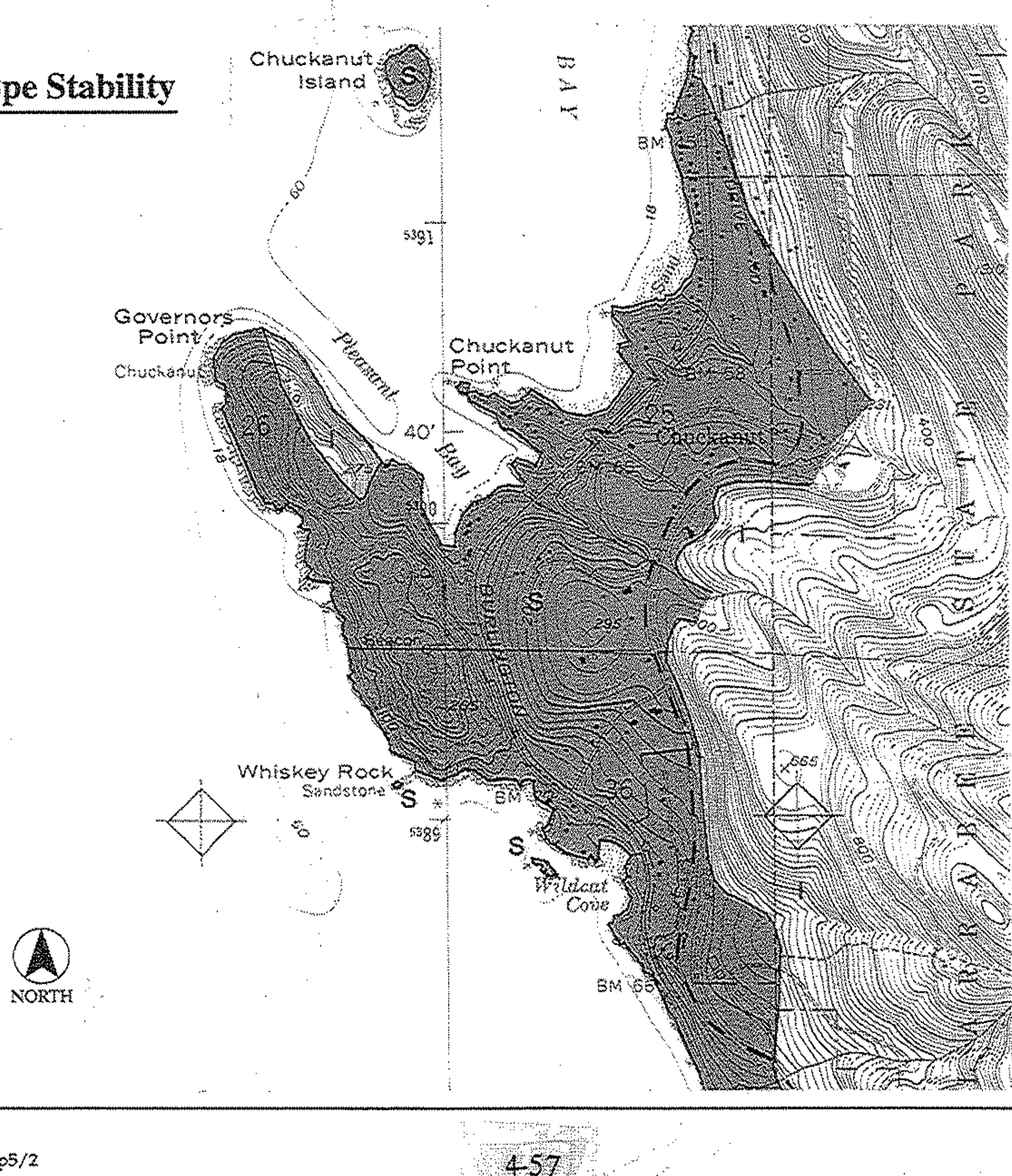
10028900p.wp5/1
5/2/94

The slopes in the area highlighted have been classified as either stable (S) or intermediate (I). Stable slopes denote areas of competent bedrock with slopes less than 15 percent. Intermediate slopes are those areas that are generally steeper than 15 percent–except where conditions conducive to ground failure exist, such as high groundwater or weak soils. No known failures exist in these areas.

It appears the majority of the slopes in this area have been classified as stable because of the dip of the bedrock units. The units are dipping to the northeast, west of the syncline axis, and to the southwest, east of the syncline axis. This orientation is favorable with respect to the exposed coastal bluffs at most locations as the rock dips *into* the hillside instead of towards the exposed bluff. At the northeast end of Governors Point and the northern portion of Chuckanut Drive, the rock exposed in the bluff dips *toward* the water, which if disturbed could result in rock slides, although none have been documented to date.

No indication is given with regards to the thickness of the glacial drift on top of the Chuckanut Formation. It is likely a thin deposit, as its lateral extent is limited. It has not negatively impacted the stability of the deposits in this area as it is located on gently sloping terrain.

Slope Stability

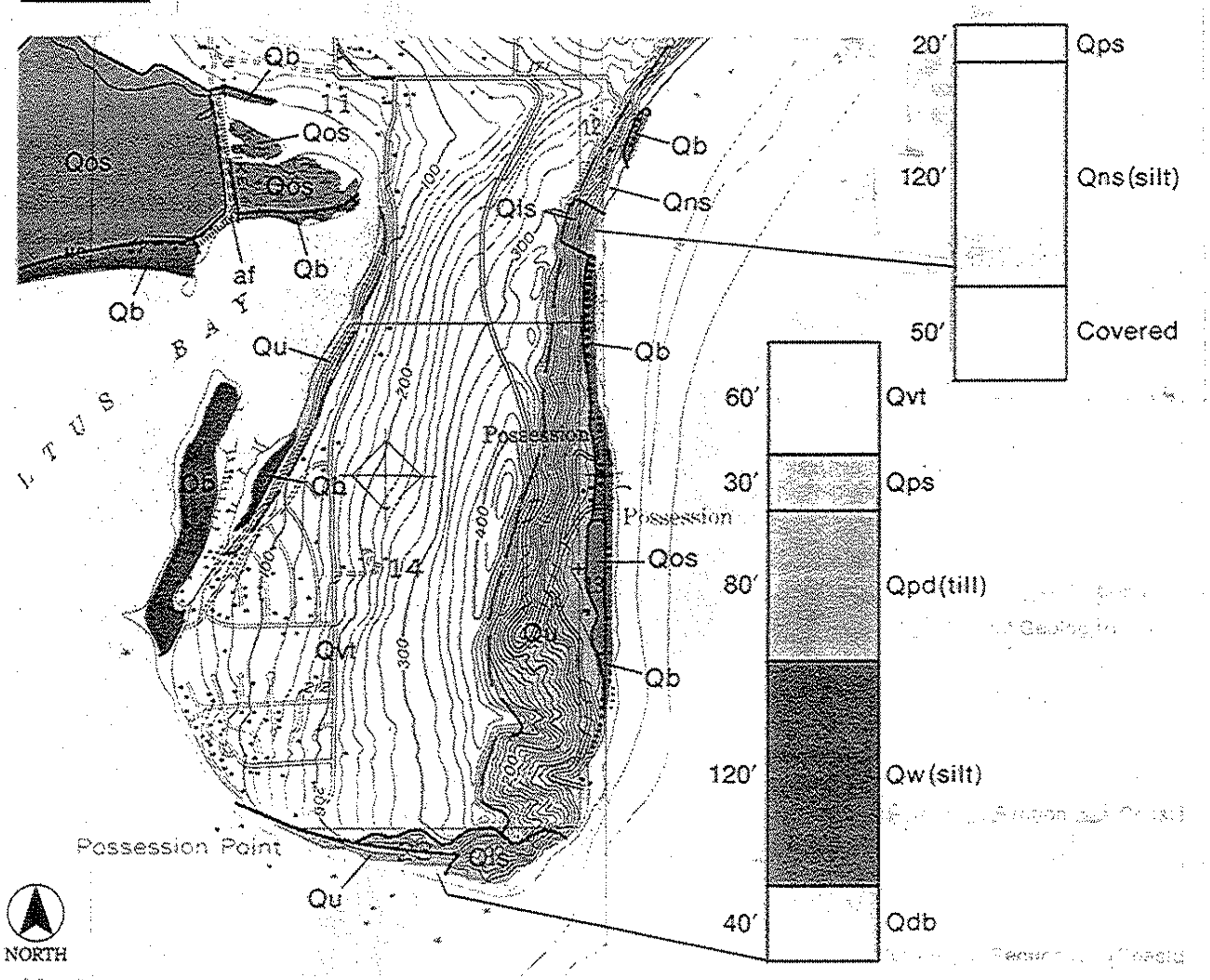


Island County–Possession Point, South Whidbey Island

The following discussion is taken from information presented in the Coastal Zone Atlas of Washington (Volume 4, 1979). The purpose of the fact sheet is to illustrate examples of local geology and their influence on bluff stability.

The geologic units mapped in the highlighted section of Island County are a series of glacial deposits. The enlarged stratigraphic section at Possession Point includes units that are mapped in detail at what geologists refer to as "type sections". Type sections represent those areas which illustrate the features of a geologic unit that are used to describe it for all future reference. These are of interest to a geologist, because the soil type indicates what type of events occurred during the deposition of the units and a more accurate geologic history can be drawn from their study. This section is unique in the region because it is the only example that exposes glacial deposits representing three separate glacial advances. For the purpose of this study, the Possession Drift, (Qpd), the Whidbey Formation, (Qw), and the Double Bluff Drift, (Qdb), are units that were deposited prior to the Fraser Glaciation (see Table 1 in text). The two drift units consist primarily of till. The Whidbey Formation is a fine grained lake deposit that correlates with the silt deposit shown (Qns) in the stratigraphic section to the north of Possession. Above these till units is a sand deposit (Qps) overlain by the Vashon till (Qvt). Because of difficulties correlating stratigraphic units, the surficial geologic mapping of the area has grouped all the geologic units exposed along the coastal bluff as "undifferentiated glacial and nonglacial deposits (Qu)," separated by landslide areas (Qls). The flat-lying areas on the coast are underlain by recent

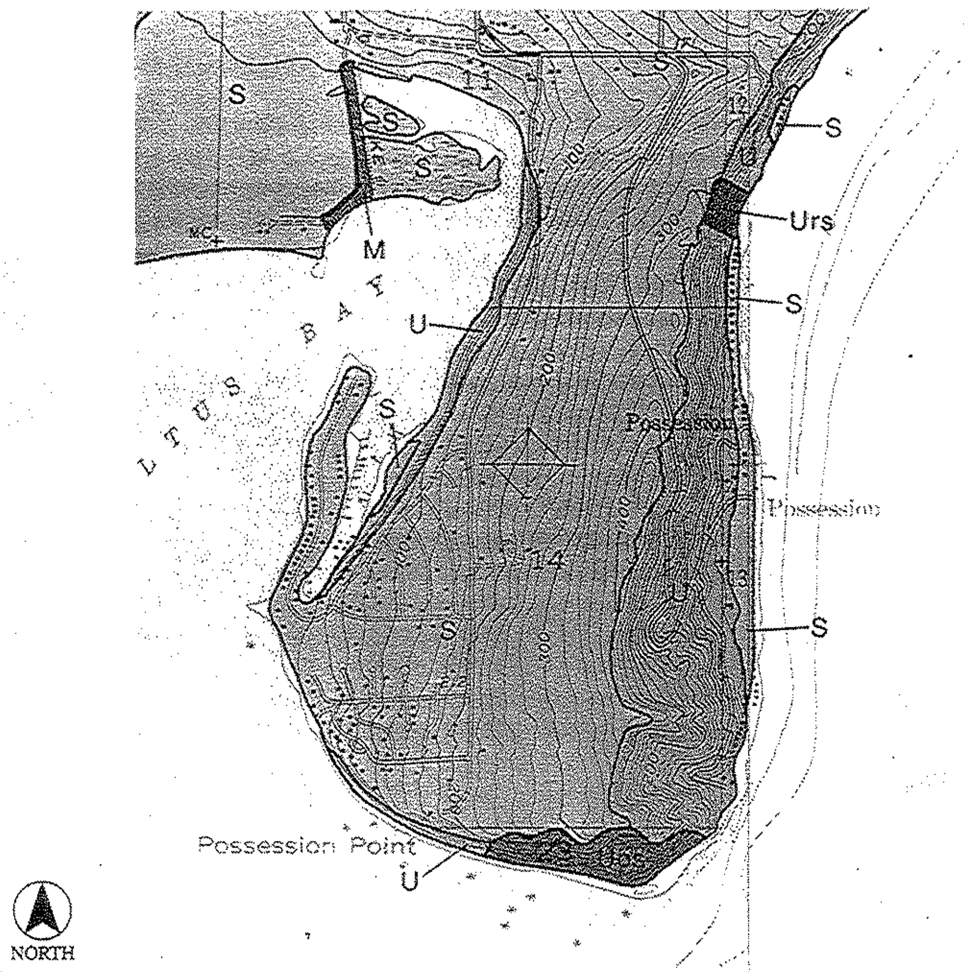
Geology



beach deposits (Qb) and swamp or marsh deposits (Qos). The majority of the upland area is underlain by Vashon till (Qvt). The slopes in this area are primarily classified as unstable, with mapped areas of unstable recent (Urs) and old (Uos) landslides. The stable areas that are mapped on the coast are the flat-lying beach sand deposits and the swamp and marsh deposits. Since these areas are bordered by unstable slopes, this classification can create a false sense of security, as failure of the upper slope can affect the safety of these flat-lying deposits for any development. The gently sloping upland area underlain by the Vashon till is also mapped as stable.

Although no information is provided regarding water levels in the slopes, the geologic stratigraphy present at this location is conducive to unstable slopes. This includes interbedded fine grained and course grained deposits where high water levels can accumulate. In this South Whidbey Island location, a permeable sand unit (Qps) overlies either an impermeable till (Qpd) or a silt (Qns), providing a location where water can saturate and accumulate, resulting in a layer of weakness where slumping can occur. Sand interbeds with high water levels may also be present within the Possession Drift (Qpd) and the Double Bluff Drift (Qdb). These units are also separated by an impermeable unit, the Whidbey Formation (Qw) which can also serve as contact for the failure of the slope. In addition, because of the steep slopes present in this location, it is likely that wave erosion at the toe of the bluffs also contributes to the instability of the east slopes.

Slope Stability

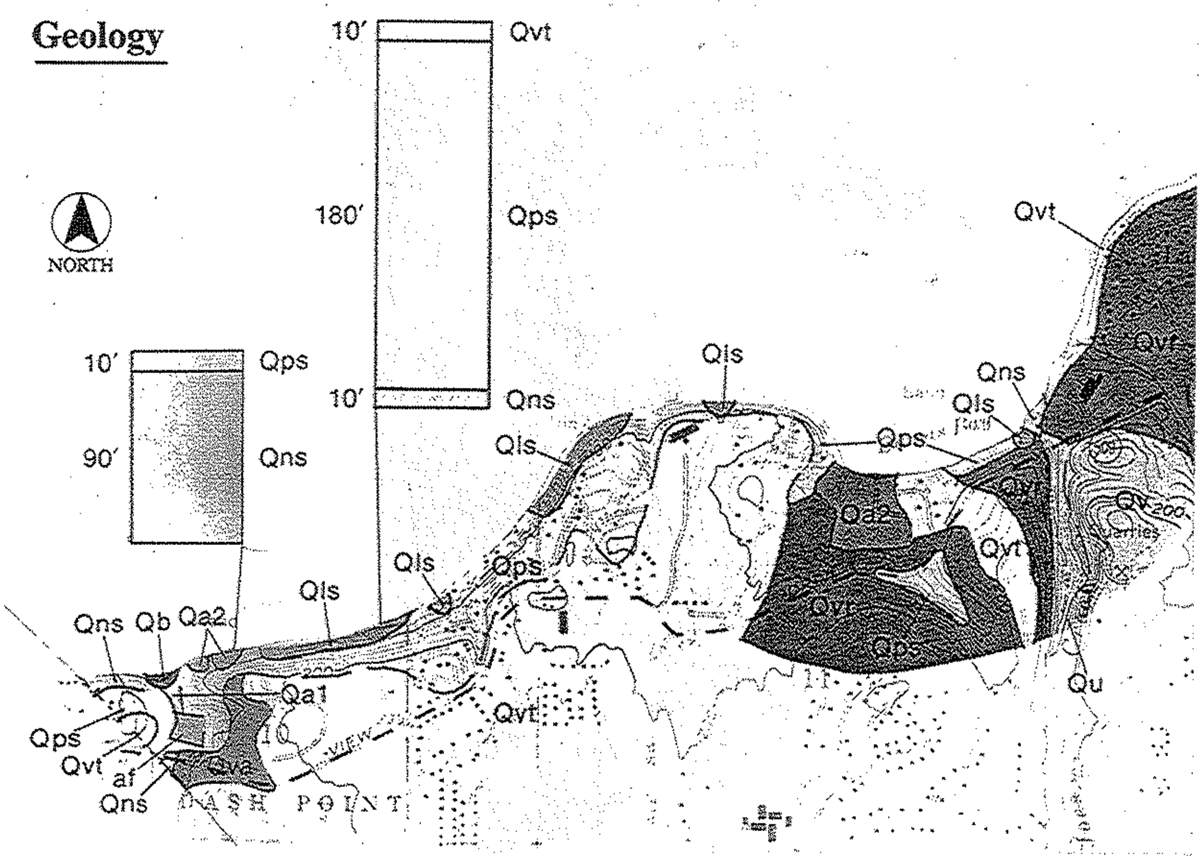


South King County–Dash Point

The following discussion is taken from information presented in the Coastal Zone Atlas of Washington (Volume 6, 1979). The purpose of the fact sheet is to illustrate examples of local geology and their influence on bluff stability.

The highlighted section includes typical glacial deposits exposed in coastal bluffs–advance outwash, lake, and till deposits. The upland area is covered with Vashon till (Qvt), the thickness of which tapers off to the south. Two stratigraphic sections are presented. It would appear initially that different geologic units are present within close proximity to each other on the bluff. In the western section, ten feet of an advance outwash sand (Qps) is mapped over a greater thickness of a fine grained lake deposit (Qns). No till is mapped in this section because the till has likely been eroded by alluvial deposits (Qa1 and Qa2) which have been mapped locally in the area. In the section to the east, a substantial thickness of the outwash sand (Qps) is present above a thin layer of the lake deposit (Qns), with the total section being capped by a thin layer of till (Qvt). This apparent anomaly in material types between two locations can occur when the deposits were originally laid down on a sloping or an erosional contact, and not horizontally bedded as one initially assumes. Landslides (Qls) have been mapped along the slope and represent both recent and ancient landslides.

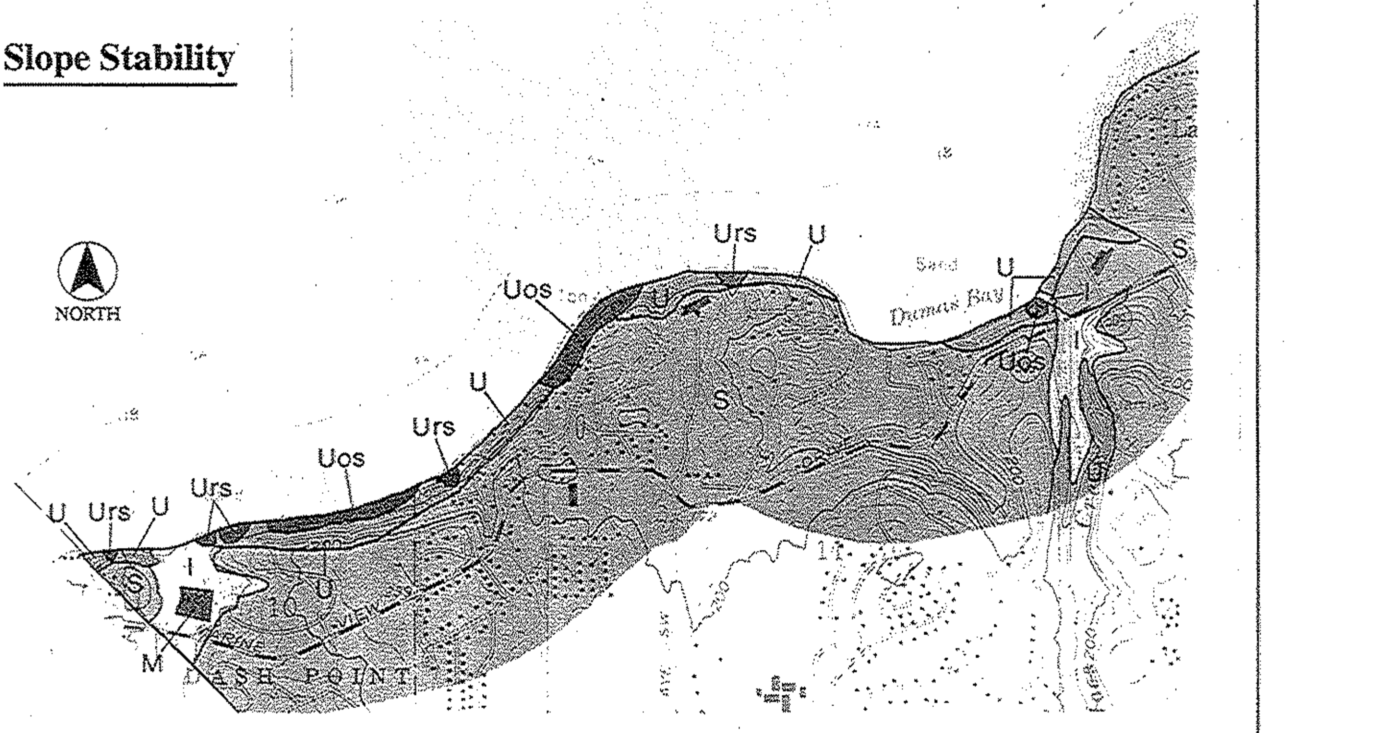
The slopes in this area vary from stable to unstable. As one would suspect, the gently sloping upland area underlain by till is considered stable (S). An



intermediate (I) classification is given to the area at the far western portion of the section. Intermediate slopes are those that are generally steeper than 15 percent, except where conditions conducive to ground failure exist–such as high groundwater or a susceptible stratigraphy. Geologic mapping suggests this area is underlain by a thin section of outwash sand, which in turn is underlain by a fine grained lake deposit. This is a situation where slope failures can occur–especially if the units become saturated. No known failures have occurred in areas which have the intermediate classification. The small section of land classified as modified (M) represents an area impacted by filling or grading. The entire coastal slope, with the exception of the small portion rated as intermediate, has been classified as unstable. Both recent (Urs) and ancient (Uos) landslides are present in this area.

Ancient failures have likely occurred as a result of the steep slopes, in conjunction with glacial stratigraphy, which includes interbedded permeable (advance outwash) and impermeable (till and lakebed) deposits. High groundwater levels present in the past would also contribute to these ancient slope failures. Recent landslides reflect continuation of this process in some areas, and may represent re-activation of the ancient landslides. Re-activation may have resulted from home and road construction, with the accompanying increase in water levels from disturbance of surface drainage, septic systems and increased lawn watering.

Slope Stability



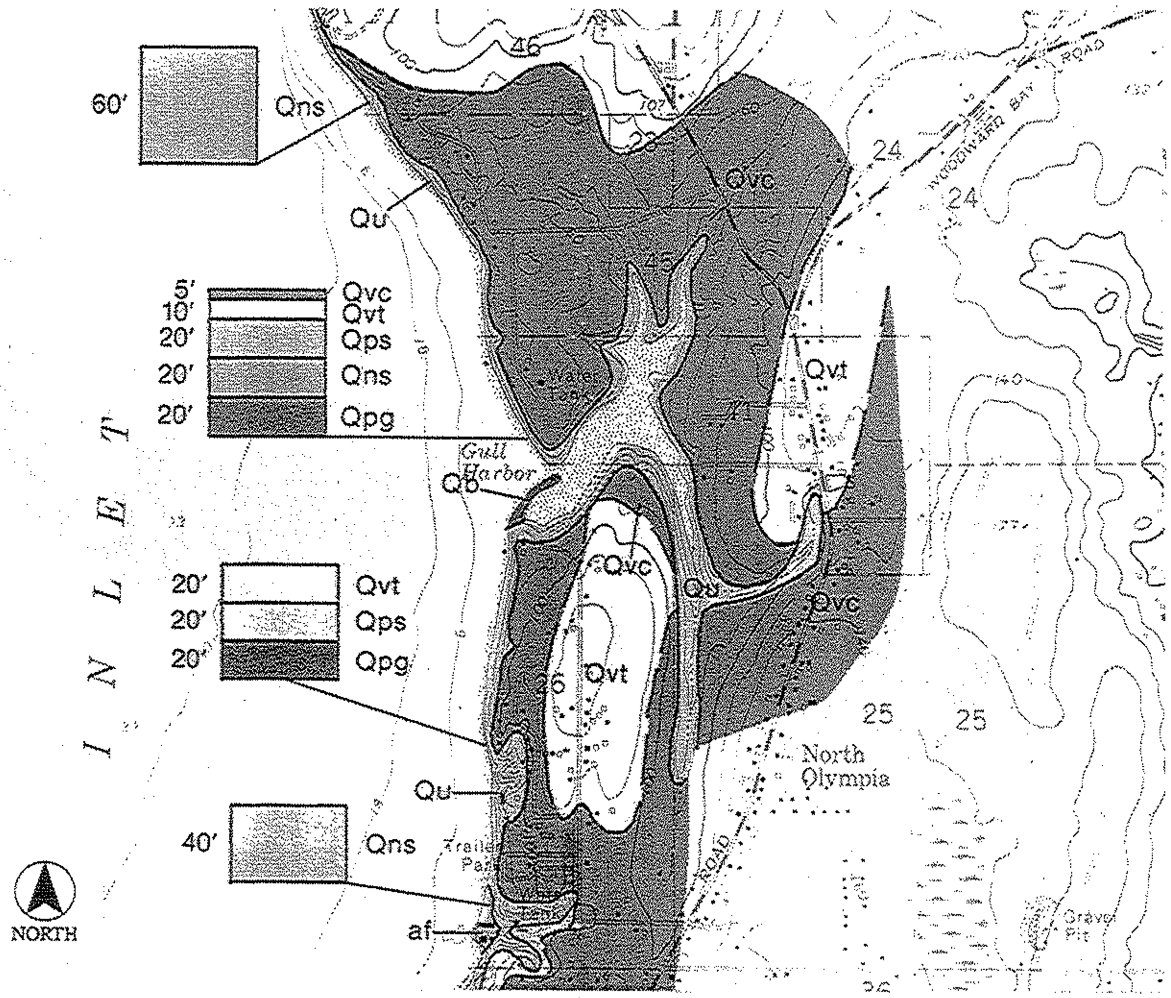
Thurston County–Gull Harbor, Budd Inlet

The following discussion is taken from information presented in the Coastal Zone Atlas of Washington (Volume 8, 1980). The purpose of the fact sheet is to illustrate examples of local geology and their influence on bluff stability.

The glacial deposits present on the east shore of Budd Inlet consist of glacial till, advance outwash and recessional lake deposits. The surficial mapping of the area shows Vashon till (Qvt) to be present at the surface at the higher elevations in the upland area. At the lower elevations in the upland area, yet above the till stratigraphically (younger) is a recessional lake deposit (Qvc) which covers the remainder of the upland area. In other words, this lake deposit cover much of the surface of the till, with portions of the till above the level of deposition. The remainder of the deposits have been mapped as undifferentiated glacial and interglacial deposits (Qu), a general term used when the existing stratigraphy is unknown or too complicated to delineate on the scale of map used.

Four stratigraphic sections are shown in the highlighted area. The sections to the far north and the far south show the unit present to consist of pre-glacial lake deposits (Qns)–typically, fine grained, impermeable silt and clay. The two center sections show the diversity which often occurs within glacial deposits. The second section to the north extend to the top of the slope and includes recessional lake deposits (Qvc) and till (Qvt) in the upper portion of the section. In the next section to the south, the recessional lake deposits are not present and may have been eroded away or not deposited in this location. Below the till in each of the sections is

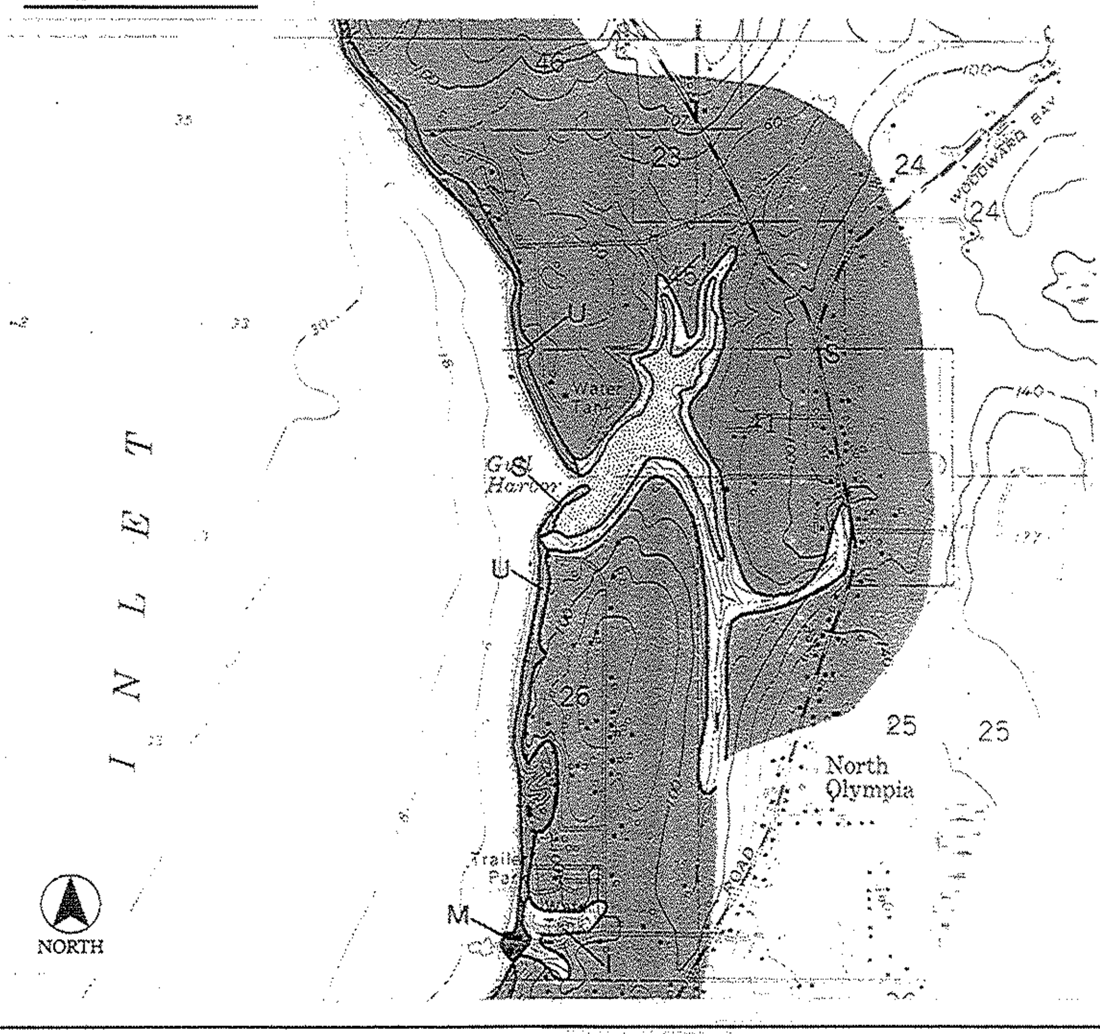
Geology



a series of glacial outwash (Qps, primarily sand and Qpg, primarily gravel) and lake deposits (Qns). The lake deposit is present only in the section to the north and lies between the gravel and the sand. This likely reflects a dynamic ice front which locally has impounded lake sediments–or alternatively, these lake sediments may have been eroded away in the more southern location. The slack water deposits which are present in Gull Harbor may be a remnant of this lake.

The slopes in this area vary from stable to unstable. The stable (S) classifications include the gently sloping upland areas underlain by till and the recessional lake deposits, which are stable because of the gentle topography. The intermediate (I) areas include the side slopes along the drainage into Gull Harbor and the incised drainage area at the south end of the section. Intermediate slopes are those that are generally steeper than 15 percent, except where conditions conducive to ground failure exist–such as high groundwater or a susceptible stratigraphy. From the existing stratigraphic sections discussed above, one could infer that there is likely interbedded permeable and impermeable units present in the undifferentiated unit (Qu) mapped. In addition, since this is a drainage area, high water levels are likely to be present, and may contribute to the possibility of slope failure. No known failures have occurred in areas having the intermediate classification. The remainder of the slopes bordering the water are classified unstable (U). This classification likely results from the steep slopes, wave erosion, and interbedded permeable and impermeable geologic units.

Slope Stability



10028900p.wp5/8
5/2/94

5.0 Managing Unstable Shoreline Slopes

5.1 General Approach

This section presents a broad array of different approaches to the management of unstable shoreline slopes. The various approaches are presented in a general sequence from least to most "intrusive"—reflecting the degree to which each approach modifies both the existing slope and natural environmental processes.

Least intrusive is the complete avoidance of construction in areas of unstable slopes and slides. Next come construction setbacks from an unstable slope- or bluff-edge, and the establishment of special blufftop construction requirements. Management practices concerning existing vegetation, surface runoff control, and groundwater drainage systems, are each somewhat more intrusive but still leave the slope largely unaltered. Biotechnical slope protection uses live vegetation to prevent erosion and arrest shallow slope failures. Substantially more intrusive approaches combine vegetation with revetments or retaining walls, transitioning into conventional structural engineering solutions—breast walls, crib walls, and shoreline bulkheading structures. Finally, most intrusive of all, is the complete reshaping of unstable slopes by cut and fill.

This sequence of increasingly intrusive approaches to unstable slope management also generally reflects increasingly costly solutions—both directly to the landowner, and indirectly in terms of increasing disruption of natural environmental processes and loss of habitat values.

5.1.1 Existing Versus Proposed Construction

Addressing watershed restoration issues, Alan Johnson recently noted: "There is no doubt, when the houses go in—the rules change.[1]" The same holds true for managing coastal slopes and shoreline hardening. While this may not reflect regulatory policy, there is little doubt that more intrusive and potentially damaging slope management solutions are used to protect existing older structures than newly constructed ones. In large part, this reflects our previous ignorance of the potential direct, indirect, and cumulative environmental impacts associated with poorly planned coastal development.

From direct landowner cost, indirect public cost, and environmental protection perspectives, it makes more sense to avoid or minimize problems associated with unstable slopes *prior to construction*—rather than pay to repair the damage after it has already been done.

Recognition of this concern appears to be implicit in *Engrossed Senate Bill 6128*, passed by the Washington State Legislature in 1992. Comprehensive erosion management standards are to be included in local government Shoreline Master Programs. The standards must give a preference for permitting of erosion protection measures for residences occupied prior to January 1, 1992, where the erosion protection measure "is designed to minimize harm to the shoreline natural environment." This implies no preference for permitting erosion protection measures for residences first occupied *after* January 1, 1992.

In this regard, the mitigation "sequencing procedure" adopted by federal agencies to protect sensitive habitats *and environmental functions or processes*, offers a potential model for managing unstable shoreline slopes. This sequencing procedure requires strict adherence to the following steps during project design:

1. Design project to completely ***avoid*** impacts to sensitive habitat (substitute—unstable slopes) areas *and functions*

---

[1]Alan Johnson (Aquatic Resource Consultants, Seattle), "Restoration Ecology: Urban Watershed Management," University of Washington Center for Urban Horticulture, Seattle. March 21, 1994.

2. Should this prove impracticable, design project to absolutely ***minimize*** impacts to . . . unstable slope habitats *and functions*

3. When project design has avoided/minimized impacts to areas and functions of... unstable slopes... to the maximum extent practicable, any remaining impacts must be offset by appropriate ***mitigation*** measures.

A recommendation that a similar sequencing procedure be followed during site developments involving potentially unstable bluffs would, at a minimum, alert the property owner and permitting agencies to possible future concerns and costs—and potentially could reduce poorly planned construction and unnecessary damage to shoreline natural resources.

5.1.2 Geotechnical Site Surveys

If existing geologic mapping indicates the potential for stability problems at a site, and therefore the need for special construction requirements, a geologic or geotechnical evaluation of the site by a qualified professional is appropriate. The bluffs of Puget Sound are typically underlain by glacial deposits or at some localities, bedrock. The glacial deposits can consist of granular deposits, generally outwash sand and gravel, whose strength is controlled primarily by the friction angle; and finer grained material, such as till or lake deposits, whose strength is controlled by a combination of friction and cohesion. At many locations, the materials in the slope consist of an interbedded sequence of both fine and coarse grained deposits, whose strength is usually dictated by the strength of the weaker material. In areas underlain by bedrock, the strength of the rock is usually controlled by fractures or bedding planes and their orientation to the slope angle. Complicating all of this is the presence of groundwater at various levels within the slope. An evaluation by a geologist or a geotechnical engineer is recommended not only to identify the various slope materials and site conditions, but to establish appropriate criteria for design and construction. What is appropriate for a site underlain by till is likely not suitable for a site underlain by granular outwash.

Two levels of site survey may be appropriate. At a minimum, the results of these surveys should be reviewed by the local permitting agency, and by an appropriately qualified geologist or geotechnical engineer for consistency with generally accepted principles of slope stability.

The initial survey would involve conducting a geologic reconnaissance of the site. A professional geologist would be contracted to review the existing published information relating to stability at the site and to conduct a brief field reconnaissance at the site to determine whether the stability problems discussed in the literature relate to this site. During this survey, the geologist would evaluate the conditions at the site as they relate to the geology, geometry (steepness and length) of the slope, groundwater and drainage conditions, and site vegetation for indications of slope stability problems. If after assessment of field conditions, the available evidence indicates that slope stability is an important factor in the development of the site, additional study would be required.

This second level geologic/geotechnical survey involves additional research and analyses to determine the cause of the stability problems and what type of solutions would be appropriate at the site. Typically, stability problems along coastlines pertain to problems resulting from toe erosion, surficial stability, deep-seated stability, or some combination of these factors. The second, more detailed survey would determine which of these factors are responsible for the stability problems at the site. Geotechnical criteria for the design of structures that are relevant to the problem would then be developed. The field work, in conjunction with the additional research and engineering, can often be expensive for the individual homeowner.

Without objective peer review, a specialized geotechnical report may be of little value to a local shoreline administrator. Yet many jurisdictions around Puget Sound cannot maintain a geologist or geotechnical engineer on staff. In these circumstances it may be beneficial for the local jurisdiction to contract out the peer review task to an appropriately qualified third party.

5.1.3 Slope Stabilization—A Caution

Property losses in areas of larger slides often lead to demands for potentially expensive pubic works projects to protect existing (public or private) developments. Kockelman (1980) points out, however, that such slide control can be self-defeating:

> "As building on slide areas continues, the number of persons and the value of the property tend to increase at a rate faster than that which protection can be provided. Development up-slope often causes trouble for down-slope developments. Grading, drainage improvements, paving, and watering, for example, may load, or cause instability of, a slide and require public expenditures for slide control.
>
> Remedial public-works construction for slide control, such as restraining structures, may encourage development of slide areas in the expectation that additional works will be forthcoming. The public may believe that the slide problem has been eliminated, rather than simply reduced. Also, earthquake-triggered slides may not be prevented by such construction. Intelligent management and regulation of the slide areas is still required."

Thorsen (1987), describing slide hazards in the Puget lowland, confirms Kockelman's conclusions:

> "In general, the individual would do well to avoid slides. Structural controls are often extremely expensive and seldom justified for low- or even moderate-density residential areas"

Discussion of possible remedial and preventative measures will be referenced back to the reasons discussed which contributed to slope instability. Though specific measures will be discussed under each section, effective landslide control typically involves a combination of methods which together have the effect of minimizing the driving forces (surcharging or adding fills or removing lateral support, and\or increase in water levels) and increasing the resisting forces (installing a buttress system). In addition to being expensive, construction methods for landslide stabilization will frequently require more space than is available in most coastal situations to safely and economically operate the construction equipment without additional slope movement developing. This alone makes preventing the situation from occurring always the more desirable option. Where structures are located in areas that are susceptible to landslide movement, the property owner should be prepared to assume long term maintenance of the buildings. This can include flexible connections for utilities, and foundations that can be re-leveled if movement reactivates and is slow enough such that remedial measures can safely counteract the motion. If required, corrective measures should be adapted to the type of materials present as well as the type of failure.

5.2 Avoidance

As noted above—from direct landowner costs, indirect public costs, and environmental protection perspectives—it makes more sense to avoid or minimize problems associated with unstable slopes *prior to construction*, rather than pay to repair the damage after it has already been done.

It should be clear from Section 4.0 that the fundamental causes of bluff instability and the various mechanisms that can trigger slumps and slides are quite well understood. In many cases, quantitative field, laboratory, and engineering research is available to quantify and model cause-and-effect relationships. Further, local resources such as the Coastal Zone Atlas (Ecology, 1977-1980) and Tubbs' (1975) studies provide an extensive quantifiable data base for specific Puget Sound situations. Given this level of understanding, using avoidance as a strategy for managing unstable shoreline slopes can be pursued in two different but complementary ways.

Residential development can be discouraged or restricted in Puget Sound shoreline areas known to have highly unstable slopes. Private landowners need to be fully appraised of the potential risks and costs of building in these areas. The public sector also needs to clearly understand the potential longterm infrastructure and public health and safety risks that may accompany approval of such development (see Section 5.1.3; Kockelman, 1980). Areas of greatest concern would probably include highly unstable slopes (see Table 4-3, and the Costal Zone Atlas, 1977-80 that are experiencing active toe erosion or frequent landsliding and are also known to be active feeder bluffs (Macdonald et al., 1993). Unstable banks and bluffs shown to be supporting other critical functions for the adjacent beach and shore-zone might also be "off limits" to development.

A less restrictive "avoidance strategy" involves performing a thorough, site-specific analysis of factors enhancing slope stability—and then carefully planning site development to specifically avoid impacting those factors. Obvious examples might include: minimal disruption (and possibly enhancement) of natural vegetation (Menashe, 1993); appropriate management ("no net changes") of onsite surface and groundwater resources; maximum use of soil bioengineering methods for slope stabilization (Myers, 1993); and use of "soft" methods of shoreline armoring (Cox et al., 1993). Indeed, the goal would be to avoid any disruption of natural processes that encourage or enhance slope stability. This approach is appropriate to development of *all* coastal bank and bluff situations and would take maximum advantage of the various slope protection methodologies outlined in greater detail below.

5.3 Establish Construction Setbacks

Erosional bluffs are a common feature around Puget Sound. Since they often provide dramatic views they are increasingly under pressure for residential development. It is important to balance the urge to build closer to the bluff crest (or even on the bluff face) to gain better views, against the increased risks (and costs) of bluff collapse and structural damage, as well as risks to personal and public safety. Risk reduction through establishment of appropriate construction setbacks from the bank or bluff edge is an obvious solution—but establishment of "appropriate" setback distances can be difficult (Canning, 1991).

Construction setbacks are conceptually straightforward. Decide the functional life of the structure being built; estimate bluff erosion/retreat expected over that time period; and set the structure a safe distance behind the projected position of the retreating bluff crest. As noted in the accompanying **Fact Sheet** (Shipman, 1993), however, coastal erosion tends to be highly episodic. Long periods of relatively minimal erosion are punctuated by unusually heavy rainfall years when slides and slumping increase dramatically (e.g., Tubbs, 1975); or by particularly powerful storms with high winds, waves, and tides that sharply increase toe erosion and resulting bluff collapse. Accurate erosion estimates might thus require that measurements be taken over a 50 or 100-year time span. One approach used successfully elsewhere is careful comparison of recent and historic (some early California photo series go back nearly 70 years to 1928) vertical aerial photo sets showing coastline features.

Because of its generally more sheltered character, Puget Sound bluff erosion rates tend to be lower than those recorded for open coast situations. Shipman notes that Keuler (U.S. Geological Survey) measured maximum long-term shoreline erosion rates of over one foot per year on the exposed west side of Whidbey Island. Other exposed feeder bluffs retreated at rates in the 4 to 8 inches per year range. Less exposed shorelines where erosion is less active probably retreat, on average, much less than 4 inches per year. Indeed, Keuler (1979) cites a mean, minimum long-term erosion rate for unconsolidated bluff materials in Skagit County of approximately 2 inches (5 cm) per year.

Several shoreline counties have already developed bluff setback criteria, that are reviewed by Canning (1991). They were originally established under the authority of Zoning Ordinances and Land Development Standards and are now being incorporated into revised Local Shoreline Master Programs, Sensitive Areas Ordinances and the recently enacted Growth Management Act (cf. Ecology, 1993; PSWQA, 1994a).

Thurston County (Figure 5-1, top) will not approve development, including onsite sewage disposal, within a 2:1 slope setback from the toe of a marine bluff judged to be hazardous by Planning or Engineering staff. A waiver may be obtained if supported by the results of special geological engineering studies and appropriate development design criteria.

Shoreline Erosion Rates

When geologists speak of coastal erosion rates, they usually mean long-term average rates of shoreline retreat. When property owners speak of coastal erosion rates, they usually mean the amount of bluff that slid during the previous winter. Both of these rates are important, and it is critical to understand the distinction.

Shoreline retreat is the rate at which the toe of the bluff moves landward and must be documented over a long enough period so as not to be influenced by short-term variations. Short-term erosion typically refers to slope failures such as landslides, slumps, or simply the sloughing of a layer of soil and vegetation. In the case of slope failures, it is useful to know the frequency and the maximum extent of such an event.

High rates of bluff retreat occur when:

- Wave energy is high. Long fetches in the direction of predominant winds, coupled with deep water close to shore, allow large waves to develop and to reach the toe of the bluff. Energetic waves can break apart rocks more easily and can rapidly remove eroded material from the base of the bluff, exposing fresh material.
- Bluff materials are weak. Many factors affect the resistance of rock to erosion, including rock type, fractures, and groundwater saturation. The glacial sediments typical of Puget Sound bluffs may erode several inches per year, whereas massive bedrock such as that in the San Juans may erode only a faction of an inch per year.
- Beaches are narrow. Beaches provide excellent natural protection, dissipating wave energy over a broad area and limiting the frequency with which waves actually reach the base of the bluff.

These three conditions are most often met on classic feeder bluffs such as Birch Point in Whatcom County, Scatchett Head on south Whidbey Island, and Green Point south of Gig Harbor. As one moves downdrift within a coastal drift sector, beaches generally become wider, and erosion rates may diminish.

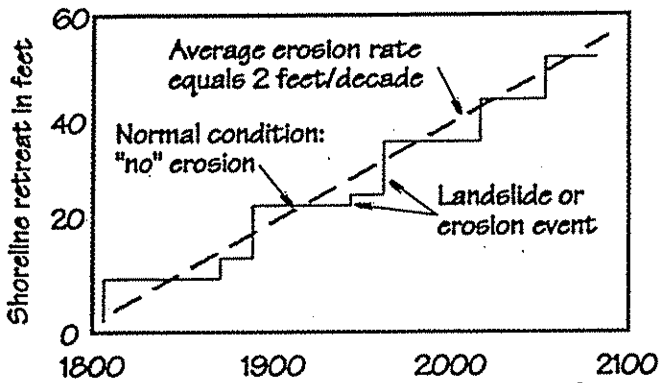


Figure 1. Long term erosion rates are an average of many landslide or erosion events over a period of decades to centuries.

Ralph Keuler, with the U.S. Geological Survey, measured long-term shoreline erosion in much of northern Puget Sound. The fastest rates are over 1 foot per year at Point Partridge on the exposed west side of Whidbey Island, but this rate is unusually high for Puget Sound. Even on exposed feeder bluffs such as Forbes Point near Oak Harbor, the north end of Marrowstone Island, or Yellow Bluff on Guemes Island, retreat rates are in the 4- to 8-inch per year range. On less exposed shorelines, the erosion rates are often much less than 4 inches per year.

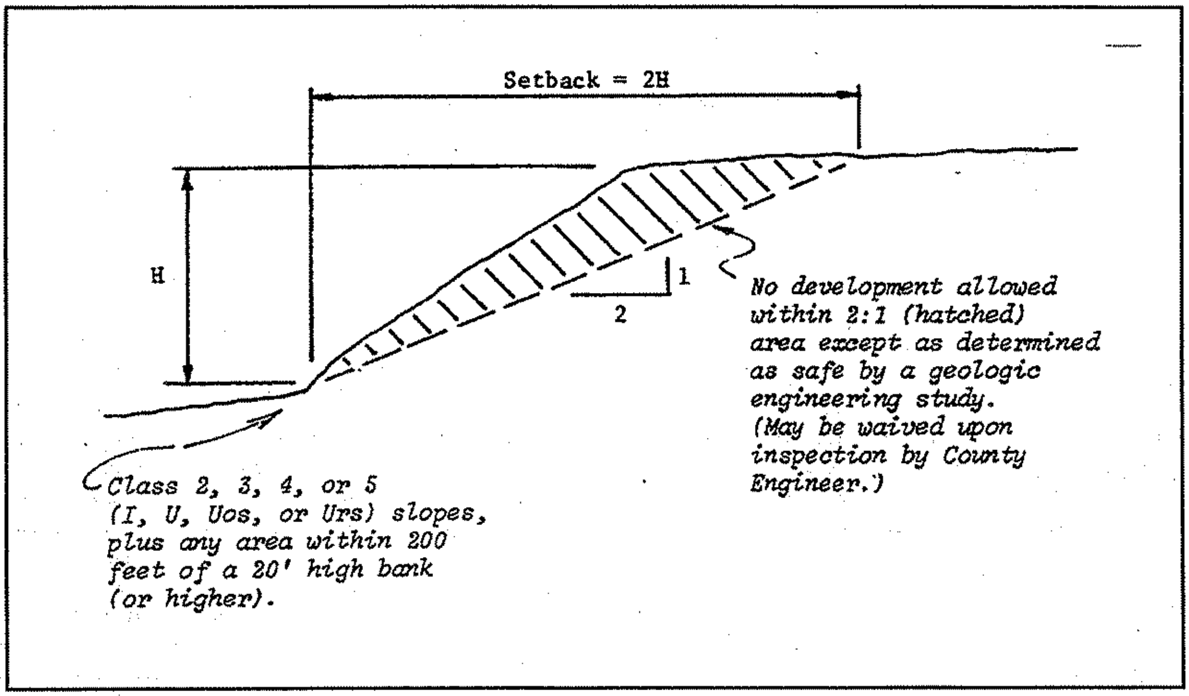
Coastal erosion is highly episodic. Long periods during which erosion is negligible are interrupted by short, impressive slumps and landslides. These slope failures are triggered by saturated soils, tree blowdown, or the combination of storm waves and high tides. Although these events may cause the top of the bank to retreat several feet, and may appear even worse since they strip away mature vegetation, the long-term rate at the location may still be very slow. It may be many decades before that portion of the bank slides again.

Shoreline property owners often accelerate erosion rates by weakening the bluff or causing the beach to diminish. The former is easily done by clearing upland vegetation and changing bluff hydrology by misdirecting storm runoff or placing sewage drain fields too close to the bluff.

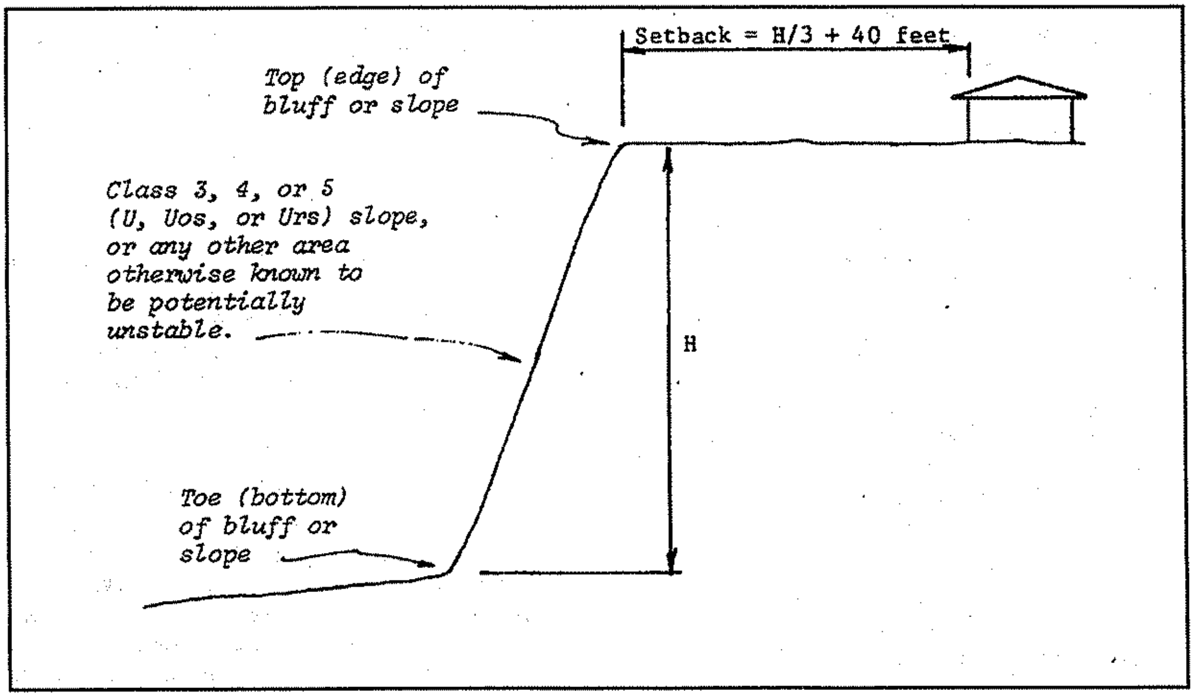
The latter is best done by armoring the shoreline updrift, effectively starving the beach of needed sediment.

There is a tendency around Puget Sound to exaggerate the rate of long-term shoreline erosion, yet ignore the potential for short-term bluff failure. When developing near marine bluffs, we need to recognize that both slope stability and chronic shoreline erosion affect the safety of the property but that, if the geology of the site is known and the structure is adequately set back, problems will be unlikely.

–Hugh Shipman (1993)



Thurston County



Island County

Source: Canning (1991)

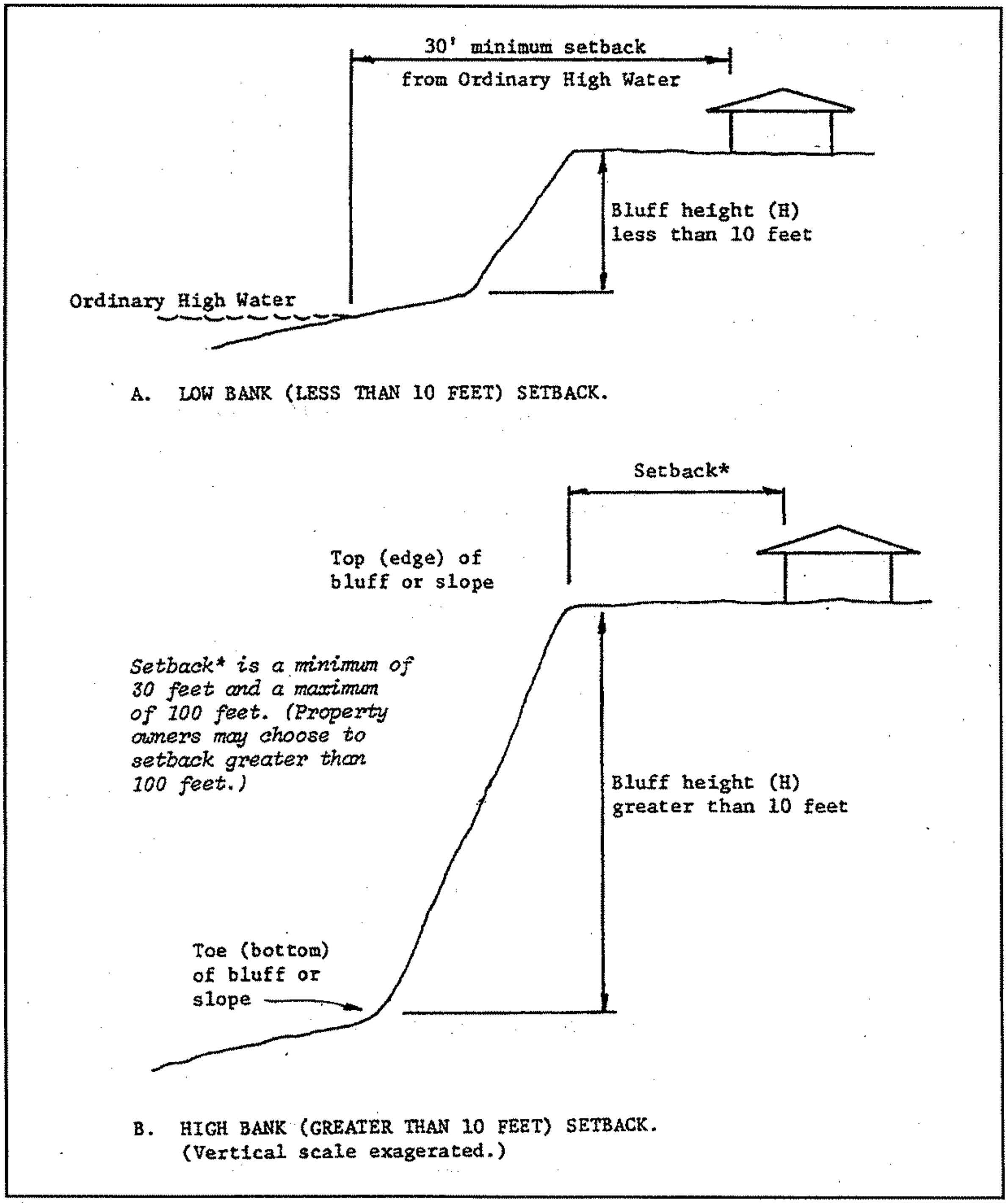
Figure 5-1
Bluff Setback Criteria

Island County (Figure 5-1, bottom) requires the County Engineer review all construction proposed for potentially hazardous bluffs. If the Engineer determines the slope is hazardous, no development is allowed within a distance of "one-third the bluff height plus forty feet." Again, a waiver may be obtained based on the outcome of appropriate geological engineering studies. In the cases of potential waivers based on appropriate geotechnical studies, keep in mind the concern noted in Section 5.1.2—that not all coastal jurisdictions maintain appropriate geotechnical specialists on staff and peer review services may need to be contracted out.

Jefferson County (Figure 5-2) has different setback requirements for low (less than 10 feet) versus high (greater than 10 feet) bank situations. Structures must be setback 30 feet inland from the Ordinary High Water line on low banks; while the high bank setback can range from 30 to 100 feet from the bluff crest. Canning (1991) notes that these are building setbacks rather than slope hazard setbacks and thus not subject to waivers based on geological studies. Jefferson County also coordinates the siting of coastline septic drainfields between the County Planning and Health Departments.

The City of Edmonds, Snohomish County, has both a Sensitive Areas Ordinance and Building Development Codes that address steep slope and landslide hazard areas (Steve Bullock, Community Services Dept., to Douglas Canning, Ecology, August 1993).

Edmonds Sensitive Areas Ordinance includes provisions for identifying both steep slope (slopes over 10 feet high with inclinations greater than 30 percent) and landslide (slopes over 15 percent; with interbedded clays; springs, or seeps, etc.) hazard areas. A buffer width of 25 feet or more from the slope is required for "steep slopes"—and buildings must be set back an additional 15 feet beyond the buffer edge. Development within the buffer is strictly limited to installation of drainpipes, utilities, trails, and some vegetation clearing (requires a preapproved plan). An exception is possible for steep slopes less than 20 feet high—provided geotechnical studies demonstrate no adverse impacts will result from proposed development.



Jefferson County

Source: Canning (1991)

Figure 5-2
Bluff Setback Criteria

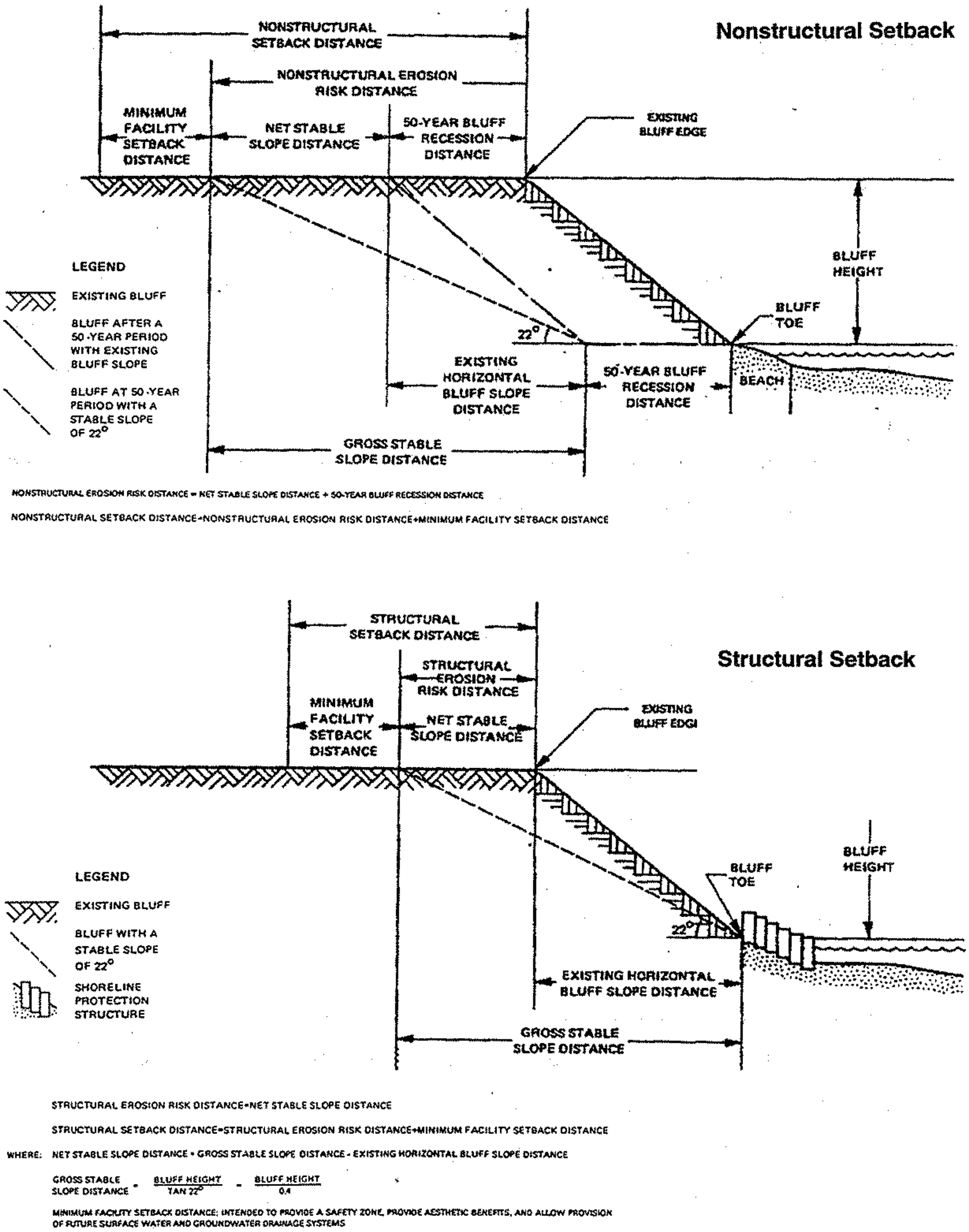
No alteration of landslide hazard areas on slopes of less than 30 percent is permitted unless it can be proved that: (a) development will not reduce the stability of any adjacent property; and (b) the proposed development design will eliminate any onsite landslide hazard.

The Development Code permits development to occur within landslide hazard areas *provided* the potential risk: (a) is demonstrated to be within "acceptable limits" as defined in the Code; (b) that the potential risk is fully disclosed in public records for future landowners; and (c) that all present and future risks associated with construction and habitation are assumed by the builders and owners. The Code defines a site as *unstable* and precludes single-family residential development if there is a greater than 30 percent risk of earth movement (slope failure) within a 25 year period. Extensive geotechnical studies are required to establish satisfactory compliance.

Additional discussion of federal, state, and local regulatory requirements that address issues of shoreline armoring and coastal slope management in Puget Sound are addressed in the **Task 4** report of this series: *Policy Alternatives for Coastal Erosion Management* (McCabe and Wellman, 1993). New and innovative regulatory strategies are discussed in the **Task 7** report: *Regional Approaches to Address Coastal Erosion Control Issues* (McCabe and Wellman, 1994).

5.3.1 Examples From Other States

Bluff hazard setback programs established in other states also offer insights that may be applicable to Puget Sound shorelines. The Southeastern Wisconsin Regional Planning Commission (SWRPC, 1988) established model ordinances for management of development on the bluffs that border the Great Lakes (Figure 5-3); see also Tainter, 1982; Herdendorf, 1984; Edil and Bosscher, 1988). Two different approaches to the problem of actively evolving/retreating coastal bluffs are considered.



Source: SEWRPC (1988)

Figure 5-3
Wisconsin Guidelines for Lake-Front Bluff Stability and Setbacks

In presently undeveloped areas, hazard mitigation can be planned and managed for an extended stretch of shoreline. (In Puget Sound planning on a coastal drift sector basis might be most appropriate.) Setback requirements for new development incorporate two components: an erosion risk distance and a minimum facility (building) setback distance (Figure 5-3, top). The former includes allowances for predictable long-term bluff erosion, as well as establishment of a more stable bluff slope angle. The facility setback provides an additional safety factor to prevent a building being sited too close to the future bluff crest (Edil and Bosscher, 1988).

A different "structural setback" approach is used for coastal bluffs that have already been extensively developed (Figure 5-3, bottom). This is a site-specific approach that is intended to slow beach and bluff-toe erosion through "hard" or "soft" methods of shoreline armoring (see Cox et al., 1993 and Macdonald et al., 1993). Bluff stabilization is enhanced through a three-pronged approach that includes (a) protection against toe erosion, (b) slope stabilization against deep slips, and (c) bluff face stabilization by proper water management and vegetative cover. The resulting structural setback can now be narrower to reflect (theoretically) a reduced bluff erosion risk distance (Figure 5-3, bottom; Edil and Bosscher, 1988).

Griggs, Pepper, and Jordan (1992) proposed guidelines for assessing the stability of coastal bluffs in California, and related setback requirements to three different levels of relative bluff stability (Figure 5-4). They proposed that "geologic stability" must be demonstrable for a structure for a time period of 50 years, that construction must not contribute to instability of any cliff or beach, and must be consistent with all other coastal zone planning policies. Further definition of their proposed stability categories is presented in Figure 5-4. Application to Puget Sound would obviously require assessment of regional/local bluff and bank retreat rates (see Fact Sheet).

Two reports from North Carolina (Henderson and Owens, 1983; Watts, 1987), while covering very different coastal regimes from those of Puget Sound, also offer useful background information.

Coastal Erosion Guidelines for Geologic Stability

All developments within the immediate beach-coastal bluff area must demonstrate geologic stability of the structure for a 50-year period, must not contribute to instability of any cliff or beach, and must be consistent with other planning policies in the coastal zone.

The following definitions of coastal stability shall apply:

High stability areas (1) less than 1 foot per year historic cliff retreat,
(2) inherently stable cliff material, and
(3) not dependent upon a beach for its stability.

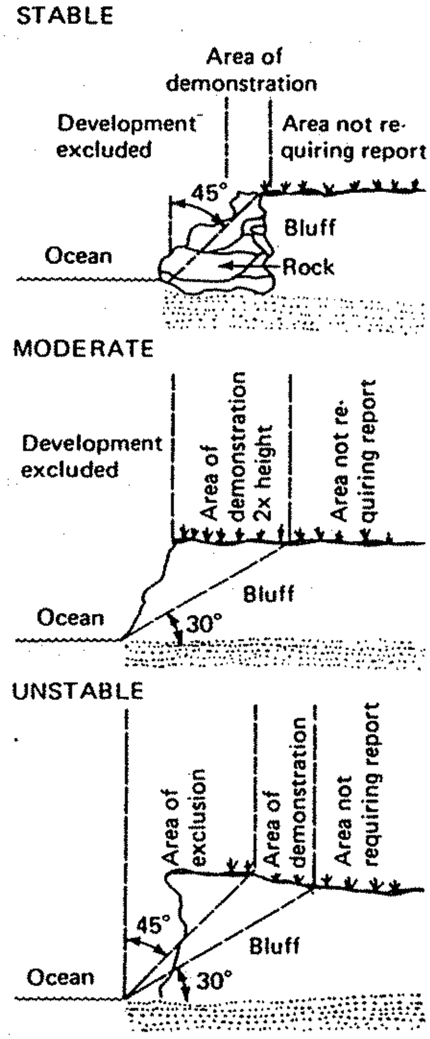
In high stability areas, any development proposed within the area from the toe of the bluff to a point on top of the bluff at a 1:1 (45°) slope from the toe must demonstrate stability as defined above (with a geologic engineering report).

Moderate stability areas (1) less than 1 foot per year historic cliff retreat,
(2) inherently unstable cliff material, and
(3) may be dependent upon a fronting beach for stability.

In moderate stability areas, any proposed development within the area of 2:1 (30°) slope from the toe to the top of the bluff must demonstrate stability as defined above.

Low stability areas (1) greater than 1 foot per year historic cliff retreat, or
(2) landslides or other inherently unstable material (such as beach sand or active dunes).

In low stability areas, any proposed development must be excluded from the area of 1:1 (45°) slope from toe to top of bluff, and from the area of active movement, and stability must be demonstrated for a 50 year economic life within the remaining area of 2:1 (30°) slope.



Source: Griggs, Pepper and Jordan (1992)

Figure 5-4
California Guidelines for Coastal Bluff Stability and Setbacks

5.3.2 Broadening Our Perspective

It will be noted that the emphasis of most examples cited above is towards *geotechnical issues*, the principal focus presumably being to avoid unnecessary property losses due to predictable long-term bluff retreat. This may be too narrow of a focus to adequately protect Puget Sound's coastal banks and bluffs. Other sections of this and related reports (Macdonald et al., 1993; Thom et al., 1994) have stressed that bluff erosion is a natural and desirable process that plays a critical role in the overall health and maintenance of Puget Sound coastal ecosystems. The importance of numbers of "landscape linkages"—processes that tie together marine and terrestrial ecosystems—has also been noted. Eroding bluffs provide a majority of sediment for Puget Sound beaches, which then in turn protect shorelines from wave erosion (Downing, 1983).

Construction setbacks around Puget Sound need to incorporate a broader perspective of coastal bank/bluff processes and values. Generic setbacks need to be tailored to site-specific conditions: for example, the geology and stratigraphy of local slopes, natural stability of slope material, prior local experience with landsliding, local long-term bluff erosion/retreat rates, unique local site features, and the potential life of the proposed structures, should all be reviewed in establishing site-specific setback requirements.

The potential impacts of proposed bluff development on regional fish and wildlife resources, public recreational and aesthetic values, public health and safety concerns, as well as regional publicly-supported hazard insurance costs, should all be rolled into construction setback considerations.

Recognition that "shore protection" methods have rarely considered the full range of functions of the natural shoreline and need to be broadened to encompass an "ecosystem approach" is gaining ground. A workshop entitled, *An Ecosystem Approach to Shoreline Treatment*, held in November 1993 by the Canadian Center for Inland Waters (Nairn, 1994), focused on

> "understanding that any shoreline treatment must function as a component of the shoreline ecosystem, not as a single purpose one-time solution to a problem."

To further quote Nairn (1994):

> "An ecosystem approach will enable us to guard against unwanted effects and achieve a greater range of benefits in the future, hopefully leading to a future shoreline which is no less productive than the original undeveloped shoreline."

More detailed understanding of the true complexity of and interactions among shoreline processes, such as recently detailed by Kreutzwiser and Gabriel (1993; see also Bauer, 1991; CCCPTF, 1993), will go a long way to supporting such broader "ecosystem approaches" to shoreline armoring and slope stabilization treatments.

5.4 Establish Blufftop Construction Requirements

In addition to establishing construction setbacks for the major building or residence planned for a shoreline bank or bluff, other special blufftop construction requirements may also be appropriate. Examples include, minimizing blufftop fill (surcharging/toploading), requiring setbacks for swimming pools and septic drainfields, and checking the site's potential for drainfield/soil saturation problems.

Typically, a generic requirement for increasing stability of slopes is to minimize fill placement, and thus decrease the loading on the slope. While this is a recommended procedure for soil slopes, the impact on slopes underlain by bedrock, may be insignificant—depending on the type of bedrock, the orientation of fractures and controlling structural features, and the depth and character of the rock surface. This information can be obtained by working with a professional geologist who is familiar with both the local geology and the problems that can result from the type of material underlying the site.

Construction setbacks may be appropriate for extensive paved surfaces, septic drainfields, or swimming pools located near the edge of a slope. Each of these examples share the possible concern that increased surface or subsurface drainage might weaken the adjacent slope—depending, of course, upon local, site-specific geological conditions. In the case of a large pool located near the edge of a slope, the added weight of the structure (toploading again) as well as accidental drainage, could be of concern.

Different criteria would be appropriate for slopes underlain by lower strength sands or clay, versus higher strength material such as till or bedrock. For construction setbacks to be site specific, knowledge of the underlying cause of the stability, as well as the failure mode is required. A geologic reconnaissance takes these natural features into account when evaluating a site.

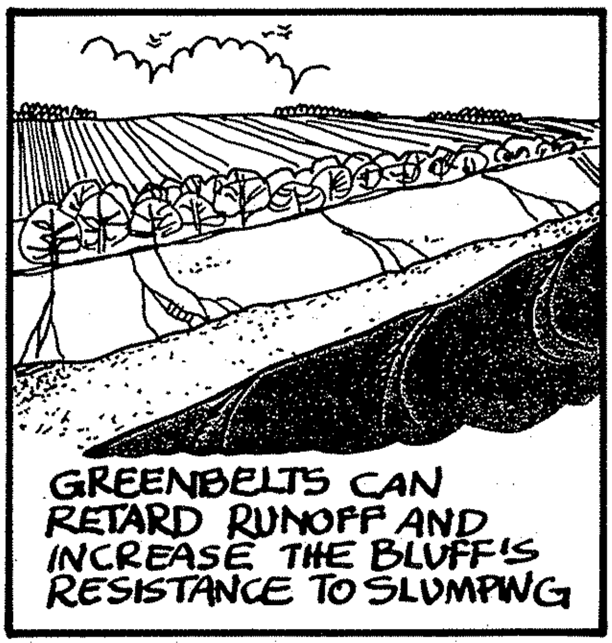
A sanitarian will locate septic drainfields a required distance above the seasonal high groundwater table or recommend alternative systems, but may not be aware of the effects of the additional saturation on the stability of the adjacent bluff slope. Because drainfields add water to the slope, the drainfields should be located such that they would not negatively impact the natural slope drainage or increase discharge in areas that are marginally stable. Similarly, leakage from swimming or landscape pools can also negatively impact the slopes. Large, quantities of water that can abruptly leak from failed pools can be the cause of sudden slope failure.

5.5 Management of Existing Vegetation

Removal of vegetation often accompanies development of a shoreline bluff to take advantage of the view. In most cases, this action is deleterious to the stability of the bluff because the roots of the trees not only remove water, but also contribute to the stability of the upper few feet of soil by the binding strength of the roots. Older trees susceptible to decay and rot, and prone to windfall, loosen the upper soil layer through the movement of the tree with wind action and allow soil fall to occur downslope. Consequently, it may be advantageous to remove these trees. If the stumps are left in the ground, certain species of deciduous trees aggressively re-sprout using the existing root system and cutting them back can have minimal effects on the stability of the slop (Urban Forestry Services, 1992). An arborist should be consulted—prior to cutting or pruning trees—regarding the existing vegetation and the long term effects on the slope with respect to the binding action of the roots.

Vegetation Management: A Guide for Puget Sound Property Owners (Menashe, 1993), recently published by Ecology's Shorelands and Coastal Zone Management program, is an excellent resource on regional shoreline vegetation management. Using a well-illustrated and easy-to-follow format, Menashe first describes Puget Sound's shoreline environments and the vegetation typical of regional coastal bluffs. He outlines factors to be considered before any trees are removed and describes both the potential consequences of—and the alternatives to—tree removal. A discussion of tree topping identifies the much greater benefits of alternative pruning practices, and Menashe concludes by outlining some local landscaping solutions to potential bluff erosion problems.

Vegetation on the bluff crest forms a protective buffer for the bluff face. A bluff-crest greenbelt keeps traffic (logging, agricultural equipment) away from the edge of the bluff and retards runoff. If the bluff edge is presently cleared, it can be left undisturbed to allow natural establishment of vegetation or planted to speed up to the process (Tainter, 1982).



Tainter (1992)

Clearly, a major reason for living on the banks and bluffs surrounding Puget Sound is to take advantage of the views. While clear-cutting trees to improve views is a common practice, it carries the risk of significantly increasing slope stability problems (See Section 4.4). A practical alternative is to use vegetation in creative ways to enhance desirable views while screening out undesirable sights. Thought should also be given to how others may view the property, from either the beach, or offshore (Figure 5-5); Tainter, 1982).

In reviewing possible **tree removal**, Menashe (1993) indicates that the following factors should be considered:

- Dominant trees, larger and usually older than those around them, are likely to have better developed, stronger root systems and thus have a greater stabilizing influence.

- Minimize removal. To quote Menashe (1993), "The valve of a healthy, strong tree on a slope or bluff far outweighs its value as lumber or firewood."

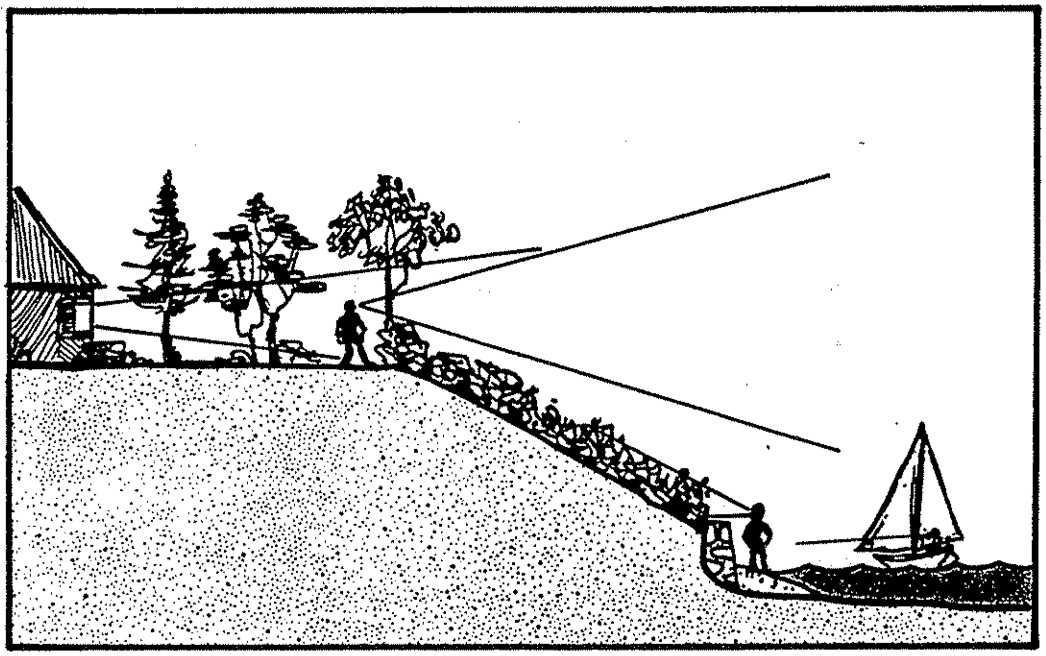
- Do not remove trees on slopes until after construction is complete—maybe they can stay. Use an accredited tree service familiar with updated tree care practices.

- Consider the species, age, and health of individual trees before removal. A red alder, for example, lives around 70 years, while a Pacific madrone can live beyond 200 years.

- Closely spaced trees should be cut or thinned with care. They may shave inter-dependant root systems or gain mutual support against wind damage (windthrow).

- Cutting trees may also result in view blockage from more vigorous growth of understory shrubs and bushes (Menashe, 1993).

- Carefully assess the specific roles of vegetation in enhancing slope stability at the site being developed.



Source: Tainter (1982)

Figure 5-5
Vegetation Management for View Ehancement

- Beware of recommendations that tree removal for site development is "routine." As Menashe (1993) notes, "...the overwhelming conclusion is, that in the vast majority of cases, vegetation (especially well-rooted, mature trees) helps to stabilize a slope."

- Consider how the tree or shrub species being cut will respond. For example, most conifers will not resprout, but willow, red alder, bigleaf and vine maple often do.

- If trees *must* be removed, try to leave the stumps undisturbed. Their root systems will offer some slope stability and erosion benefits while new replacement growth is developing.

As with tree removal, **tree topping** is strongly discouraged. Despite common arguments promoting topping—it reduces height, protects views, decreases wind resistance—it has been clearly demonstrated to be a poor, shortsighted, and damaging practice (Menashe, 1993). Several practical tree trimming practices are available as successful alternatives to both tree removal and topping. Some of these are illustrated in Figure 5-6.

Menashe (1993) also addresses a variety of other issues relating to shoreline vegetation management:

- The values and limitations of lawns—shallow rooting limits erosion control value (good groundcover for septic drainfields); becomes saturated easily, resulting in ponding or runoff.

- The importance of using deep-rooted groundcovers near the crests of slopes (e.g., salal, Oregon grape, wild rose, etc.), to better reduce surface water runoff and thus soil erosion.

- Avoiding construction damage during development—soil compaction, burial or exposure of tree roots, mechanical injury of trees by heavy equipment.

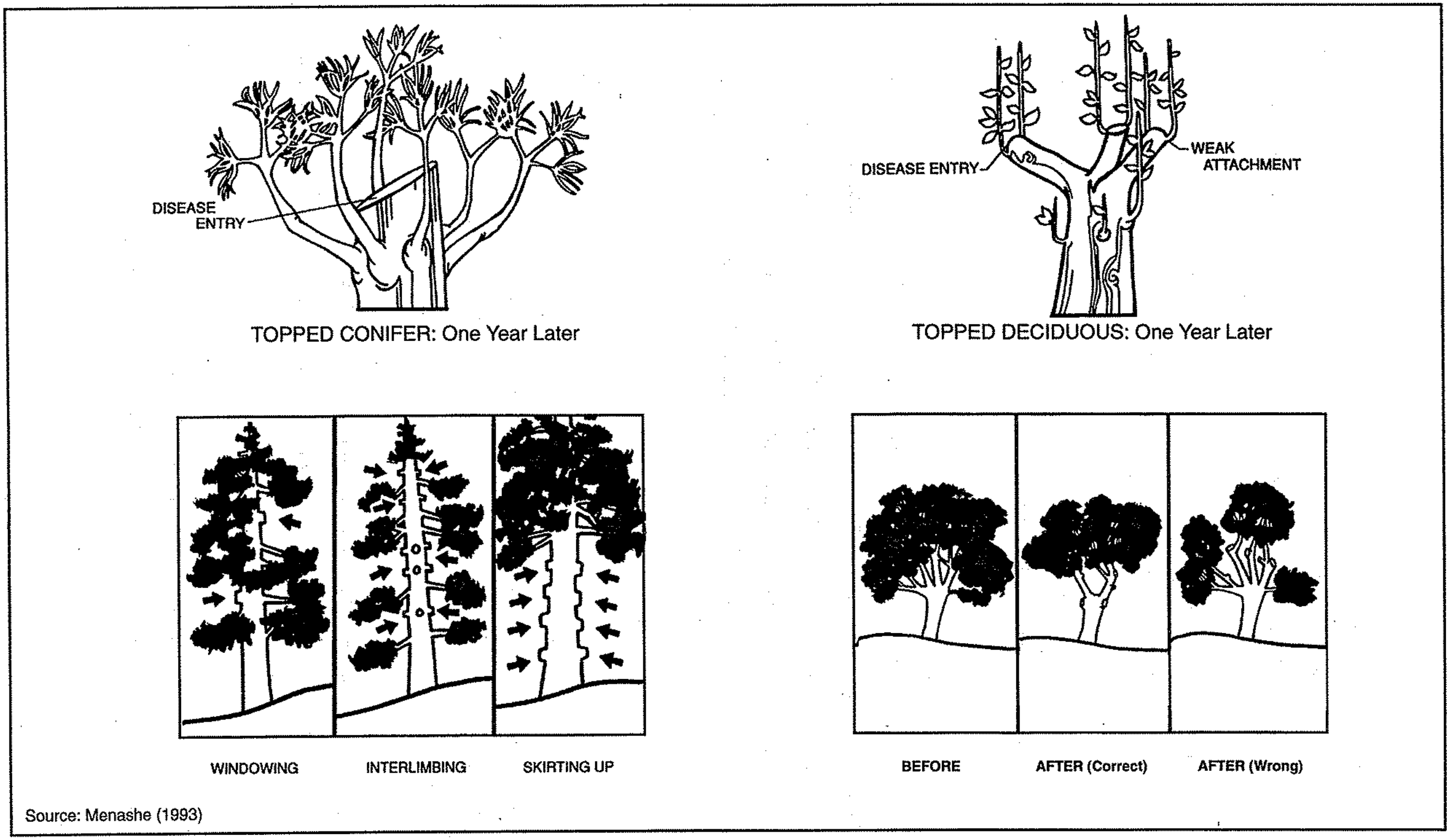


Figure 5-6
Vegetation Management
Alternatives to Tree Topping or Removal

- Removal of cleared plant debris—by chipping, *not* pushing it over the bluff!

- Identifying and avoiding potential conflicts between maintenance requirements for native vegetation versus introduced landscaping. A mature Pacific madrone, for example, can be killed by root disturbance and summer watering—yet tilling and watering may be common requirements for surrounding flowerbeds.

- The value of **snags**—dead, standing trees; big ones can persist for years, offering critical perching and nesting sites for a wide variety of birds and wildlife.

This section has stressed the benefits of protecting and maintaining native vegetation that is *already present* on a potential bluff development site. Vegetation can also be installed "proactively" using techniques that reduce erosion and increase slope stability. Some of these "soil bioengineering" or "biotechnical engineering" approaches are described in Section 5.8.

Presently, there is no clear regional policy for protection and management of native vegetation on the banks and bluffs surrounding Puget Sound. There is local precedent for using "Clearing and Grading Codes," or "Tree Protection Ordinances," to encourage appropriate vegetation management strategies (Canning, 1991; Johnson and Stypula, 1993).

5.6 Surface Runoff Control

Minimizing surface runoff at a development site, particularly over the crest and down the face of a bank or bluff, will reduce surface erosion and help maintain slope stability. Temporary measures for use during actual site construction, as well as measures that promote more permanent, long-term runoff control are both important. Basic approaches include source reduction, enhancing infiltration, and the diversion, collection, and controlled removal of surface runoff.

The most useful regional reference outlining surface runoff controls is Ecology's, *Stormwater Management Manual for the Puget Sound Basin (The Technical Manual)*, published in February 1992. Additional useful sources include, *Bluff Slumping and Stability, a Consumer's Guide* (Tainter 1982), and *Guide to Lake Erie Bluff Stabilization* (Herdendorf 1984)—both of which deal with glacial till bluffs around the Great Lakes. Local clearing and grading ordinances, requirements for site grading and sediment control plans, and Best Management Practices (BMPs) for construction sites, are also likely to address some of these issues.

5.6.1 Source Reduction

Clearly rainfall can't be stopped—although layered vegetation consisting of trees, shrubs, and groundcover *can* reduce the amount of rainfall that actually reaches the ground. Rather, the concept here is to minimize all *additional* sources of surface water that might contribute to runoff.

The most obvious example is the addition of water (irrigation) for landscaping purposes, either by hand or with automated sprinkler systems. While automated systems may be "convenient" for the homeowner they should be monitored to preclude unnecessary watering in wet weather or when the ground is already saturated. Pressure washing driveways, the roof or house-siding, hosing off a deck, draining a hot tub, spa, or swimming pool, even washing the car, are all activities that potentially can contribute to increased surface runoff.

A very common but less obvious potential source of added surface water runoff comes from rainfall landing on any impervious surface. Roadways, driveways, parking areas, patios, decks, roofs of houses or other buildings, areas lacking vegetation—especially if the soils are compacted or have low permeability—are all sites where rainfall can runoff into adjacent areas potentially increasing surface erosion and sediment transport.

5.6.2 Enhancing Infiltration

Surface runoff can be dealt with in two different ways. The first is to slow it down. Reducing the velocity of the flow diminishes its capacity for soil erosion, allows sediment particles being carried in the flow to drop out, and may provide a better opportunity for infiltration and percolation into the ground. The second approach is to collect the runoff and drain it away in the manner that has the least potential for further harm.

More efficient infiltration offers both benefits and risks. The reduction in runoff slows surface erosion. Rills and gullies are less likely to form on shoreline slopes and less sediment and organic material will be washed downslope. As surface water percolates into the ground, however, some of it may contribute to soil saturation (reducing slope stability), some may be removed by plant transpiration (increasing slope stability) and some may join the groundwater—another potential source of slope stability problems.

Clearly, the most effective long-term solution to slowing runoff and encouraging infiltration is development of a dense, continuous groundcover of vegetation. Menashe (1993) notes that grasses and lawns can be effective on upland sites—provided they slope away from (and thus drain away from) the bluff crest. On the crests of banks and bluffs and in downslope situations deeper-rooted groundcovers like salal, Oregon grape, wild rose, trailing blackberry, kinnikinnick, or other low-growing plants, are recommended. Development of a multilayered vegetation structure with shrubs and trees, as well as groundcovers, is likely to increase slope stability.

Alternative methods are available for temporary use during site development when vegetation is being cleared and soils left exposed to rainfall. Methods available to reduce runoff velocity and encourage infiltration here include the use of mulches, temporary seeding, and erosion blankets (nets and mats), as well as more mechanical approaches such as surface roughening, grooving, and stair stepping of cut slopes. Some of these approaches are illustrated in Figure 5-7 and detailed descriptions are provided in the Technical Manual (Ecology, 1992; see also Johnson and Stypula, 1993).

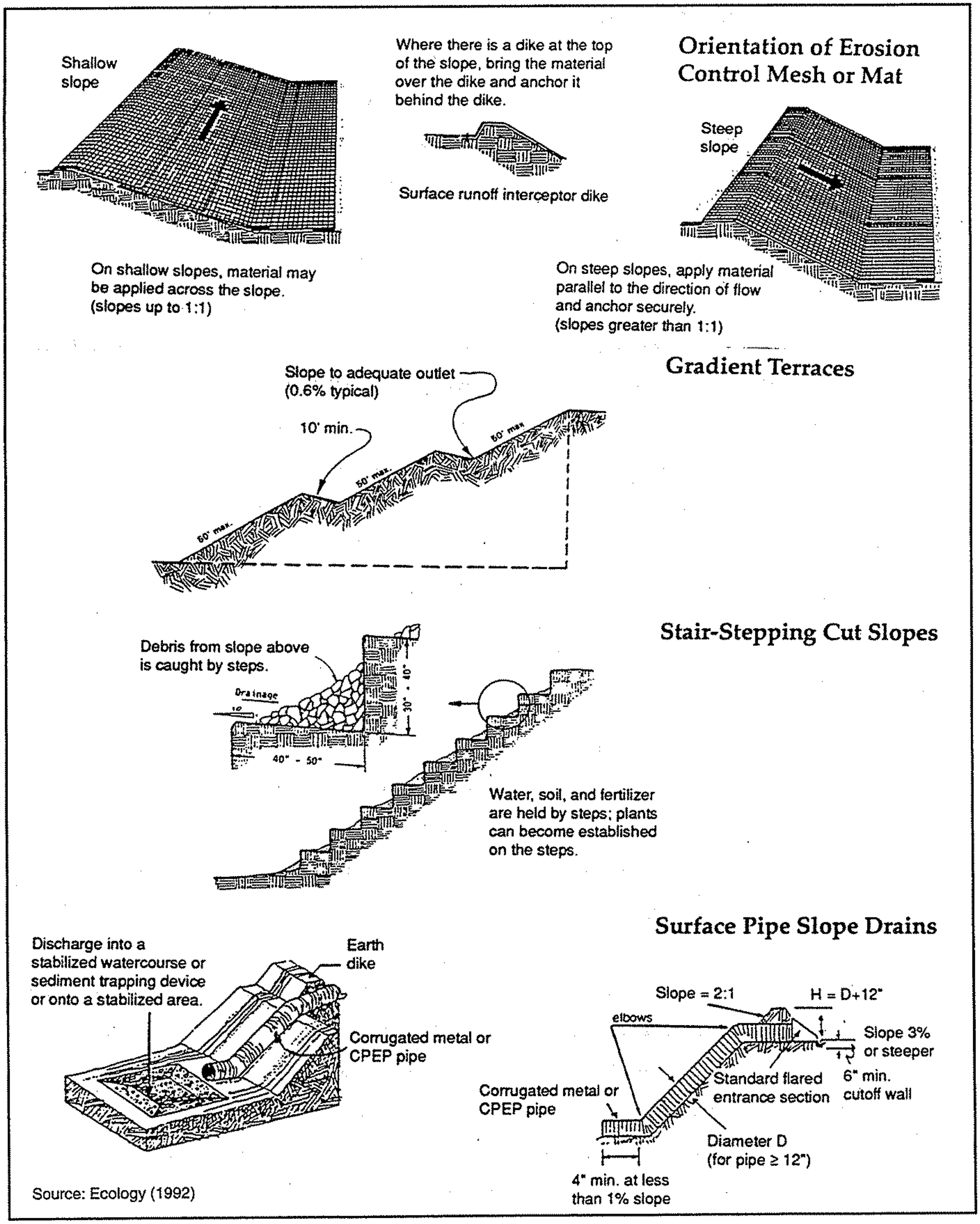


Figure 5-7
Surface Runoff Control

Mulching—preferable with organic mulch materials such as straw, wood chips, bark and wood fiber—provides instant protection to exposed soils. A surface mulch is recognized as one of the most effective means of controlling runoff and erosion on disturbed land. It can increase the infiltration rate, reduce soil moisture loss from evaporation, prevent crusting or sealing of the soil surface, modify soil temperatures, hold fertilizer, seed, and topsoil in place, and provide a suitable microclimate for seed germination (Ecology, 1992, BMP E1.15[2]). Unlike plastic sheeting, an organic mulch need not be removed for vegetation can grow right through it.

Nets and mats (typically made of plant fibers such as jute or coconut; Figure 5-7) may be used alone or in connection with organic mulches (i.e., **erosion blankets**), where soils are highly erodible, on slopes up to 50 percent, and along the banks of waterways. correct orientation of the netting and secure anchoring to the underlying soil are both important considerations (Ecology, 1992).

A smooth, graded soil surface tends to "crust" or harden up. Infiltration is reduced, vegetation hard to establish, and the potential for damaging runoff and soil erosion increases. A variety of **surface roughening** techniques can reduce these potential problems and are especially applicable on newly graded slopes (Ecology, 1992, BMP E2.35/40). Figure 5-7 illustrates gradient terraces and stair-step grading of cut slopes. Other methods include grooving, furrowing, and tracking (with bulldozer treads)—but the potential for unnecessary soil compaction from heavy equipment must be considered. Surface roughening offers only temporary benefits and seeding should be accomplished at the earliest opportunity.

5.6.3 Diversion, Collection, and Removal of Surface Runoff

Source reduction and infiltration enhancement provide solutions to runoff concerns that depend respectively on avoidance of the problem, and taking advantage of natural

---

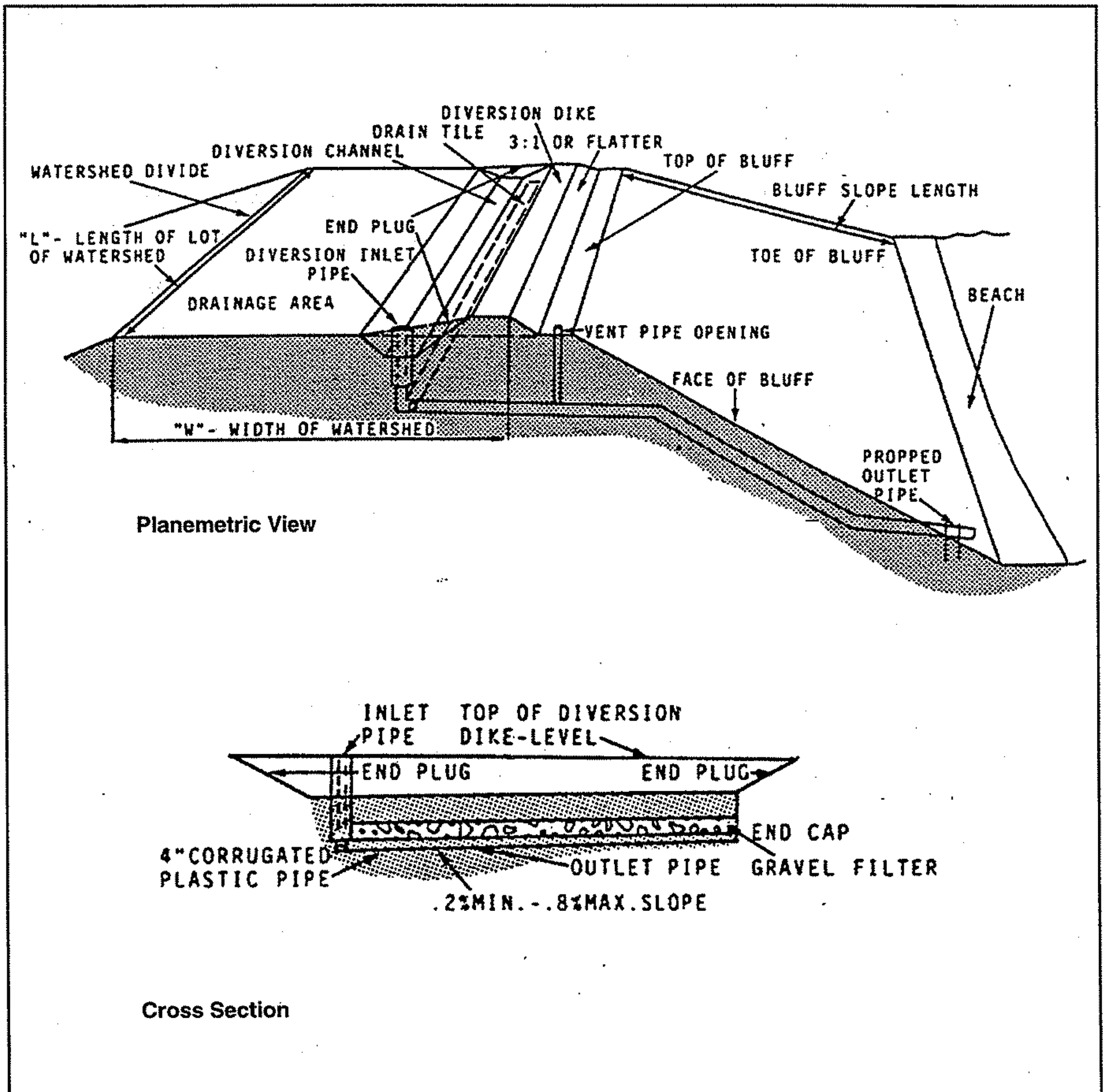
[2]BMP E1.15—Refers to specific Best Management Practices described in the Stormwater Management Manual for Puget Sound Basin (Ecology, 1992).

environmental processes. This third approach provides engineering/construction solutions to surface runoff control. The goal is to identify and collect together as many sources of surface runoff as possible from across a development site. Depending on specific site characteristics it may be appropriate to grade shallow drainage swales or install low interceptor dikes (e.g., Ecology, 1992, BMP E3.35) to channel sheet flow and surface runoff into a diversion channel or small holding pond (sediment trap). Once in the channel or pond, runoff would be carried via an inlet structure and closed "tightline" drain pipe from the top to the bottom of the shoreline bank or bluff (Figure 5-8; Herdendorf, 1984). The tightline drain can run down the surface of the bluff or be buried in a trench. (Be sure the trench itself does not become a drain or erosional gulley!) The purpose, of course, is to get the runoff to the beach without causing any erosion down the bluff face.

The upslope inlet structure allows excess water to drain, while trapping any sediment that has settled out in the diversion channel or pond. This reduces runoff-related turbidity problems. The drain outlet at the bottom of the bluff also needs to be designed to reduce outflow velocity and minimize beach erosion (Figure 5-7, bottom; Ecology, 1992, BMP E2.25). Discharge across a pile of rocks or cobbles may be appropriate.

Clearly, this type of engineering solution requires careful planning and is likely to be more expensive than the previous alternatives. Drainage swales, diversion channels, or ponds must all be sited carefully to avoid adding undesirable weight close to the bluff crest (i.e., surcharging). The diversion channel and temporary storage ponds should be lined with impermeable material (clay layer or plastic liner) to preclude infiltration. The purpose, remember, is to get as much surface runoff offsite as possible while avoiding both overland flow (and surface erosion) and infiltration (which adds to groundwater concerns).

Alternative approaches to that just described might be to collect runoff from all impervious surfaces and drain it in a direction completely away from the shoreline bank or bluff slopes—or drain it into the local storm water sewer system. The availability and/or appropriateness of these solutions will depend on the site location and local regulatory policies.



Source: Herdendorf (1984)

Figure 5-8
Blufftop Drainage System

In addition to development-related runoff, natural surface water, seeps, or springs that occur onsite can be collected in shallow interceptor trenches and diverted from the hillside by piping to a point below the slope.

The key to a successful drainage plan is one that will continue to work with minimal maintenance. Often pipes are placed on slopes that experience a slow failure or soil creep, which can displace and break the pipe. This can add more water to the slope and to critical stratigraphic units, compounding the problem rather than relieving it. Drainage pipes should be periodically checked, especially on slopes after periods of intense rainfall to see that they are operating as designed.

5.7 Groundwater Drainage Systems

It is more difficult to adequately control groundwater. Frequently, high groundwater levels are a result of interbedded and erratic sand lenses which can occasionally be intersected and pumped with wells or drains. But because of the fine nature of the soils which can surround the sand lenses, it can be difficult to intersect and effectively lower the water levels. Often, the source of groundwater recharge at the site comes from an area at a distance from the site and, as a result, it is hard to regulate the amount that is present at the site. Key approaches here include groundwater source reduction and the installation of different forms of subsurface drainage systems.

5.7.1 Source Reduction

Source reduction is a very significant component of controlling groundwater concerns for many coastal banks and bluffs. Capturing surface runoff from impervious areas and removing it before it infiltrates into the ground can reduce potential groundwater sources. The use and location of septic systems and septic drainfields also deserves particularly careful attention.

Canning (1991) notes that residential onsite sewage disposal systems can inject 40 to 100 gallons per person per day into the ground through the drain (leaching) field. If underlying strata or impervious horizons slope towards the shore then this additional source of groundwater can increase soil saturation at the bank or bluff face and increase landsliding hazards. As noted in Section 5.4, a qualified sanitarian should be consulted to help locate the new septic drainfield. An understanding of local stratigraphy and subsurface drainage patterns is critical, and recommended or required setbacks from the bluff crest may also be appropriate.

Once again source reduction is important. While installation of a drainfield may be unavoidable, its use can be minimized. More thought needs to be given throughout the Puget Sound coastal region to requiring installation of "water saver" toilets, with low flush volume requirements (Johnson and Stypula, 1993). Septic holding tanks with pump-out facilities may be preferable to drainfields in some locations, and use of totally self-contained "composting toilets" that have no drainfield, holding tank, nor chemical requirements deserves greater consideration. While these applications are not presently common they offer regional water-saving benefits, can reduce groundwater/soil saturation concerns, and could reduce nearshore pollution of shellfish beds that typically results in part, from poorly installed or inadequately maintained shoreline septic systems (Dunagan, 1991; PSWQA, 1992; Sargeant, 1993; PSWQA, 1994b).

5.7.2 Subsurface Drains

References cited for Section 5.6—Ecology (1992), Tainter (1982), and Herdendorf (1984)—also provide guidance for groundwater drainage systems. Additional details are included in *A Lake Michigan Shoreline Erosion Management Plan for Northern Milwaukee County, Wisconsin* (SEWRPG, 1988).

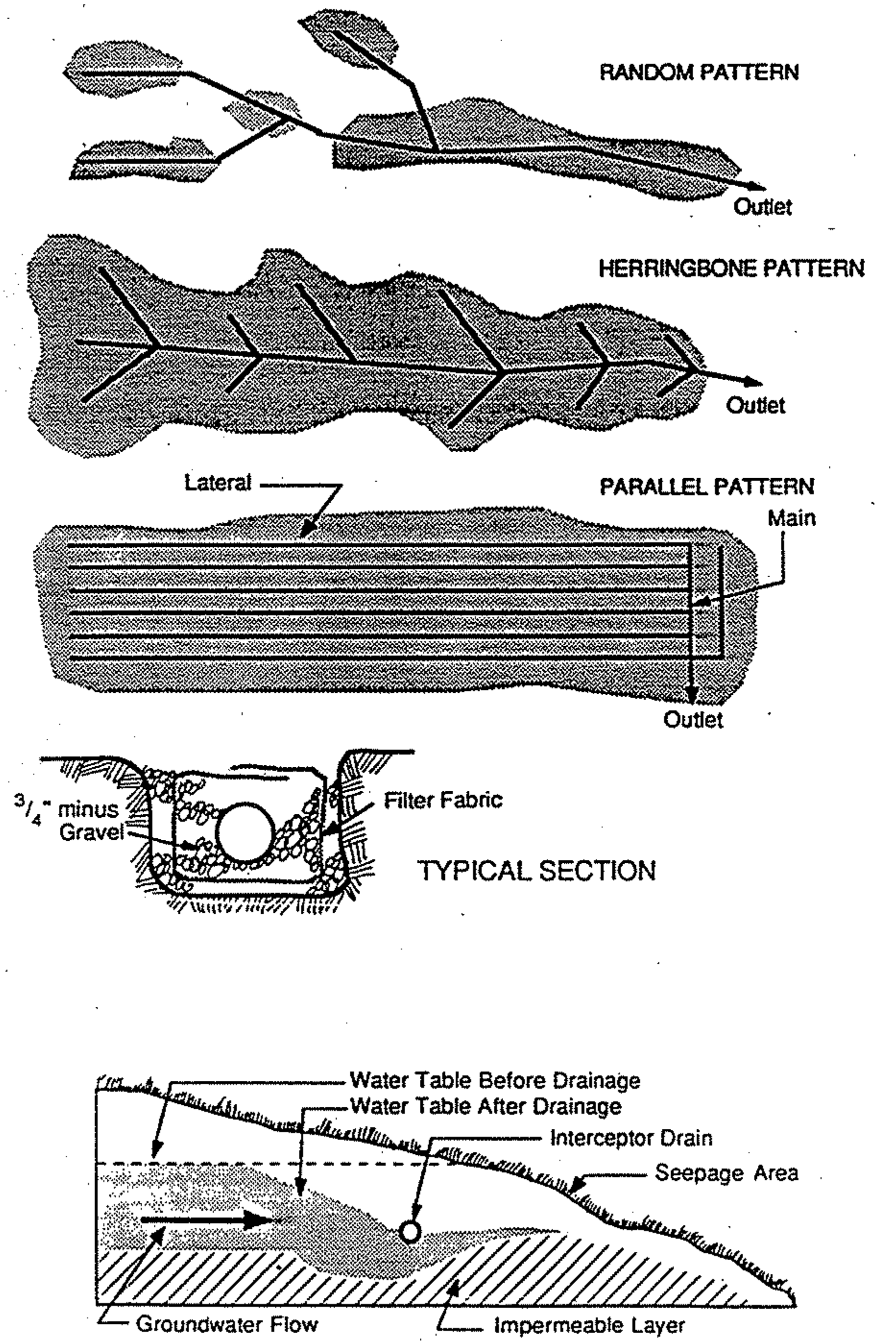
Subsurface drains provide a dewatering mechanism for draining excessively wet, sloping soils. A perforated conduit of pipe, tubing or tile is installed beneath the ground to intercept the groundwater and carry it away. The soil must be relatively deep and permeable for the system to be effective.

Relief drains are used to lower the water table (to improve vegetation growth, for example) or remove surface water. They are installed along a slope and drain in the direction of the slope. Typical installation patterns are shown at the top of Figure 5-9 (Ecology, 1992, BMP E2.30).

Interceptor drains are used to remove water as it seeps down a slope, thus reducing soil saturation and the associated risk of slippage. Here, the installation typically consists of a single underground perforated pipe that cuts *across* the slope and drains to the side of the slope. Figure 5-9 shows an installation cross section. The pipe is surrounded by gravel and wrapped in filter fabric to prevent infiltration and clogging of the drain with fine sediments. Figure 5-9 (bottom) illustrates how a successful interceptor drain modifies the local groundwater table. Given the regional groundwater/landsliding relationships documented by Tubbs (1975), lowering of the groundwater table should result in increased slope stability.

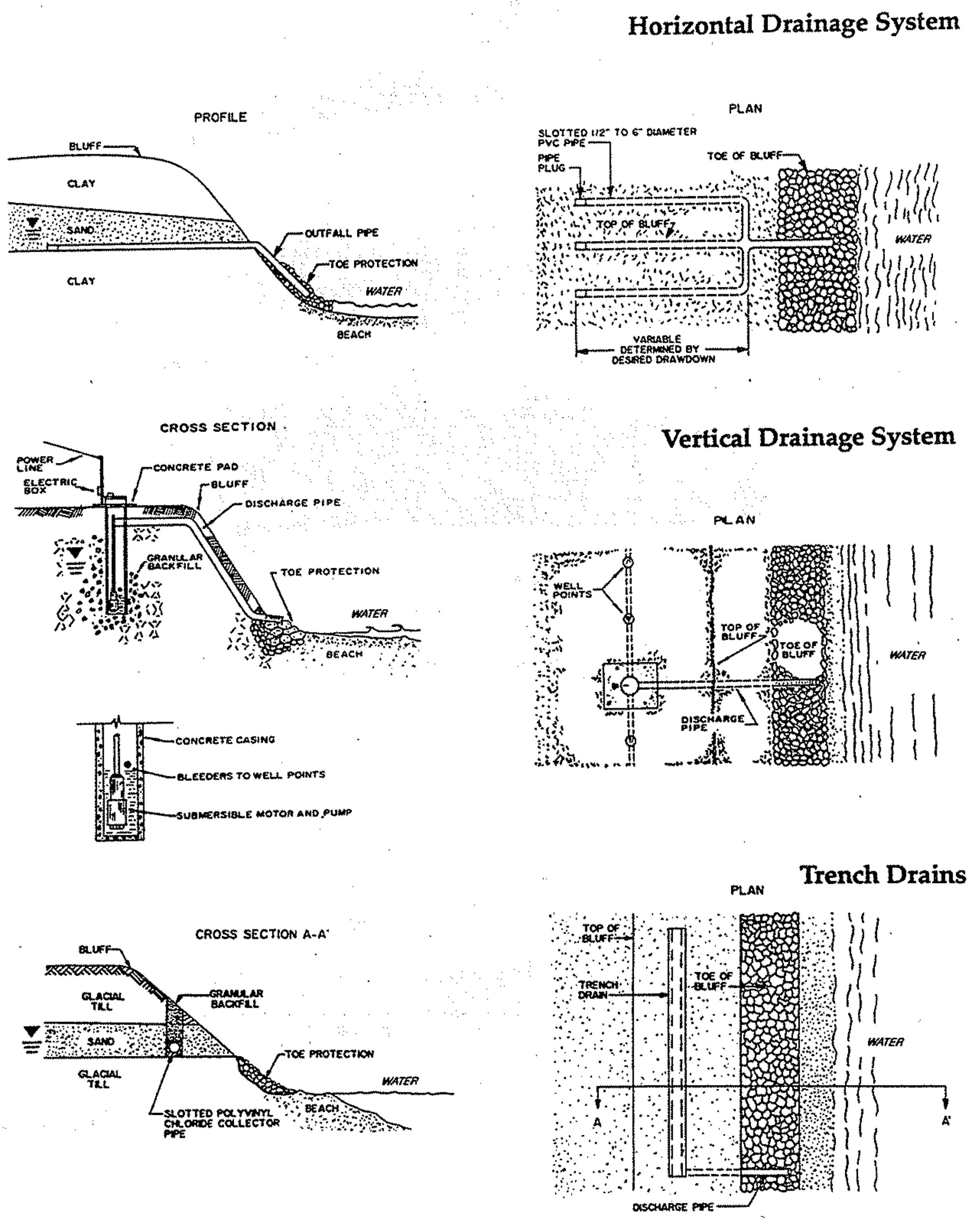
As with surface drains, it is very important that the outlet of a subsurface drain empty into a sediment trap or pond. If the flow is free of sediment it can be discharged into a receiving channel, drainage swale, or stable well-vegetated area adequately protected from surface erosion (Ecology, 1992, BMP E2.30). If appropriate, discharge could again be "tightlined" to the toe of the bank or bluff, for release over a pile of rock or cobbles, and across the beach. Subsurface drains need to be maintained to be sure they are free-flowing. Tree roots can be a problem for subsurface drains and buried pipes must be adequately protected if crossed by heavy vehicles.

Figure 5-10 (SEWRFC, 1988) illustrates three variations of groundwater drainage systems that may be appropriate for dewatering coastal banks and bluffs. The inverted triangle in each diagram indicates the location of the groundwater table. The horizontal drainage system (top) is operating as a relief drain; while the vertical well drainage system (center)



Source: Ecology (1992)

Figure 5-9
Subsurface Drains



Source: SEWRPC (1988)

Figure 5-10
Groundwater Drainage

and trench drains (bottom) are each modifications of interceptor drains. Finally, Figure 5-11 (Herdendorf, 1984) illustrates a conceptual bluff drainage system, also from the Great Lakes, that incorporates both vertical well and horizontal drainage systems—and as in Figure 5-8 carries the outflow to the toe of the bluff for discharge. Additional design details are presented in Herdendorf (1984).

It is important to remember with all the surface and subsurface drainage systems described above (Sections 5.6 and 5.7) that individual site conditions will dictate specific solutions. The specifics of drainage design must also be adequate to handle "design storm" runoff and infiltration characteristics given the size, slopes, and cover types of the site. Professional advice should be sought before installing such systems (Tainter, 1982).

5.8 Biotechnical Slope Protection

Slope stabilization has been traditionally viewed as an "engineering problem" and a common first response is to recommend building something—preferable something big and heavy. The sheer mass and strength of a reinforced concrete wall, cantilevered pilings, or a sheetpile bulkhead may certainly do the job, and in some situations, may represent the only viable solution. This is the "brute force" approach to overcoming natural slope processes, however, and it tends to be expensive, may require heavy equipment access, and is visually intrusive—especially in a natural forested bluff or shoreline setting.

Biotechnical slope protection (Gray and Leiser, 1982) offers a range of poorly known but increasingly popular alternatives in which vegetation is used to provide slope reinforcement and barriers to soil movement. Here, the key is to understand and take advantage (i.e., leverage) natural slope processes rather than overcome them by brute force. A broad range of biotechnical slope protection methods is available (Table 5-1). Some rely solely on the use of vegetation (soil bioengineering; Myers, 1993), while others combine the soil reinforcement and buttressing qualities of vegetation with other slope stability structures (biotechnical engineering; Myers, 1993). Conventional structures—the

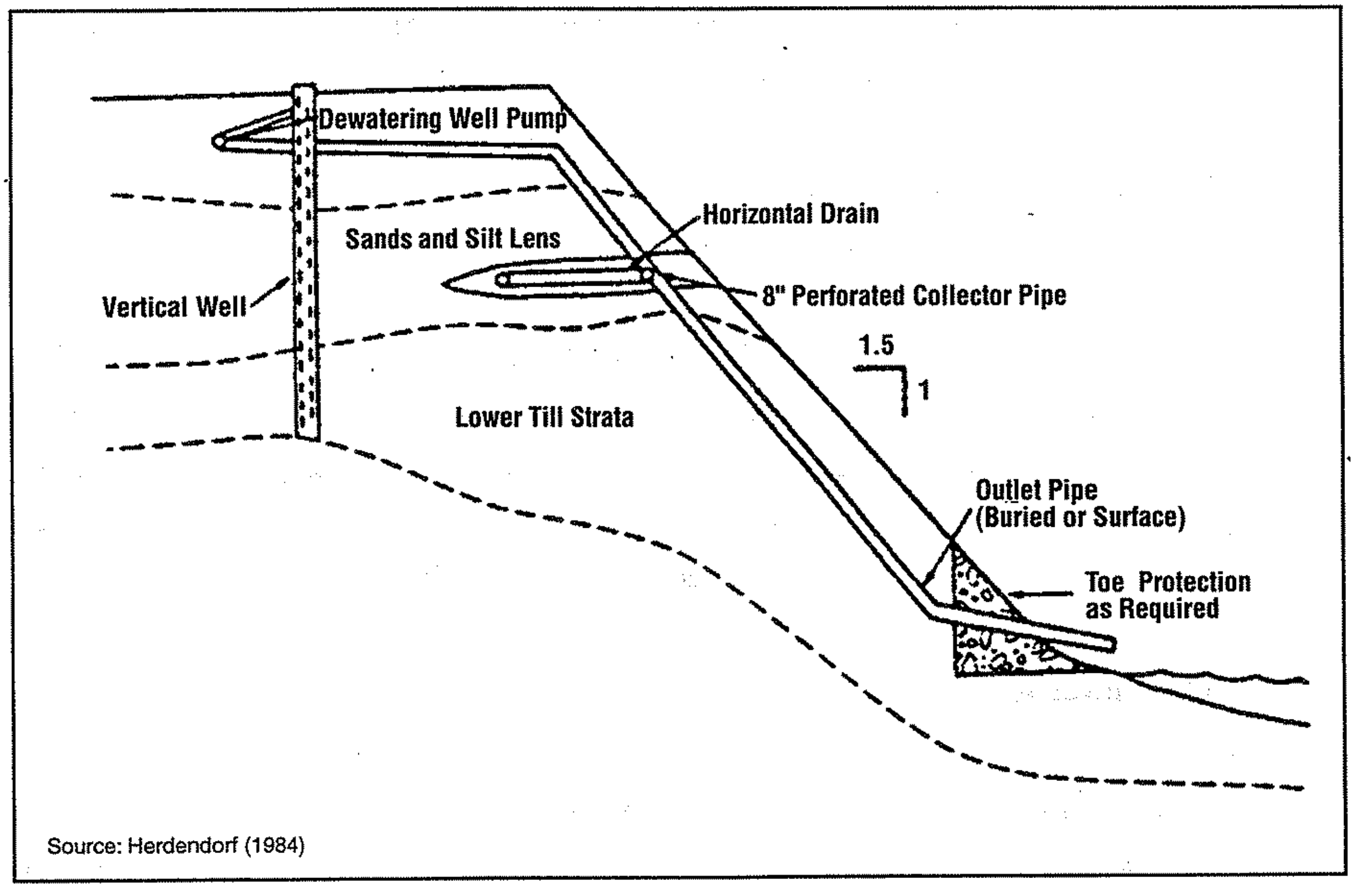


Figure 5-11
Vertical Well and Horizontal Drain Systems for Groundwater Control

Table 5-1
Approaches to Biotechnical Slope Protection

	Category	Examples	Appropriate uses	Stabilizing mechanism or role of vegetation
Live construction	Conventional plantings	—Grass seeding —Transplants	—Control of surficial rainfall & wind erosion —To minimize frost effects	—To bind & restrain soil particles —To filter soil from runoff —To intercept raindrops —To maintain infiltration —To change thermal character of ground surface
Mixed construction	Woody plants used as reinforcement & as barriers to soil movement	—Live staking —Contour-wattling —Brush-layering —Reed-trench-terracing —Brush mats	—Control of surficial rainfall erosion (rilling & gullying) —Control of shallow (translational) mass movement	Same as above, but also to reinforce soil & resist downslope movement of earth masses by buttressing & soil arching action.
Mixed construction	Woody plants grown in interstices of low, porous structures or benches of tiered structures	—Vegetated *revetments* (riprap, grids, gabion mats, blocks) —Vegetated *retaining walls* (open cribs, gabions, stepped-back walls, & welded-wire walls)	—Control of shallow mass movements & resistance to low-mod. earth forces —Improvement of appearance & performance of structures	—To reinforce & indurate soil or fill behind structure into monolithic mass. —To deplete & remove moisture from soil or fill behind structure.
Mixed construction	Toe walls at foot of slope used in conjunction w/ plantings on the face	Low, breast walls (stone, masonry, etc.) with vegetated slope above (grasses and shrubs)	Control of erosion on cut & fill slopes subject to undermining at the toe	To stop or prevent erosion on slope face above retaining wall
Inert Construction	Conventional structures	—Gravity walls —Cantilever walls —Pile walls —Reinforced earth walls	—Control of deep-seated mass-movement & restraint of high lat. earth forces —Retention of toxic or aggressive fills & soil	Mainly decorative role

Source: Gray and Leiser (1982)

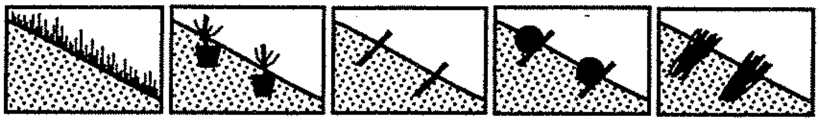
brute force solutions, discussed in Section 5.9—may also use vegetation, but solely in a decorative role.

There are an increasing number of excellent sources available—several of them focused specifically on the Puget Sound region—that provide descriptions of biotechnical slope protection methods. These references typically outline detailed planning and installation procedures, list plant species (preferably native plants) appropriate to the different methods, and include photo sequences of before-during-after field installation. The following references are particularly useful: *Biotechnical Slope Protection and Erosion Control* (Gray and Leiser, 1982); *Slope Stabilization and Erosion Control Using Vegetation; A Manual of Practice for Coastal Property Owners* (Myers, 1993); *Guidelines for Bank Stabilization Projects in the Riverine Environments of King County* (Johnson and Stypula, 1993); and *Soil Bioengineering for Upland Slope Protection and Erosion Reduction* (Soil Conservation Service, 1992).

This section of the report, rather than repeating the excellent material available in these references, briefly outlines the most commonly used slope stabilization planting techniques and provides typical illustrations of each method. The reader is referred back to the original references for more specific installation and performance details. The methods outlined include: seeding, container or bare root plantings, live staking, contour wattling, reed trench terracing, and contour brush layering. Myers (1993) provides a table, reproduced here as Figure 5-12, summarizing the general applicability (advantages/disadvantages) of most of these methods.

Myers' (1993) introductory discussion reinforces the value of maintaining native vegetation onsite; leaving a dense, protective greenbelt along the crest of the bluff; and carefully planning the specific location of a bluff- or bank-site residence. He recommends separate planting approaches be used for the crest (strengthen soils, reduce erosion), face (resist shallow sliding and manage surface runoff), and toe (resist downslope soil movements, wet soils, some saltwater spray) of a slope, and provides an extensive plant selection guide for Puget Sound sites.

GENERAL APPLICABILITY



ADVANTAGES/ DISADVANTAGES	SEEDING (MIXED SPECIES)	CONTAINER BARE ROOT	LIVE STAKING	CONTOUR WATTLING	BRUSH LAYERING
Rainfall Erosion: Foliage intercepts raindrops	●	●	●	●	●
Runoff Erosion Control: Roots bind surface soil particles	●	●	●	●	●
Wind Erosion Control: Plants reduce wind exposure	●	●	●	●	●
Frost Action Erosion Control: Roots restrain soil movement	●	●	●	●	●
Slope Stabilization: Reinforce soil & resists shallow seated landsliding		●	●	●	●
Slope Stabilization: Plants help dewater slope		●	●	●	●
Runoff Erosion Control: Plants filter soil particles from runoff	●			●	●
Immediate Erosion Control/Slope Stabilization	●				
Slope Stabilization: Resistance to deep seated landsliding					
Low initial maintenance	●				
Low long-term maintenance	●	●	●	●	●
Low impact construction	●	●	●	●	
Plants prevent slope undercutting by waves					
Relative low-cost construction	●	●	●	●	●
Plants combine with other structural features	●	●	●	●	●
Aesthetic/wildlife benefits		●	●	●	●

Source: Myers Biodynamics (1993)

Figure 5-12
Applicability of Planting Techniques

Seeding

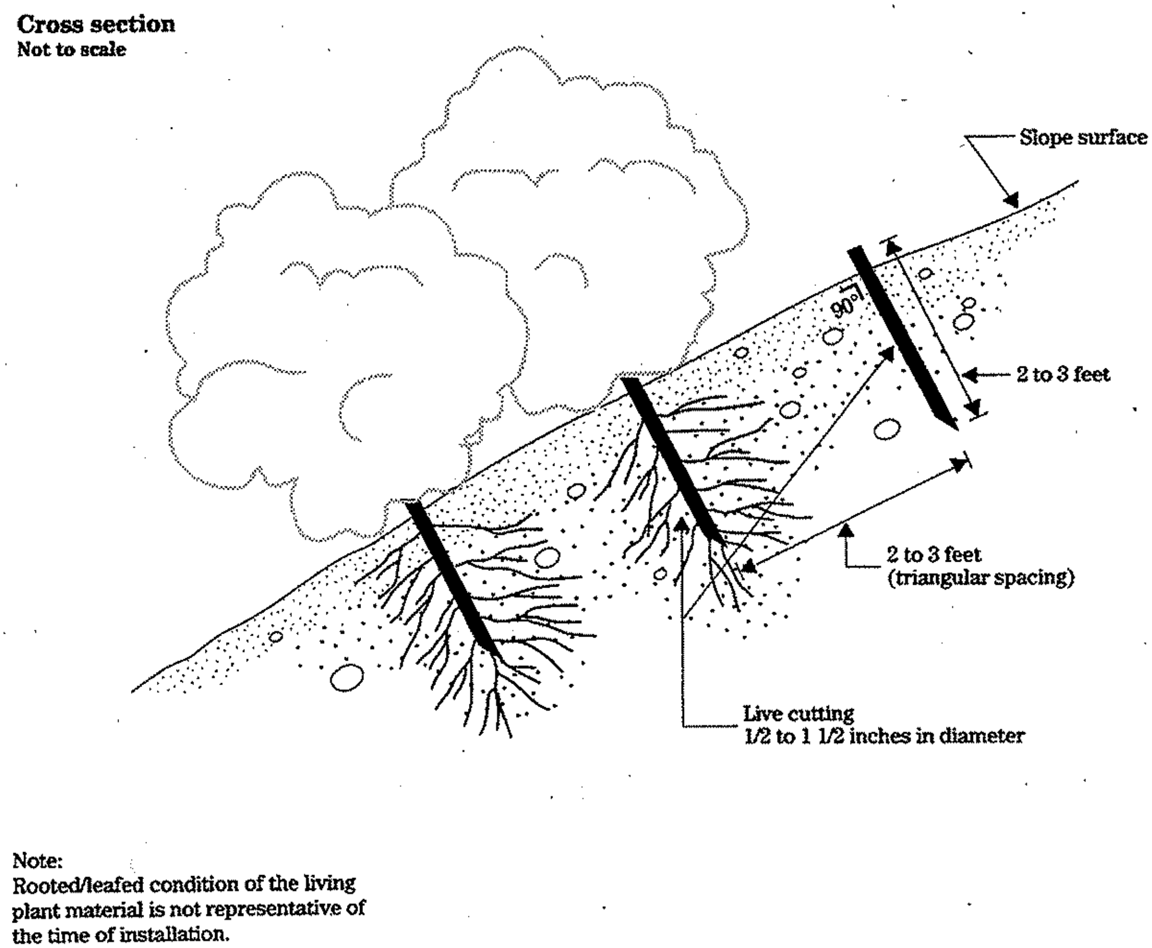
The application of grass, forb, and woody plant seeds to slope areas—by hand-broadcasting seed mixes, placing seeds in individual holes, or hydroseeding—creates a shallow, fiberous rooting zone that effectively binds near-surface soils against surface runoff and wind erosion. The use of fertilizers, mulches, and matting (Section 5.6.2) may all be appropriate.

Container or Bare Root Plantings

Use of nursery-grown container or bare root plantings, installed in holes excavated on the bank/bluff crest or face, achieves faster rooting results than seeding. Plant material is best installed in the fall or spring. Myers (1993) suggests planting closely-spaced groups of mixed species. This way, a variety of difference rooting structures is developed and the species best adapted to the particular planting microhabitat will become dominant. Watering can be a problem during plant establishment and mulching can be beneficial.

Live Staking

Live staking (Figure 5-13) involves cutting lengths of live woody plant branches (2-3 feet long, 0.5-1.5 inches diameter) and installing them into a slope face. The plant material is both cut and installed in the fall or spring, when dormant. Live stakes should be placed in predrilled holes a little smaller than the stake diameter. Myers (1993) suggests planting in a diamond pattern across the slope so that consecutive rows of live stakes are offset from one another. Hardy species that root easily and grow into mature woody shrubs are preferred (see Myers, 1993). Stake sources are plentiful and inexpensive, but it takes time for the stakes to root and grow sufficiently to offer slope stability and protection against erosion.



Source: SCS (1992)

Figure 5-13
Live Stake Installation

Contour Wattling

Contour wattling (also referred to as live wattling or live fascine installation) involves bundling together a group of long, live branches. Cut and uncut ends are alternated to create a bundle—often of mixed species or species sources—6 to 10 inches in diameter, 4 to 8 feet long, and tied with twine at 12 to 15 inch intervals (Figures 5-14 and 5-15).

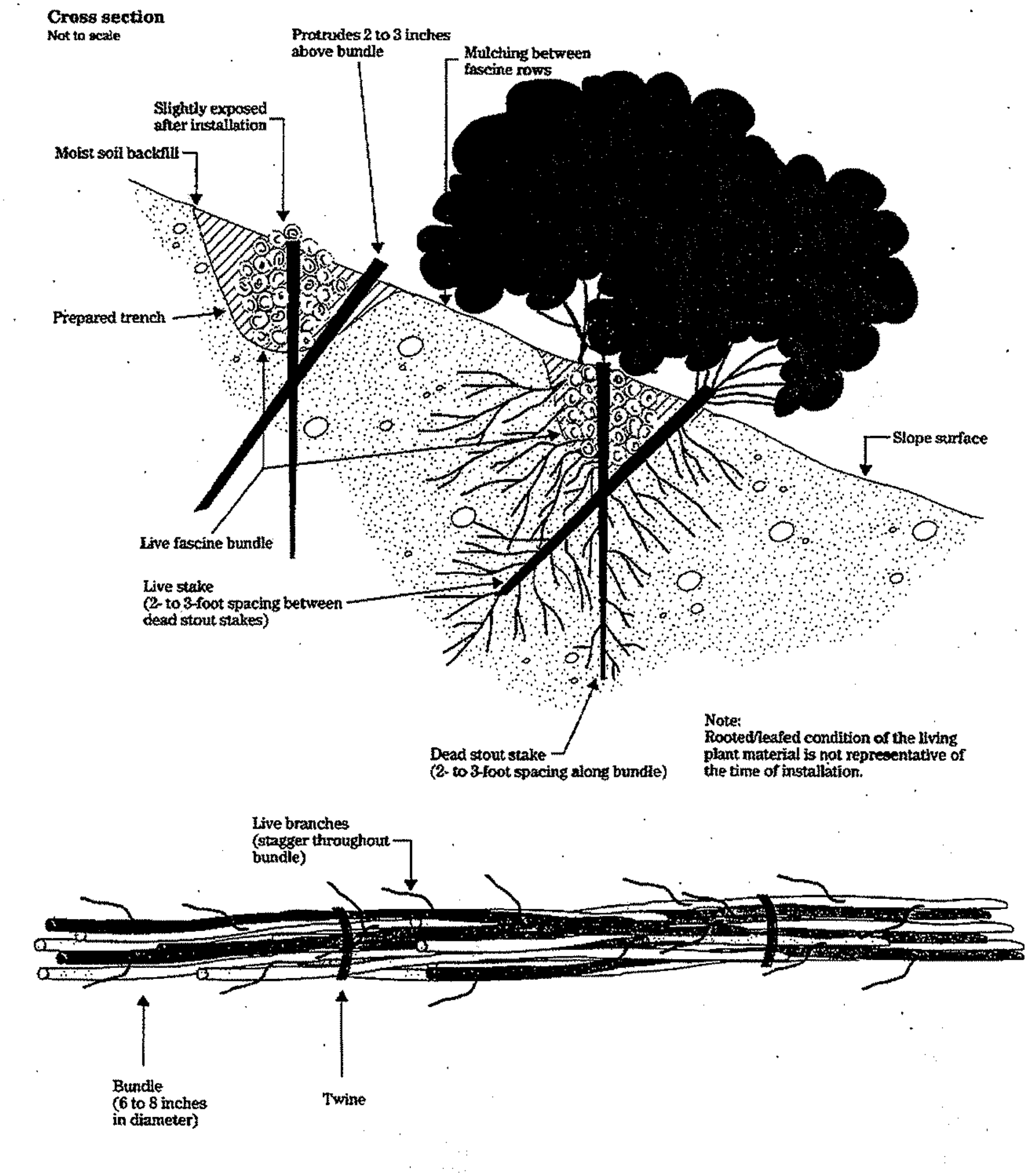
These wattles or fascines are then installed in shallow trenches cut parallel with the contours across a sloping bank or bluff face. Wooden stakes and live stakes are used to anchor the wattles in place, and the trench is backfilled with moist soil (Figure 5-15). A small amount of the wattle material (20 percent) should remain above the soil after installation.

The end result, show immediately after installation in Figure 5-16, creates a series of steps or ridges that parallel the slope contours, helping to intercept both surface runoff (and sediment) and route it laterally before it causes problems.

Myers (1993) notes that willow, red-osier dogwood, and snowberry are local, woody plants particularly suited to contour wattling. The method is rather slow and time consuming, requires considerable plant material, and may initially require additional watering to get the plants started. As both the wattle material and live stakes take root and grow, this method provides good erosion control.

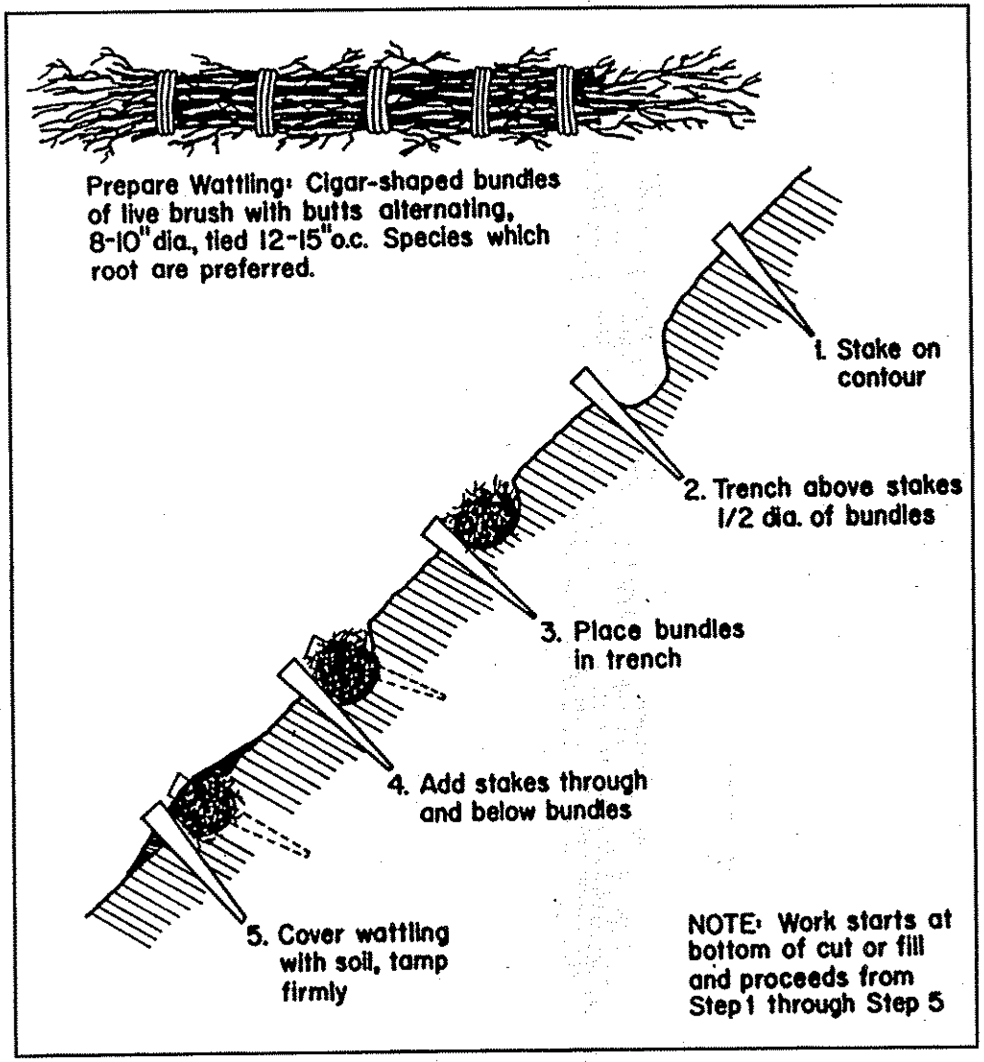
Reed-Trench Terracing

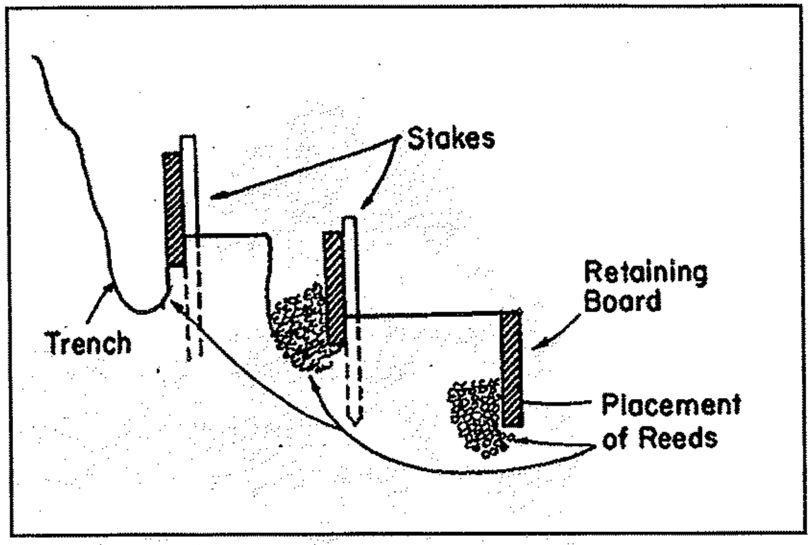
Reed-trench terracing (Figure 5-15) involves burying bundles of reeds in the bottom of a narrow trench, dug across a slope and supported by a downslope retaining board. It is most commonly used to stabilize sandy banks and bluffs. The effect is to create a series of shallow benches or terraces that stop sandfall and allow the establishment of more permanent slope-holding vegetation.



Source: SCS (1992)

Figure 5-14
Live Wattling (Fascine) Installation





Cutaway diagram of reed-trench terracing. Reeds are placed in narrow trenches dug behind retaining boards. Center-of-mass of reeds should be at juncture where wood meets sand.

Preparation of wattling and installation procedure. Sequence of operations is shown schematically in the diagram.

Source: Gray and Leiser (1982)

Figure 5-15
Live Wattling and Reed-Trench Terracing

Newly recontoured slope stabilized by contour wattling, Redwood National Park, California

Source: Gray and Leiser (1982)

Figure 5-16
Contour Wattling

The buried reeds perform both mechanical and organic functions. They prevent sand washing out below the bottom of the retaining boards and they absorb and retain water. This reduces erosion and gullying while at the same time providing a source of moisture and soil aeration to support new plant growth (Gray and Leiser, 1982).

Common reed grass (*Phragmites communis*) is primarily an East Coast species, although it occurs as an exotic in Washington. Other species such as cattails might serve a similar purpose if not taken from a protected wetland site.

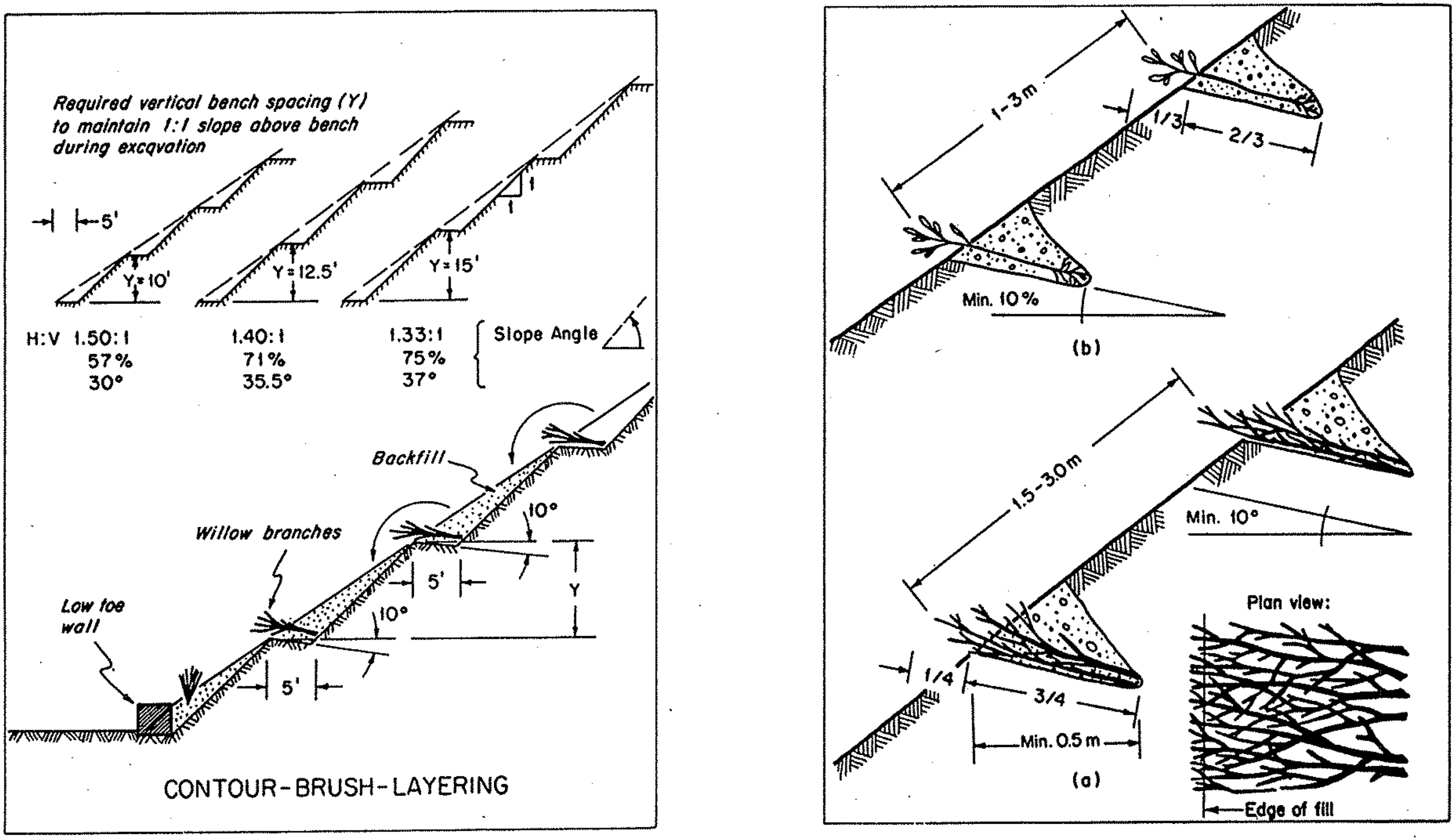
Contour Brush Layering

Brush layering (Figure 5-17) involves installing a continuous layer or band of live plant material (either cut green branches or live saplings) across a series of contoured terraces or trenches dug on a slope face. Unlike wattling where the plant material is installed parallel with the slope face, in brush layering, the live plant material protrudes at a right angle from the slope. The brush layers, in effect, act as fences to capture debris that would otherwise move downslope. Myers (1993) notes that this technique can be highly disruptive of natural slopes and is best used in situations where coastal slopes are already highly disturbed or badly eroded. With some modification, the brush layering approach can also be used to restore highly eroded gully areas (Gray and Leiser, 1982).

It should be noted with regard to all of the biotechnical slope protection approaches described above, that they work best on slopes of up to about 33 degrees (1.5:1). Vegetation is difficult to establish on slopes that are steeper than this without also employing other slope reinforcement techniques (Gray and Leiser, 1982). Examples of these more conventional construction techniques are described in Section 5.9.

5.9 Conventional Structures

Prior to discussing conventional structures for slope stabilization, it is important to review the processes that affect the stability of coastal bluffs. Recognition of these processes and



Source: Gray and Leiser (1982)

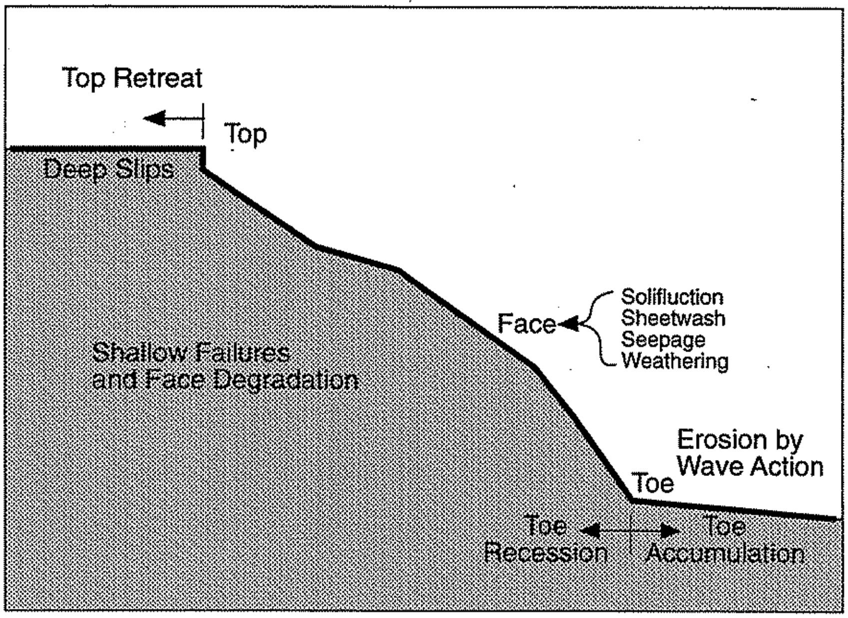
Figure 5-17
Contour Brush Layering

how they impact the slope will alert the property owner to the most appropriate methods for slope stabilization. The three processes and the engineering solutions are shown schematically in Figure 5-18. Structural stabilization implements solutions that are site-specific and reduce coastal erosion. These solutions are accomplished by providing an artificial protective barrier against direct wave attack on the beach and bluff toe, by increasing the extent of the beach to absorb and dissipate wave energy before the water reaches the bluff and/or by stabilizing bluff slopes. The problems associated with structural solutions are generally of three types: (1) attempts that are not engineered and fail to solve the problem; (2) engineered solutions that neglect to consider all the processes shown in Figure 5-18 and how they apply to a site and; (3) solutions that address a short length of shoreline rather than the entire shoreline reach, and therefore result in adverse affects on adjacent shoreline areas (Edil and Bosscher, 1988).

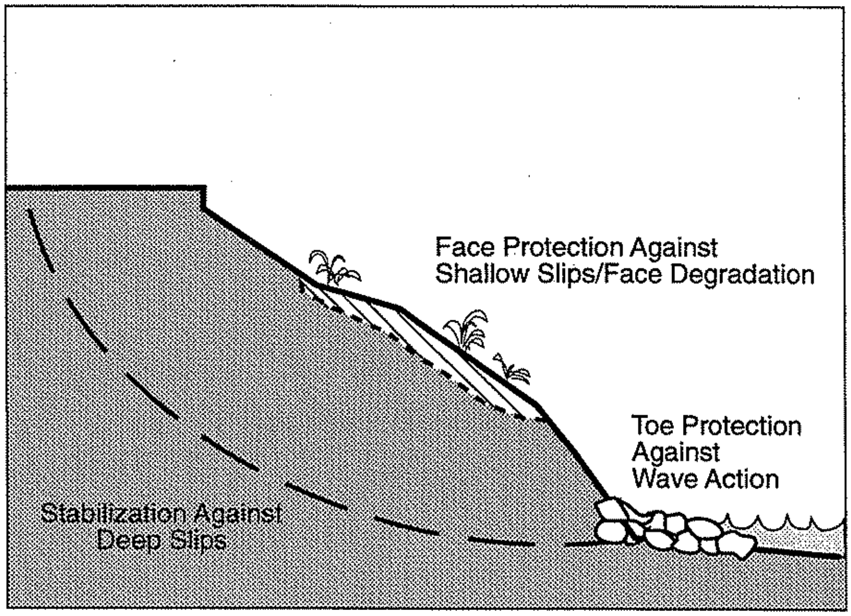
It must be remembered in many cases slide areas extend beyond limits of one piece of property and to properly stabilize an area, a stabilization scheme must incorporate the total landslide area and the cooperation of all involved. Costs involved with stabilizing large landslide can often be prohibitively expensive. When dealing with large landslides, construction sequencing becomes critical, so that any further disturbance does not initiate any additional movement.

5.9.1 Slope Stability

Factors that dictate the inherent stability of the slope are those related to the geometry (slope height and slope inclination), drainage (surface water and groundwater), stratigraphy (type and orientation of geologic units), and forces that act on the slope (wave, water, and wind erosion). The extent of these factors acting on the slope will determine whether the slope is subject to either deep or shallow failures, or degradation of the face of the slope, and will dictate which solutions are most appropriate. A knowledge of the potential type of slope failure is essential in evaluating natural slopes and in determining a solution to prevent such a failure. Additional information regarding the causes of slope instability is presented in Section 4.0 of this report.



Slope Processess and Mass Movement



Engineering Solutions

Source: Edil (1980)

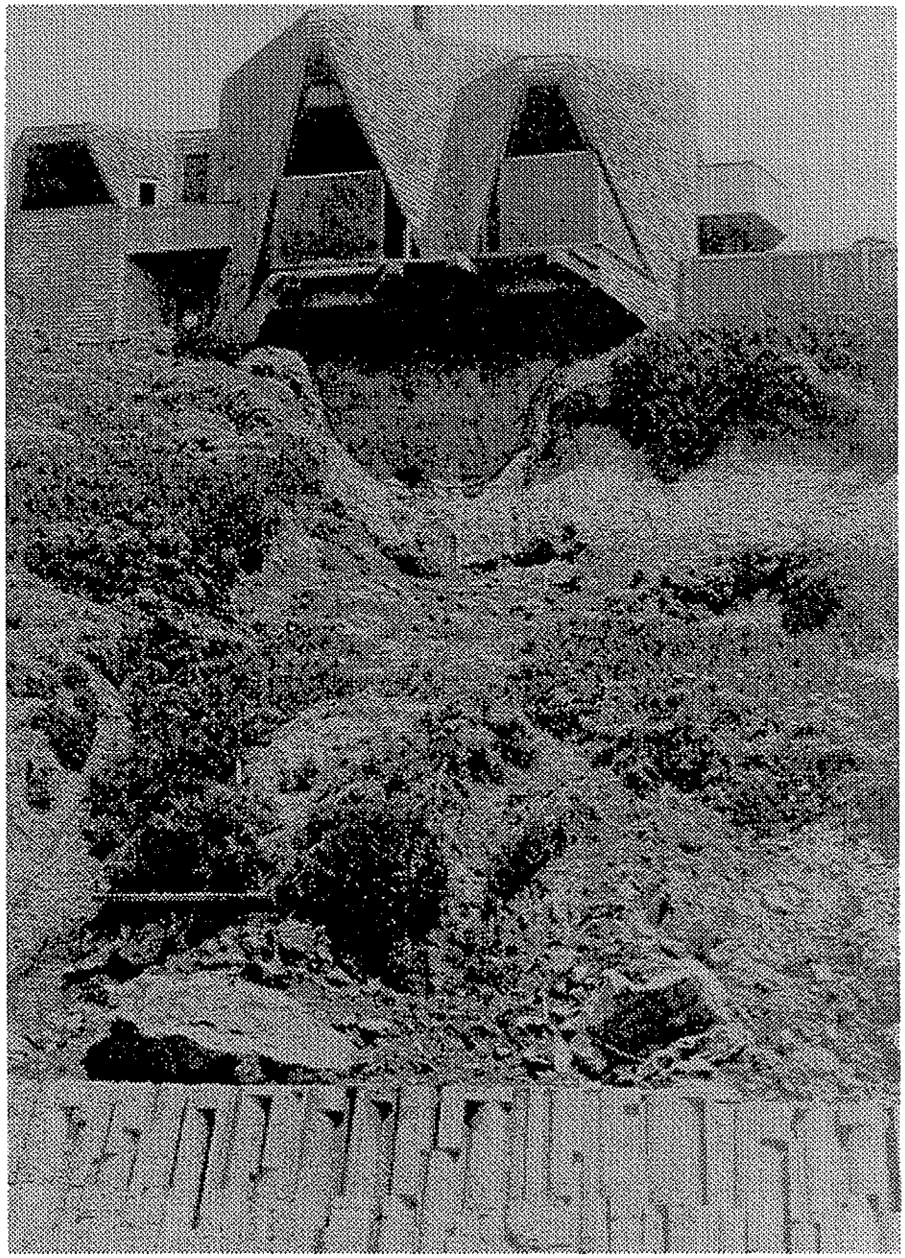
Figure 5-18
Engineering Solutions to Slope Instability

5.9.2 Toe Erosion

Starting at the base of the shoreline bank or bluff, one of the major factors in reshaping the slope is wave action resulting in toe erosion (Figure 5-18). Toe erosion undermines the slope and can result in slope instability. **However, it should be noted that controlling toe erosion will not prevent a landslide on a slope that is marginally stable from factors not related to wave action** (Figure 5-19). Wilcock, Miller and Kerlin (1992) confirm that recession of the middle and upper portions of coastal bluffs (in Chesapeake Bay—as in Puget Sound) is driven by hydrogeological erosion processes related to surface runoff and groundwater seepage rather than wave undercutting, which impacts the lower slopes (i.e., toe erosion). Toe erosion has be prevented with man-made structures for decades at two of their Calvert Cliffs study sites, yet active erosion of the middle and upper slopes continues.

Various factors must be considered in evaluating wave action that itself is not a constant and also varies from site to site. The extent of wave erosion on a slope will be dependent on the following factors: (1) wave climate (velocity, duration, and fetch); (2) nearshore and offshore bathymetry; (3) shore configuration (orientation); (4) water level; (5) composition of bluff (underlying geologic units); and man-made coastal structures (Edil and Vallejo, 1980; Shih 1992). The extent of wave action on the toe of a slope should be evaluated by a qualified coastal engineer. Engineered approaches that resist toe erosion include "hard solutions" such as seawalls, bulkheads, and revetments, as well as "soft solutions" such as beach nourishment. Many of these approaches are discussed in the Task 2 report titled "Engineering and Geotechnical Techniques for Shoreline Protection in Puget Sound". Additional information regarding the design of these structures can be found in the Shore Protection Manual (U.S. Army Corps of Engineers, 1973).

Cutting the toe of the slope whether by natural or manmade alterations, will also negatively impact the stability of the slope. Often, the action can be as minor as a small cut to open up an area for construction. In the case of shoreline slopes, constant wave action at the toe of the slope will eventually weaken the materials in contact with the waves, causing failure or slippage of that unit, and in many cases, the overlying units. A variety of methods can



Concrete seawall protecting Mendocino coast home. Wave erosion has been temporarily halted, but runoff and slumping are still taking place upslope.

Source: Griggs, Pepper and Jordan (1992)

Figure 5-19
Seawall Fails to Stop Bluff Runoff and Slumping

be used to reduce the impact from removal of this support. However, it must be remembered in many cases slide areas extend beyond limits of one piece of property and to properly stabilize an area, a stabilization scheme must incorporate the total landslide area and cooperation of all involved. Costs involved with stabilizing large landslides can often be prohibitively expensive. When dealing with large landslides, construction sequencing becomes critical, so that any further disturbance does not initiate any additional movement.

5.9.3 Deep-Seated Slope Failures

Engineered solutions that protect against deep-seated slope failures include: regrading to remove the unstable material, buttresses, and various retaining structures—often used in conjunction with drainage improvements where feasible. It is often difficult to adequately drain deep landslides. Frequently, high water levels are a result of interbedded and erratic sand lenses that can occasionally be intersected and pumped with wells or drains. But because fine-grained soils often surround the sand lenses, it can be difficult to intersect them and effectively lower the water levels. In addition, the existing strata are often disturbed so extensively from landslide movements that there is no continuous permeable layer from which to pump or drain water, even though the deposit itself is saturated. Often, the source of groundwater recharge to a particular site is located some distance away from the site and, as a result, it is hard to regulate the amount of groundwater that is present at the site.

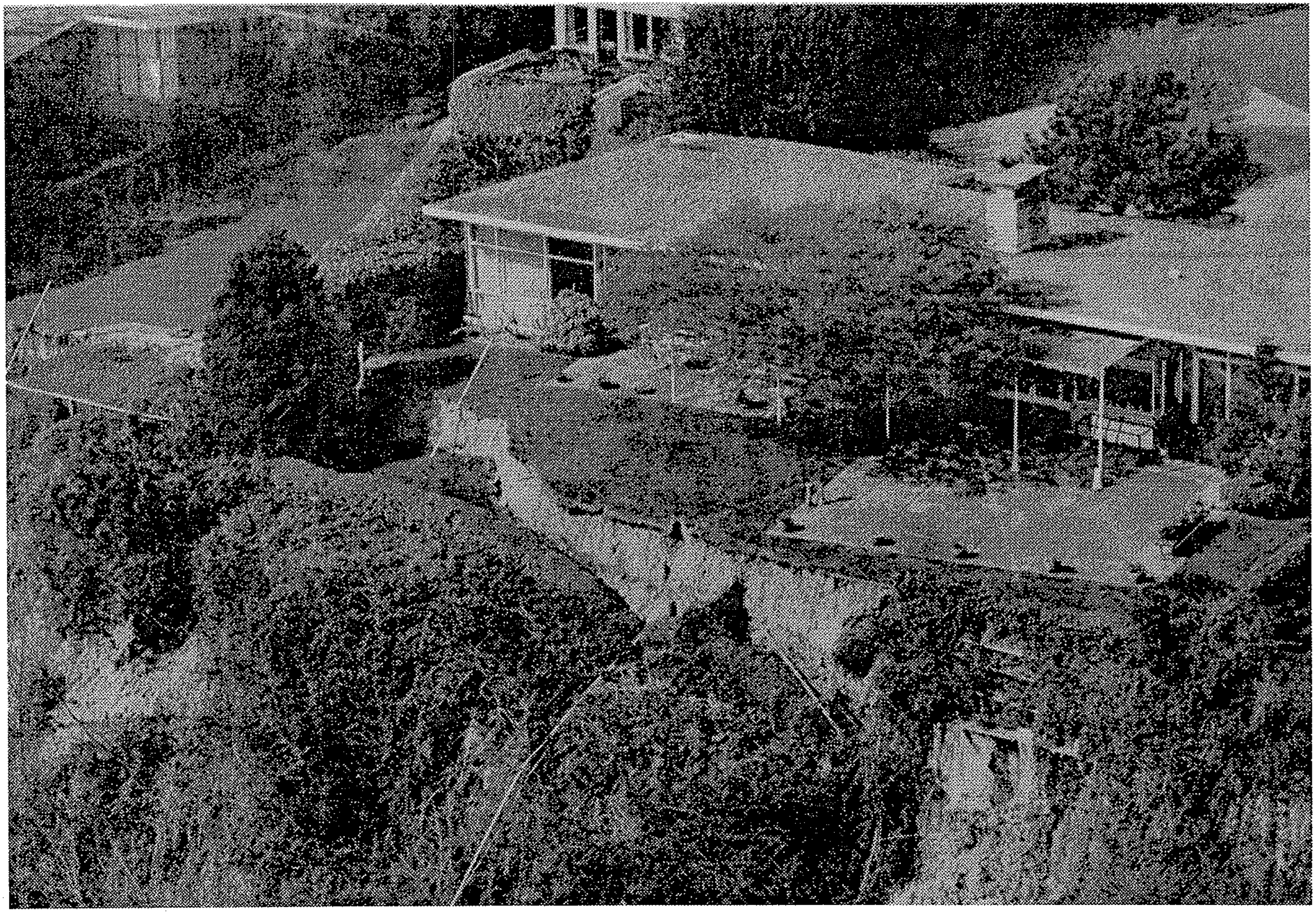
Effective landslide control typically involves a combination of methods that together have the effect of *minimizing the driving forces* (surcharging or adding fills or removing lateral support, and/or increases in water levels) *and increasing the resisting forces* (installing a buttress system). In addition to being expensive, construction methods for landslide stabilization can frequently require more space than is available in most coastal situations to safely and economically operate the construction equipment without additional slope movement occurring.

Magnolia Bluff, immediately behind Elliott Bay Small Craft Harbor in Seattle, provides an example of major, deep-seated, rotational slide movements on a coastal bluff that have been stabilized with a gravity fill. Two adjacent deep-seated slides, each several hundred feet across, were impacting as many as ten or more home sites on top of Magnolia Bluff (Figure 5-20). As each slide rotated downslope, its toe was causing uplift in the intertidal zone. As part of the marina construction plan, both slides were stabilized by adding an average of 25 feet of fill over the slide toes (Figure 5-21). This provided sufficient mass to halt rotational movement within the bluff (U.S. Army Corps of Engineers, 1987).

Buttressing

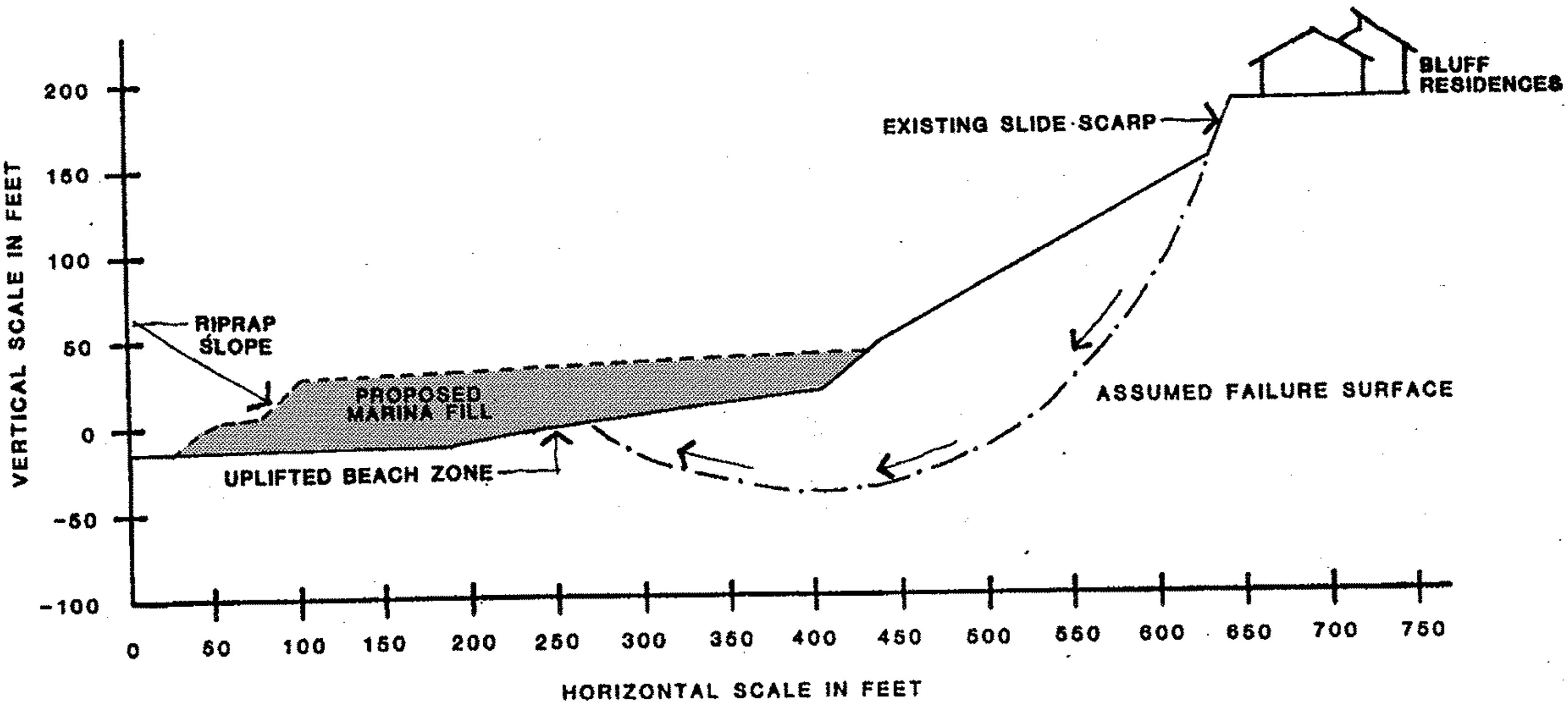
Buttressing the toe of a slope is a common method for slope stabilization. A buttress system provides sufficient dead weight or artificially reinforced restraint near the toe to prevent mass movement (Gedney and Weber, 1978). A series of figures, illustrating various methods of buttressing slopes are included as Figures 5-22 through 5-25. In addition to restraining the slope from moving, to be effective in the long term, a buttress must also be founded on a layer that is stable. Drainage systems, usually incorporating graded sediment filters and use of geotextiles (Peck et al., 1974; Department of Navy, 1982; Hout, 1984), need to be incorporated within the retaining walls and buttress systems to minimize "piping" or groundwater washouts of the buttressed slope material (Hunt, 1986).

In the case of shoreline stability, the buttress system must also be designed to withstand the effects of wave erosion. A layer of rip-rap (sized for the appropriate wave and storm action), can be placed at the toe of the buttress above the expected high water level (Cox et al., 1993; Notes from Slope Stability and Landslides, Technical Course, 1988). Buttress systems can be constructed with earth or rock components, the weight of which provides the buttress. Other construction systems are available that use the buttressing concept. These include reinforced earth, timber, metal, or concrete crib walls, retaining walls, and gabions. Again, construction using these methods may be difficult in shoreline areas because of space limitations for the necessary equipment.



Source: ACOE (1987)

Figure 5-20
Magnolia Bluffs, Elliot Bay Marina, Seattle
Main Scarp at Head of Major Slide



Source: ACOE (1987)

Figure 5-21
Magnolia Bluffs Cross Section
Slide Stabilization by Fill Over Toe

Gravity Retaining Walls

Timber, metal, and concrete crib walls, reinforced earth, and gabions are all types of gravity retaining walls. These structures depend on their mass to resist the load imposed by the failing slope (Rodgers, 1988). Examples of these types of walls are shown in Figures 5-22, 5-23, and 5-24.

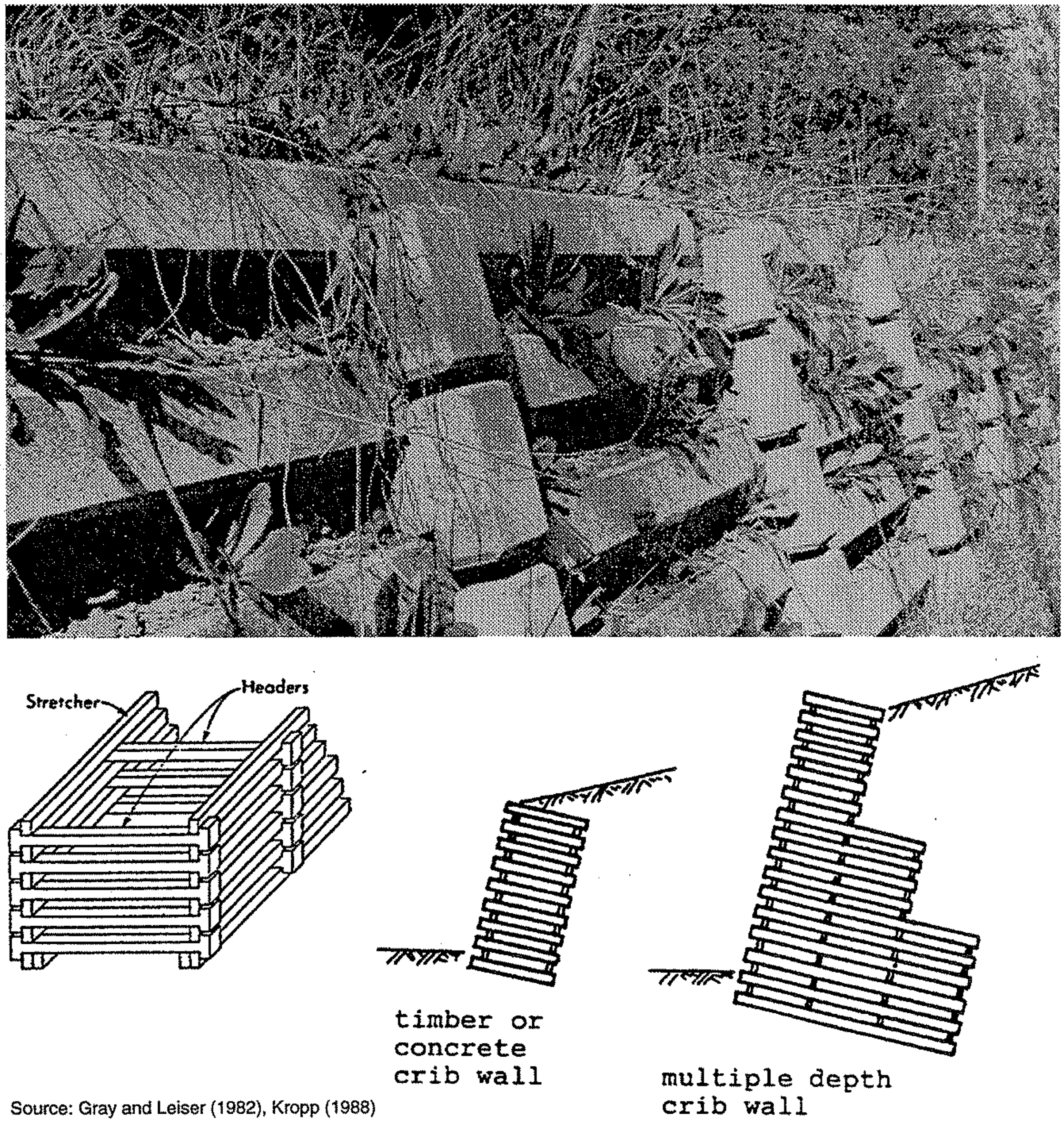
Uncemented rock walls which function as gravity walls are a common form of bluff toe protection and shoreline armoring around Puget Sound. Cox et al. (1993) provide general guidance on the installation of rock walls, but note that rigorous, fully-tested design criteria are not available for Puget Sound. While rock walls do well in calm conditions, they may collapse if undermined by larger storm waves. Rock (rockery) walls are commonly used in upland settings throughout the Puget Lowlands. Standardized construction guidelines and specifications have recently been proposed (Associated Rockery Contractors, 1992; Hemphill Consulting Engineers, undated). Hopefully, additional studies of the use of rock walls in coastal shoreline settings will also be forthcoming.

Recently, geotextile walls have also been used as gravity retaining walls. These walls use synthetic fabrics and geogrids to provide reinforcement and drainage for the slope. A benefit of these systems over the more traditional buttressing systems is their flexibility. Geotextile walls can tolerate some slope movement without failure.

Many of these retaining wall structures can be combined with biotechnical slope restoration plantings (Figure 5-25), thus allowing the stabilized slope to assume a more natural condition (Notes for Slope Stability and Landslides, Technical Course, 1988).

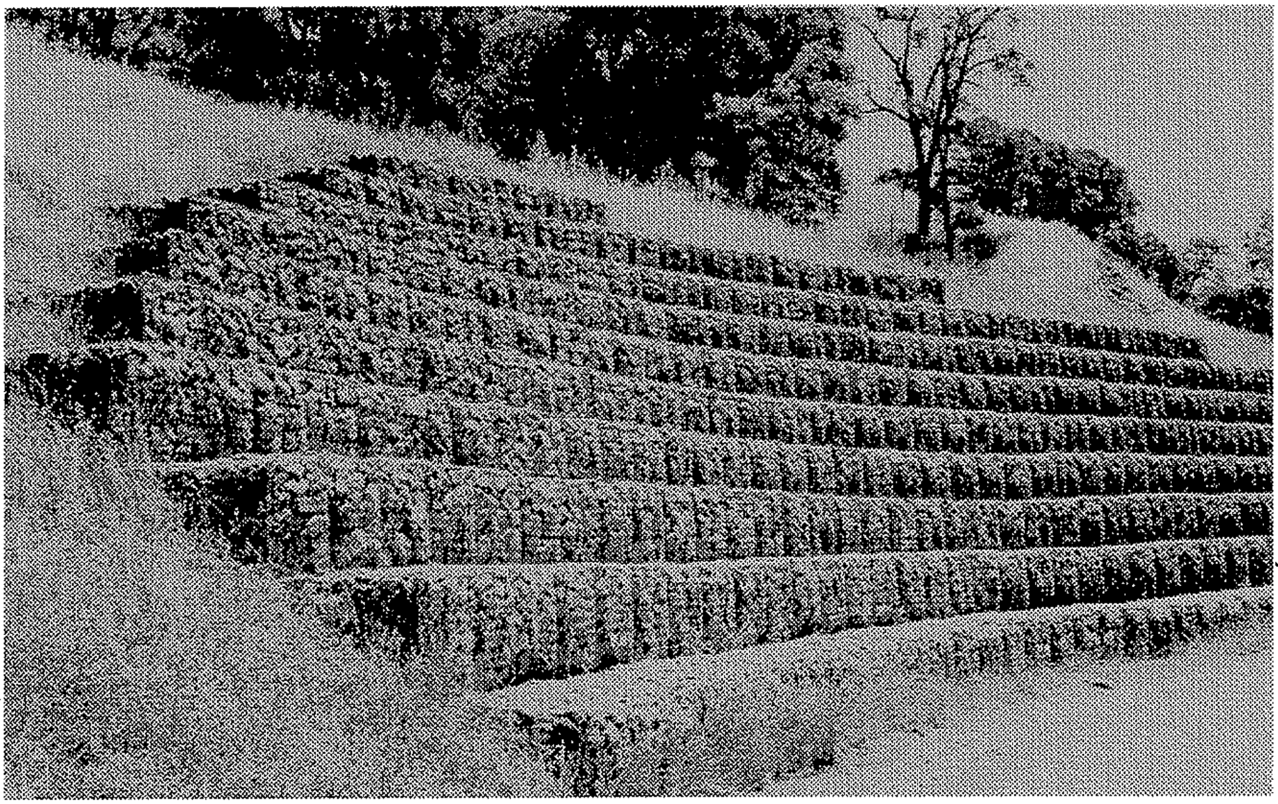
Cantilevered Retaining Structures

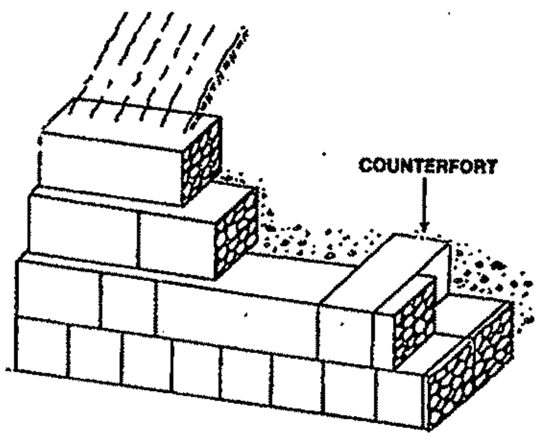
Cantilevered retaining structures resist the driving forces of slope failure by imbedding piles, piers, or a reinforced concrete stem or "key" on a retaining wall, into stable material underneath the slide mass. Examples are shown in Figure 5-26. Pipe or pier



Source: Gray and Leiser (1982), Kropp (1988)

Figure 5-22
Crib Walls

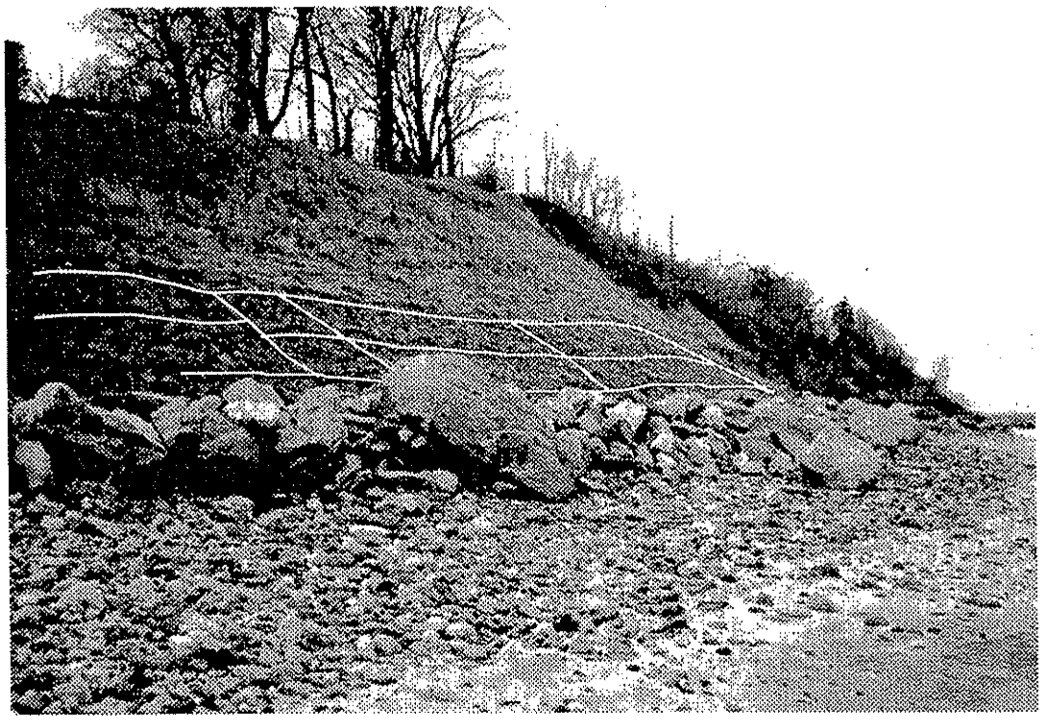




Source: Gray and Leiser (1982)

Figure 5-23
Gabion Wall

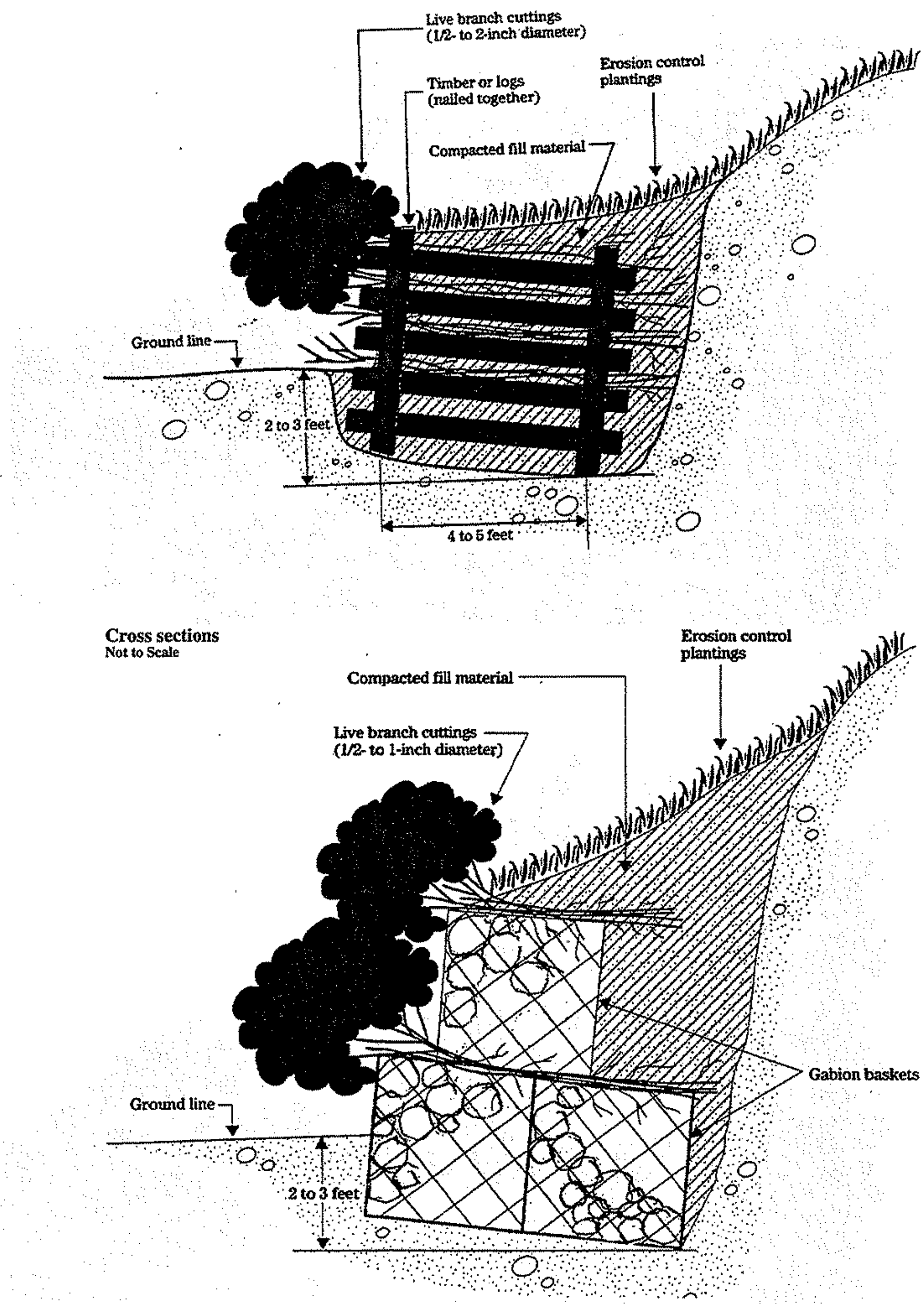
New England Shoreline Bluff Before Restoration



After Restortation (gabions outlined in white)

Source: Bowman (1994)

Figure 5-24
Bluff Restoration: Revegetated Slope Above Gabion Mattress and Rock Toe Protection



Note: Rooted/leafed condition of the living plant material is not representative of the time of installation.

Source: SCS (1992)

Figure 5-25
Live Cribwall and Gabions

foundations are typically used in conjunction with concrete or timber lagging, to reinforce the unstable slide mass.

Tie-back walls

Other methods that can be used to stabilize slopes are anchor systems that include tie-back walls. These wall designs use the principal of transferring the load with the use of cables, rods or bolts, to an area behind the slide mass where adequate resistance can be established by the anchor system (Kockelman, 1986). Tie-backs can be used in combination with cantilever systems to obtain additional load capacity. An example of these is shown in Figure 5-27. Costs associated with installing these types of systems are dependent on whether the area is accessible for a drill rig and whether the material can be drilled economically (Rodgers, 1988). The drillability of the material would be more of a concern in fractured rock areas—which are rare around Puget Sound. Problems can occur if the tie-backs corrode, or if the soil mass in which the tie-backs are anchored is subject to movement (Notes from Slope Stability and Landslides, Technical Course, 1988).

Flexible Walls

A final more recently used retention structure is a flexible structure that can bend or deflect, so that the soil mass can mobilize its strength (Rodgers, 1988). Examples include steel sheetpile bulkhead walls, sackcrete walls (composed of bags of concrete in which the concrete sets up over time; a.k.a. grout-filled bags), and concrete block walls (preformed interlocking blocks of concrete which are vertically stacked). These are shown in Figure 5-28. The concrete walls are cost efficient, but because of their rigid structure in combination with their flexibility, they offer poor resistance to earthquake loading (Notes from Slope Stability and Landslides, Technical Course, 1988).

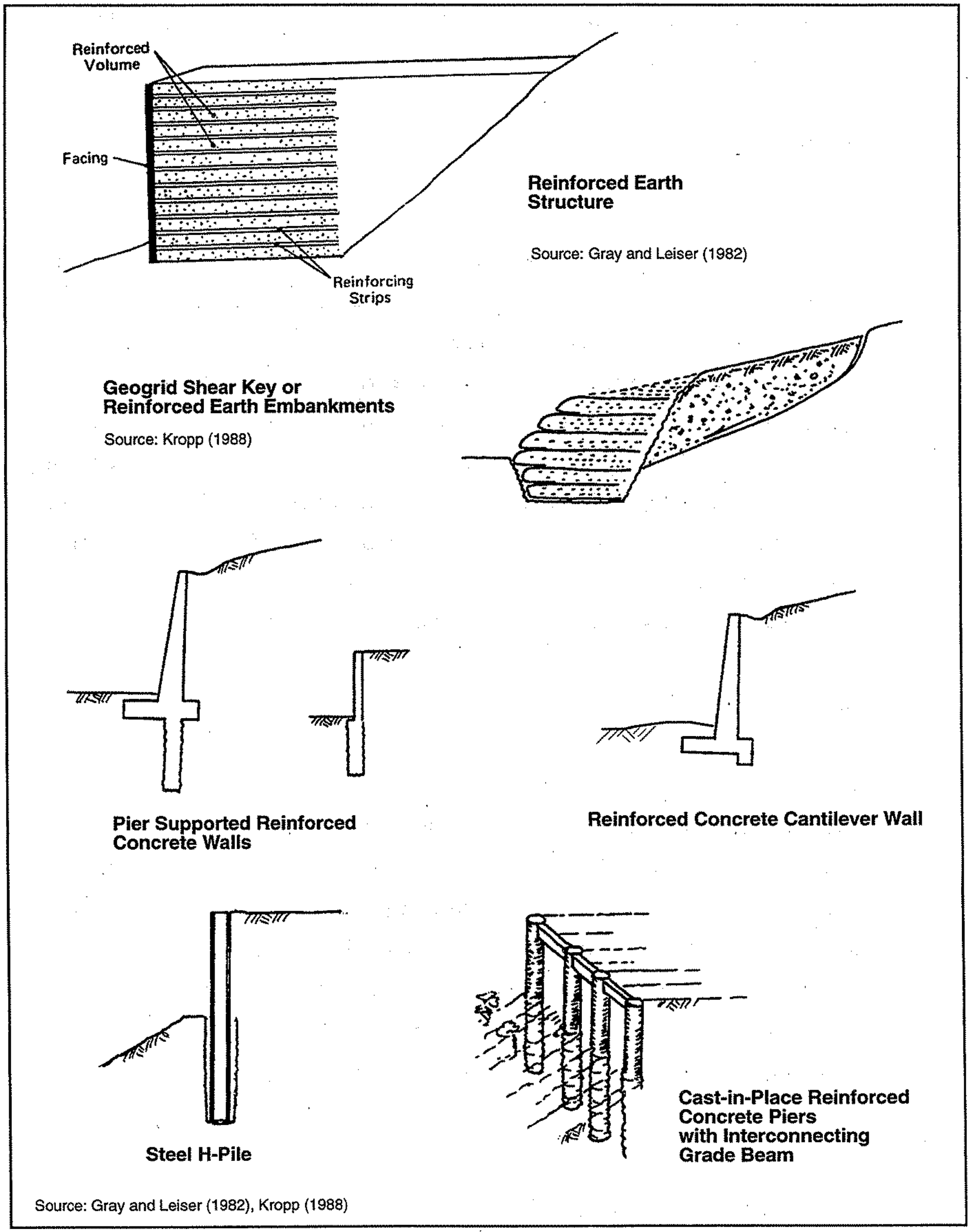


Figure 5-26
Gravity and Cantilevered Retaining Structures

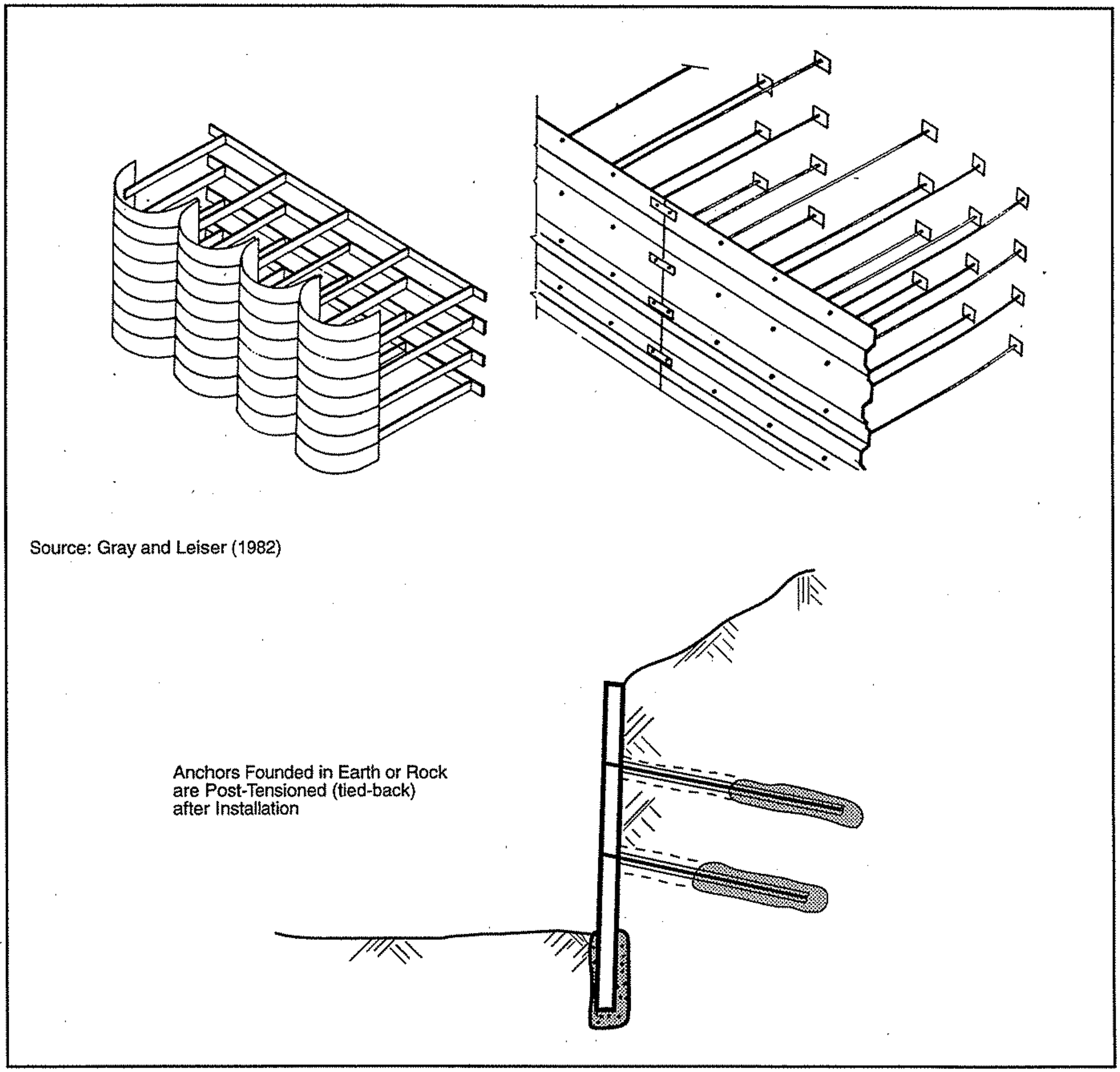
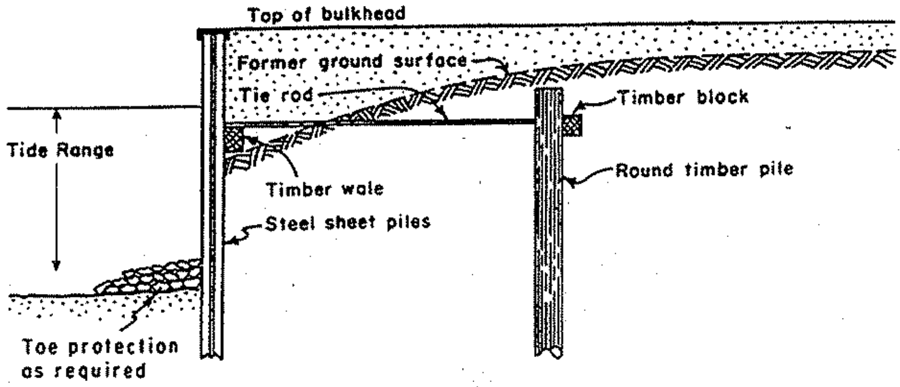
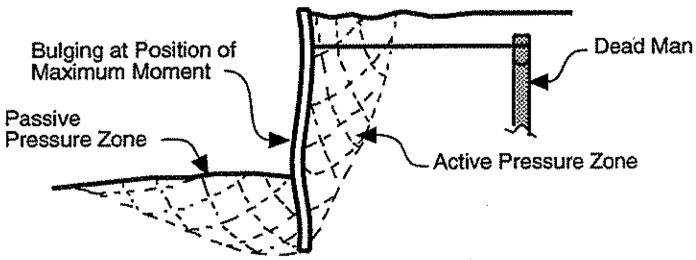


Figure 5-27
Tie-Back Walls

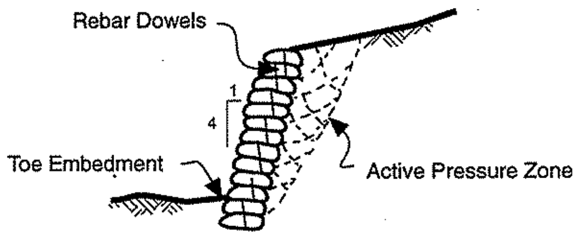


Typical Bulkhead Cross-Section

Source: Shorelines, Inc. (1992)



Steel Sheetpile Bulkhead Wall



Sackrete Wall

Source: Redrawn from Kropp (1988)

Figure 5-28
Flexible Walls

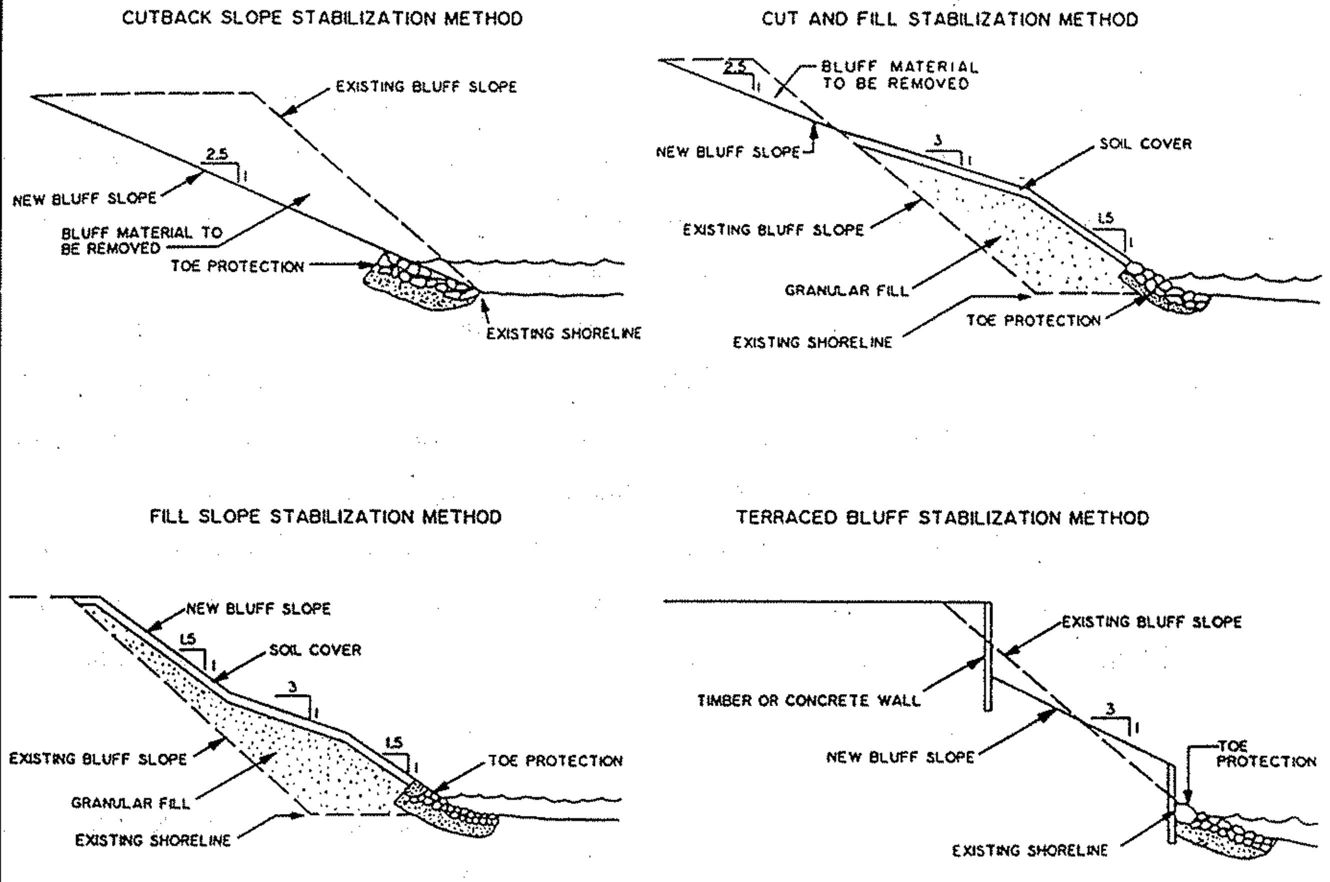
5.10 Reshaping Unstable Slopes

If adequate room is available, slopes can be regraded and flattened to obtain a stable configuration. This has the effect of unloading the top of the slope. The final slope angle will be a function of the stratigraphy or what geologic and soil materials are present and how they are arranged, groundwater levels in the slope, and what type of wave action would be expected in the future. In addition, an assessment of the risk of future slope failure would be required. For example, areas that are underlain by till, which has a high friction angle and cohesive strength, will likely stand on very steep slopes. Till generally fails from superficial weathering—which causes the material to slough down the slope; or more dramatically from block failures—where larger blocks of till are loosened from stress cracking or freeze-thaw of water within the till. If the use of the land near the edge of the slope is not critical, all that may be required for development in this case is an adequate setback for structures.

Four different methods are generally used for reshaping unstable slopes. All four methods of reshaping aim to flatten slopes to a more stable angle of natural repose. Some methods also provide a buttress at the toe to reinforce the slope. The four methods of reshaping slopes discussed here include:

- Cutback Stabilization Method
- Fill Stabilization Method
- Cut and Fill Stabilization Method
- Terraced Stabilization Method

These methods are shown schematically in Figure 5-29. The suitability of each method is dependent not only on the proposed use of the site, but also on natural features of the site including site geology, slope geometry, and drainage features. It is assumed that these methods would only be used to stabilize slopes that are potentially unstable in their existing state (for example, naturally oversteepened slopes, or slopes with high groundwater tables). In addition, these methods are used in conjunction with toe protection to provide defense



Source: SEWRPC (1988)

Note: The design specifications shown herein are for a typical structure the detailed design of shore protection measures must be based on a detailed analysis of wave climate, cost and availabilty of construction material, specific gravity and quality of the stone, type of foundation material , and existing shoreline geometry.

Figure 5-29

Alternative Methods of Reshaping Unstable Slopes

against wave erosion. **These methods alone will not protect a slope that is subject to wave erosion, so it is essential to understand the forces that are affecting the slope.**

The site owner needs to be forewarned that it may be difficult to mobilize the construction equipment required for reshaping high bluff slopes. In addition, mobilizing the construction equipment to the site is not only disruptive to the natural environment of the site, but can be expensive for the property owner. Construction on lower banks is more feasible and cost-effective. The information presented outlines general guidelines only. Each individual site has unique design requirements that should be evaluated by an appropriately qualified geotechnical engineer.

5.10.1 Cutback Stabilization Method

This method cuts the existing slope back to a stable angle of natural repose. Many of the slopes bordering Puget Sound are oversteepened as a result of glacial scouring, and are unstable in their existing configuration. The cutback stabilization method is most appropriate for Puget Sound bluffs on slopes that are underlain by granular materials or where a shallow landslide exists and can be removed completely by cutting back to a stable angle. Slopes underlain by till or rock, have higher strength and it is difficult to assess a stable slope angle. Till and rock slopes typically fail as blocks that separate from the slope. As a result, it is likely not worth either the cost to construct, or the loss of land at the top of the slope, to remove these materials to an assumed stable configuration. Known values exist for stable slope configurations for granular material (Hunt, 1986) and the potential for a successful slope stabilization exists in these types of materials. It is advisable to remove landslide deposits from the face of a slope. Because of the disturbed state of the landslide debris on the slope, natural drainage is often blocked, which may lead to even more stability problems. In addition, new vegetation may not be sufficiently established in the landslide deposits on the slope because of the wet conditions typically associated with landslide material and the potential for additional movement, which would shear plant root systems.

5.10.2 Fill Stabilization Method

The fill stabilization method adds fill to oversteepened slopes to bring the slope to an acceptable angle of natural repose. The majority of the fill is placed at the bottom of the bank or bluff, so toe protection from wave erosion may be critical and must be assessed for this method to be successful. The specified fill material should be granular and free-draining so as to not impede drainage on the slope. This method of slope stabilization generally adds more fill to the lower portions of the slope and in a sense, acts as a berm or a buttress in stabilizing the existing slope. This method is most appropriate in those areas where the slope is underlain by an interbedded sequence of geologic units of different permeabilities. An example of this would be fine grained material such as till or lakebed deposits (silt and clay) interbedded with outwash (sand and gravel). In combination with a seasonally high groundwater table, the contact between these units is typically a potentially unstable zone. Placing a permeable, free-draining fill against the slope allows the groundwater seepage to exit the slope, while the fill acts as a berm to keep the material on the slope. In the case where substantial seepage is expected along the slope, consideration should be given to placing a geotextile/geofilter designed to intercept drainage under the fill. While this method would also work with slopes underlain by other materials, such as till or rock, it would be advisable to understand the potential failure mechanism so as not to *overdesign* the remedial measure. Slopes in permeable material will likely naturally assume the angle of repose over time through surface erosion, as well as wave erosion at the toe. In order to maintain the stable slope configuration, toe protection from further wave erosion and slope protection from surface erosion are both required.

5.10.3 Cut and Fill Stabilization Method

The cut and fill stabilization method uses a combination of the above techniques to stabilize the slope. In this method the upper portion of the slope is cut while the lower portion of the slope is filled. Generally, it is assumed that the fill material placed at the bottom of the slope is the cut material taken from the top of the slope. In order for this method or any fill method to work successfully, the fill material that is placed must be permeable. If the upper cut material is fine grained, it should be disposed of and replaced with suitable fill material. Alternately, a geotextile or geofilter designed to intercept the drainage can be placed between the contact of the existing slope and the fill material. The cut and fill stabilization method can be used for the types of slope material discussed in both the cutback and fill stabilization methods. This method is particularly suitable in interbedded sequences where permeable material is located at the top of the slope and has had some small initial failures. In the cut and fill stabilization method, this failed material would be removed and could be used as fill at the base of the slope. The placement of this fill material at the base of the slope would serve as a berm or buttress against further failures of the slope. In areas where till or a fine grained deposit is underlain by a sand or gravel at the base of the slope—which has failed because of oversteepening from wave erosion—toe protection, in conjunction with a fill placement, would restore the natural angle of repose at the base of the slope. In this case, minimal cutting at the top of the slope would be required because of the high existing strength of the native materials.

5.10.4 Terraced Stabilization Method

The terraced stabilization method uses a series of retaining walls separated by a regraded slope at various elevations along the bank or bluff. This method would be suitable for slopes underlain by either granular outwash (sand and gravel) or interbedded deposits that show evidence of shallow failure. In granular material where it is important to maintain the property at the top of the slope, the terrace stabilization method offers an alternative to the cutback stabilization method. The series of retaining walls can be driven into stable material and the excess material from regrading the slope can be used as backfill for the retaining walls. Where this method is used in interbedded deposits exhibiting shallow slope failures, it is essential that the retaining walls be founded in stable material below the zone of failure. As for all retaining walls, adequate embedment must be provided in the native material, and retaining structures located near the base of the slope must be protected from wave action. Adequate drainage should also be provided for each of the retaining walls. The terraced stabilization method would not be suitable for slopes underlain by rock because of the nature of the construction on the underlying material.

5.10.5 Rock Slopes

The above methods of stabilization (sections 5.10.1 through 5.10.4) are primarily suited for soil slopes. Removal of failed surficial rock can be accomplished by the cutback stabilization method, however the intent is not to grade the slope to a stable angle of repose but simply to remove failed material. In addition, a rock slope that is failing may also be stabilized by the fill stabilization method. In this case, the fill is acting as a buttress or retaining wall, a common but expensive method used to stabilize rock slopes. On rock slopes that are unstable because of unfavorably oriented fractures or discontinuities with respect to the slope, rock bolts are often used to secure the rock face. Where there is concern that loose ravelling rock on the slope may cause damage to structures below the slope, wire mesh is frequently used to cover the slope to capture the falling rock. When appropriate, all of these methods can be used in conjunction with improved drainage to aid in the stabilization of the rock slope (Notes for Slope Stability and Landslides, Technical Course, 1988).

sea1002840A.wp5

6.0 Summary: Selecting Appropriate Solutions

What are some of the major conclusions to be drawn from the preceding report sections?

Section 2.0, Regional Overview, confirms that steeply sloping banks and bluffs fronted by narrow, gravelly beaches are common landforms along the shores of Puget Sound. The majority of these banks and bluffs are composed of relatively unconsolidated glacial deposits—glacial till, outwash sands and gravels, and clayey lacustrine deposits. Shoreline outcrops of consolidated bedrock are uncommon around the Sound—but do occur in Skagit County and the San Juan Islands.

A key feature of the Sound's banks and bluffs is their variability. Several closely spaced home sites, for example, could easily exhibit differences in bluff height, slope angles, and/or stratigraphic sequences.

Section 3.0, Types of Slope Failure, concludes that relatively shallow, surficial debris slides and/or slumps that develop into debris avalanches are the most common form of slope failure around the Sound. These are often small scale slides that might impact a single home site; thoughtful site vegetation and water management can often substantially reduce their risk of occurrence. Deep-seated rotational slides are a much more serious hazard; they typically involve larger stretches of shoreline (several home sites, for example) and are more difficult and costly to stabilize.

Section 4.0, Causes of Slope Instability, confirms that bluff height, slope angles, and local geology/stratigraphy all influence slope stability. Slope stability is also impacted by other processes in quite different ways. Wave action and toe erosion can undermine a slope from below, while vegetation clearing and poor surface and groundwater management practices can cause surficial slumping higher up the bluff face. These processes are largely independent of one another. Shoreline armoring, for example, may temporarily slow toe erosion, but will not halt slumping from the bluff face due to tree cutting or soil saturation. Similarly, vegetation management alone can do little to halt toe erosion.

Another key conclusion from Section 4.0 is that human disturbance of natural, undisturbed slopes during land development, construction, and habitation is a *major* cause of increased slope instability.

Section 5.0, Managing Shoreline Slopes, describes potential management approaches to minimize the causes of slope instability (i.e., risk factors) identified in the preceding section. The clearly preferred approach to minimize property losses, protect public safety, and minimize disruption of important natural shoreline processes and habitat values is to first avoid unstable slopes; second, to minimize potential problems at their source (i.e., minimize vegetation removal, surface runoff, soil saturation); and only then begin implementing control measures. An increasingly complex and expensive series of control measures includes surface runoff control, groundwater drainage systems, biotechnical slope protection, conventional engineering structures (retaining walls, shoreline armoring, etc.), and finally the complete reshaping of unstable slopes.

The diversity of coastal banks and bluffs around the Sound requires that each existing or potential development site be subject to site-specific studies. Only when the site characteristics and potential local causes of slope instability are thoroughly understood can an appropriate series of site management strategies be developed.

6.1 Homeowner Questionnaires

Homeowner questionnaires provide a valuable tool to organize relevant information about a site that is either already developed or is about to be. Several samples of such questionnaires (Canning, 1991; Myers, 1993; Menashe, 1993; King County, 1990; and Tainter, 1982) are included in **Appendix A.**

By carefully observing the study site and systematically answering the questions, the property owner is preparing a preliminary site evaluation. What is the nature of the bank or bluff—its toe, face, and crest? What are the existing soil and vegetation conditions? What evidence is there of slope problems or potentially hazardous areas? What evidence is there of factors that could contribute to slope instability—groundwater seepage, soil saturation, wave action, toe erosion, etc.?

Once collected and organized, this information can be compared with the material in Sections 3.0 and 4.0 of this report. Has the study site already experienced slope failure and, if so, of what type? Is there evidence of potential causes of slope instability as outlined in Section 4.0? Once these potential problems are identified, then finding the appropriate solutions can follow. Other resources that should be checked include the *Coastal Zone Atlas of Washington* (Ecology, 1977-1980) and Terich (1987). Keep in mind that, while these sources provide useful regional and local perspective, their scales preclude detailed study of a single-family home site.

As noted in Section 4.0, it may also be appropriate to have the site inspected by a geologist, geotechnical engineer, sanitarian, and/or arborist. Each of these specialists can provide a greater level of understanding about a site and its potential stability problems. Keep in mind that many of the approaches outlined in this report are only now gaining familiarity in the Pacific Northwest and they are not yet widely practiced. Check the credentials, experience, and references of specialists called to a site to confirm they are aware of these more progressive approaches to unstable slope management.

6.2 Selecting Appropriate Solutions

By now the philosophy underlying the unstable slope management strategy presented in this report should be quite clear:

> **Identify the common causes of local slope instability—and then identify management methods to either minimize or eliminate them.**

The procedure for identifying the most appropriate solutions to deal with site-specific causes of slope instability readily follows:

1. First, know your site and know your slope.

2. Review all the key factors likely to control onsite slope stability—bluff height and slope angle, local geology and sedimentary sequence, beach processes including wave action and toe erosion, existing vegetation, surface runoff, and groundwater seepage conditions. Which of these factors appear to offer the greatest risks to onsite slope stability?

3. Next, examine the site from a "landscape perspective." What position does the site occupy on the shoreline and within a coastal drift sector? What environmental or ecological processes may be taking place between the study site and adjacent upland or offshore areas? This knowledge of potential "landscape linkages" will provide a more adequate perspective for selecting the least environmentally damaging management alternatives to protect the site.

4. Having identified the processes that need to be protected against and the landscape setting in which protection needs to be accomplished—select the solutions (Section 5.0) that appear most appropriate.

   Geological features of the site must be assessed to determine if active or dormant slides are already present, and to assess the inherent stability/instability of local sedimentary sequences. If the site is clearly an unstable one, it should either be left undeveloped—or development should be carefully planned and well set back from the bluff crest to minimize future problems.

   Beach processes impacting the toe of the bank or bluff need to be monitored to assess the potential for wave-generated toe erosion. Local planning records should be checked, and surrounding property owners contacted, to see how the area responded during unusually powerful storm events. This information can be used to assess whether or not shoreline armoring might offer real benefits—and, if so, how it can be best accomplished with a minimum of harm to natural resources, both on-site and downdrift.

Careful attention should be given to the role of vegetation—especially deeper-rooted shrubs and trees—in stabilizing slopes before any cutting or clearing is begun. Alternative pruning techniques should be given higher priority (to enhance views) than tree removal. If the site has already been cut and cleared, the potential for slope failure should be assessed and an appropriate revegetation plan developed.

During site planning, careful attention needs to be given to any increase in surface water accumulation and runoff that will result from construction of any proposed hard surfaces (including compacted bare ground). Every effort should be made to avoid increasing surface runoff down the bluff or bank face. Plans need to be included for collecting this increased runoff and either diverting it to the local stormwater sewer system or "tight lining" it down the bluff face to the beach below.

If groundwater seepage and soil saturation are obvious across the bluff face, thought should first be given to reducing groundwater sources and, second, to the least disruptive forms of groundwater drainage.

5. At this point, it would be wise to check potential slope management approaches and solutions with several appropriate professionals to be sure the proposed approaches will be as expected. Proposed solutions will also need to be checked out through the local/state/federal permit approval process, as may be appropriate.

6.3 Regulatory Review

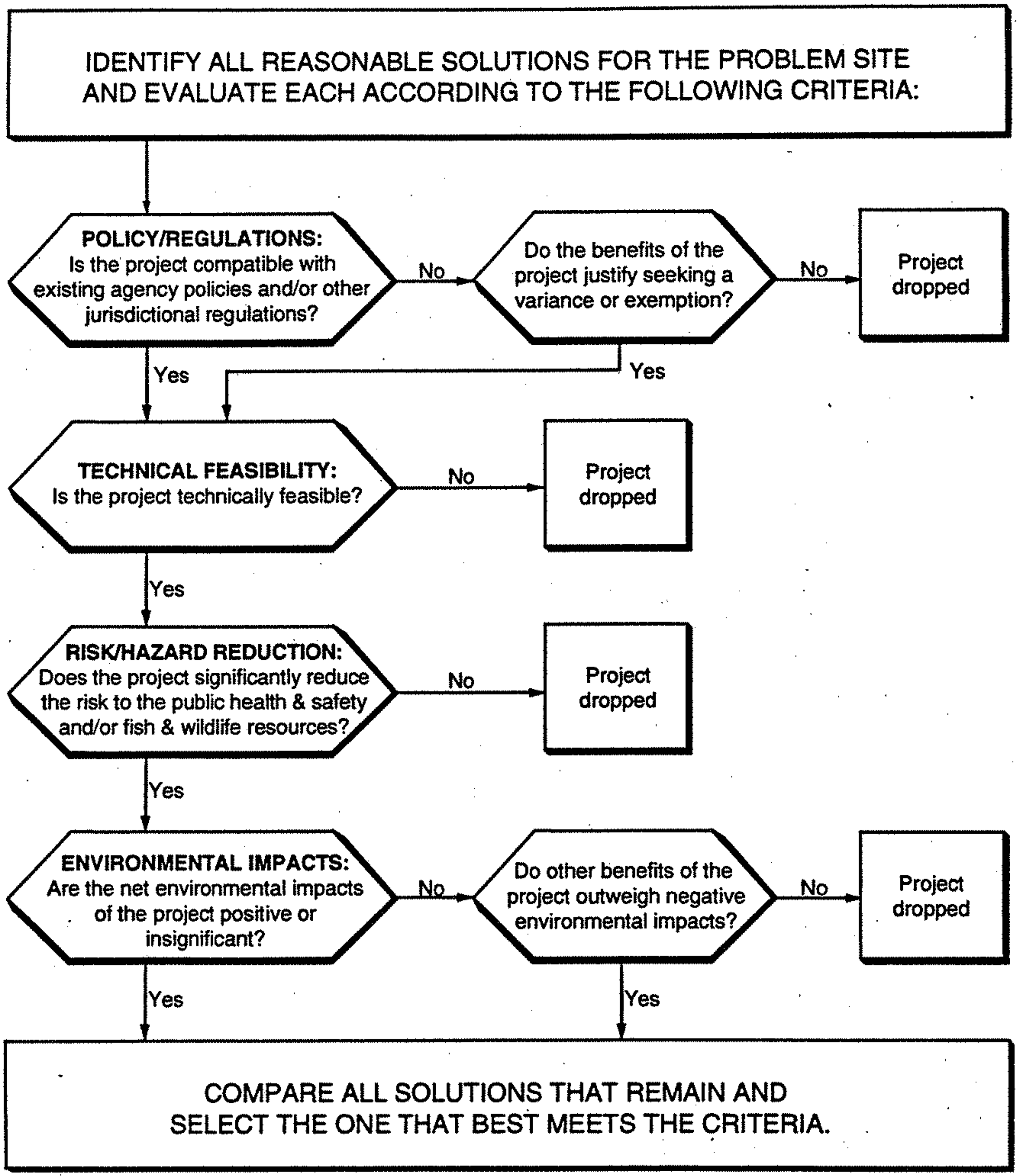
A review of potential regulatory requirements that might need to be addressed prior to developing a shoreline or blufftop site—or further altering an already developed site—is beyond the scope of this report. It is important to note, however, that a variety of local, state, and even federal regulations may need to be addressed. A variety of special plans and specifications will need to be submitted before local (city, county, special districts) and state permits can be approved and issued. Figure 6-1 (King County, 1993) provides a *generic* outline of the regulatory evaluation process that a proposal for new shoreline development will need to go through.

It admittedly can be a cumbersome and rather frustrating process, but it should be clear from this and related task reports that *there is considerable potential for significant impacts* to environmental and public resources well beyond the immediate development site. It is also encouraging to note that many state and local jurisdictions are actively exploring ways in which the regulatory process can be speeded up and simplified, while still retaining much needed environmental and "public trust" protections (Washington State, 1994; Slade, et al., 1990).

6.4 Future Research and Management Needs

As noted in Section 4.0, the common causes of slope failure around Puget Sound, as well as a broad array of slope management strategies to deal with most of them, are quite well known. This is quite different from the **Task 4** (Macdonald, et al., 1993) conclusion that considerable basic research is still needed to fully assess the affects of shoreline armoring on physical coastal processes in Puget Sound.

While several "unstable slopes" topics undoubtedly warrant more research, the greater need for unstable slopes *management* seems to be better public dissemination and implementation of what is already known. Outstanding examples that meet this need are Ecology's recent publications on bluff vegetation management (Menashe, 1993) and the use of vegetation for slope stabilization (Myers, 1993).



Source: King County (1993)

Figure 6-1
Regulatory Evaluation

An increasing number of slope stabilization **demonstration projects** have been undertaken by public agencies—Ecology, King County Surface Water Management, Snohomish County Stormwater Management, and Seattle Parks Department, for example. These are now yielding valuable field data, before-and-after site comparisons, and important "how to" implementation tips that are available for others. These examples and their practical successes—and failures—need to be more widely publicized.

To date, most demonstration projects have involved bank stabilization and stream restoration issues; vegetation techniques are commonly stressed. There is an obvious need to expand demonstration projects to coastal banks and bluffs—and to incorporate surface runoff and groundwater management solutions as well as vegetation management.

To encourage the growing interest in bioengineering approaches to slope stability (and habitat restoration), Ecology recently hosted a series of workshops around the state that promoted some of the soil bioengineering methods described in Section 5.0. Again, the workshop focus has been on stream and riverbank protection, but it could easily be expanded to include coastal settings.

There is a need to more thoroughly inform both owners and potential buyers of shoreline property of the inherent hazards that might accompany shoreline or blufftop development. Commercial and residential real estate sales staff—at least those dealing with coastal properties—also need to become much more familiar with both potential concerns regarding shoreline/bluff development and the potential solutions that are out there to help. **Homeowner questionnaires** such as produced by King County (1993) are a significant contribution in this regard.

More field practitioners who are familiar with and can implement the various slope stabilization methods described in this report are needed. More land developers, architects and builders, civil engineers, and landscaping specialists need to understand the broad range of relatively "low-tech" solutions that are available and appropriate to deal with unstable shoreline slopes around Puget Sound.

Finally, the public at large needs to be better informed about the roles of shoreline bluffs and beach processes in promoting the overall health and well being of Puget Sound and its biological resources. In particular, the concept of **"landscape linkages"** and the significance of their disruption needs to be more widely understood and promoted. More awareness of the importance of these linkages between uplands, shore, and Sound is likely to result in more thoughtful long-term stewardship of Puget Sound's coastal resources in general.

6.5 Postscript

This report was last to be completed of the seven Task reports **(Tasks 1-7)** produced to date. As an author/contributor to four of the reports Macdonald has had a unique opportunity to see how results from the various studies overlap and fit together. With this in mind it is now apparent that several conclusions involving earlier studies deserve more emphasis than they formerly received. It is also likely that they will be further developed or modified during Ecology's remaining study tasks.

1. The impacts of both shoreline armoring and bluff development are substantially more wide-ranging than was realized at the beginning of these studies.

2. There is a lot of good information "out there" concerning alternative approaches to shoreline armoring, unstable slope management, and resource values of bluffs and nearshore/shoreline habitats, as well as potential impacts to such resources.

   Much of the information, however, is scattered and hard to obtain. While some of it has been gathered here, more remains to be added—and most importantly, it deserves easier access and wider public dissemination. In particular, there is a critical need to synthesize, publish and distribute the tremendous wealth of field observation and experience of the Washington State's fish and wildlife biologists. These data are critical to the tasks at hand but inadequate financial support is available to get them into print.

3. The conclusions drawn from study **Tasks 3, 5,** and **6** strongly support the view that a number of critical landscape linkages exist between the banks and bluffs that surround Puget Sound, their associated intertidal beaches, and shallow subtidal habitats offshore. Some of the more obvious linkages are shown in Figure 6-2. Disruption of these linkages, due to inappropriate or short-sighted development along the shoreline, can be expected to have rather complex and broad-ranging impacts.

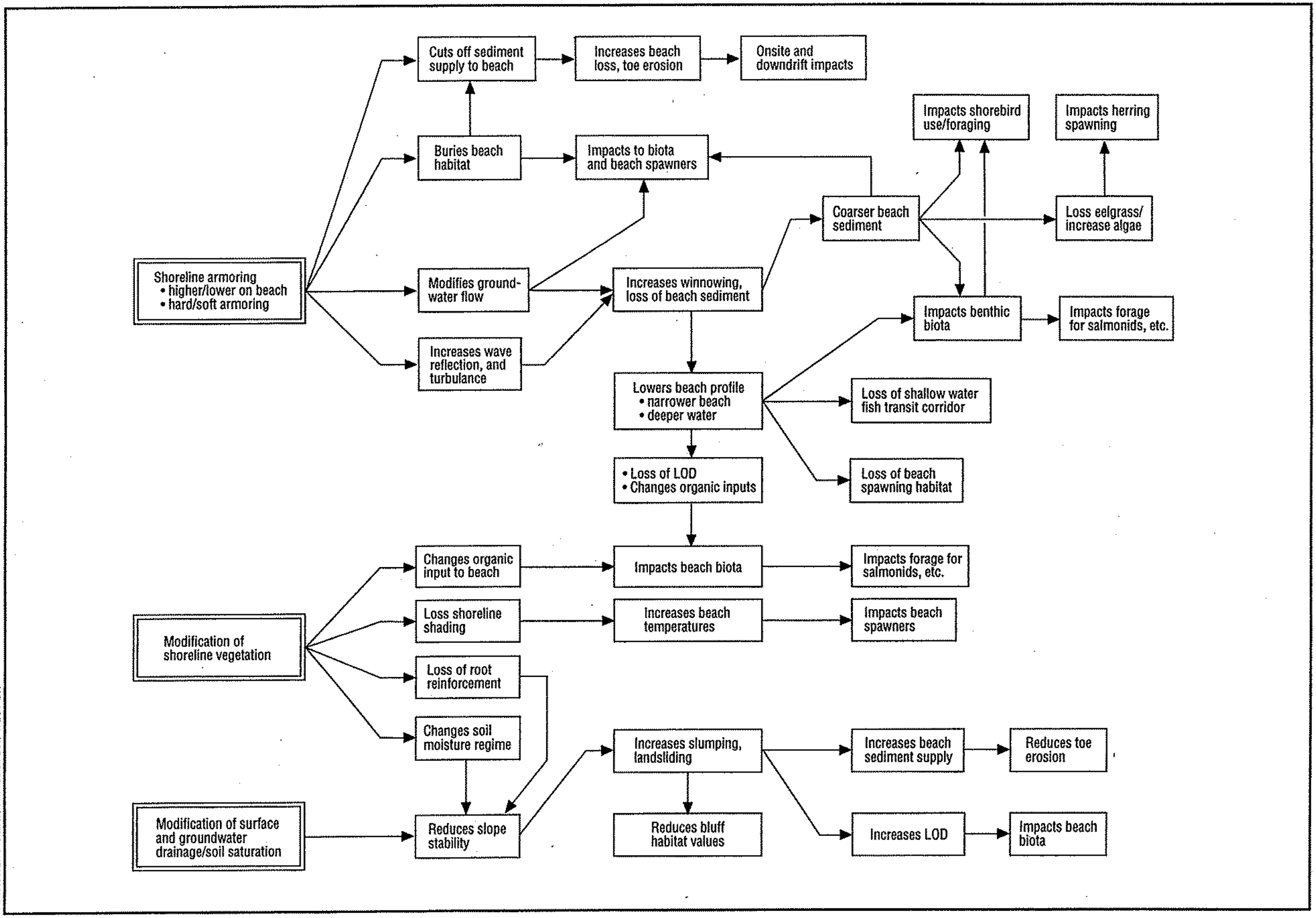
4. A broad array of general information (but very few specific studies) supports the view that identical shoreline armoring will cause very different impacts depending on where it is placed. This is true of both its position in the landscape and its position on the beach. It also appears likely that the specific nature of the armoring can also significantly alter its impact. These concepts are summarized in flow diagram form in Figure 6-3.

   To the extent that this observation is confirmed, it could be valuable to generate shoreline armoring/bluff development "risk assessment maps" for Puget Sound. These maps would rank the relative severity of impacts that shoreline armoring could be expected to have on beach erosion, bluff stability, and/or natural resource values around the Sound.

5. A broad array of hypotheses have been proposed herein, regarding the impacts of shoreline armoring on physical and biological processes, as well as potential linkages between shoreline bluff and beach processes. The information available to rigorously test these hypotheses remains very uneven and there is a critical need for field measurements and documentation. In many cases, relatively simple field data gathering would allow the significance of proposed interrelationships to be quantified:

   - Measure beach parameters before and after bulkheading

   - Measure old bulkhead footings and related beach elevations



NPW35072.T6 Shoreline Arm./Bluff Dev. 7/1/94 DK

Figure 6-2
Shoreline Armoring and Bluff Development Disrupt "Landscape Linkages" Around Puget Sound

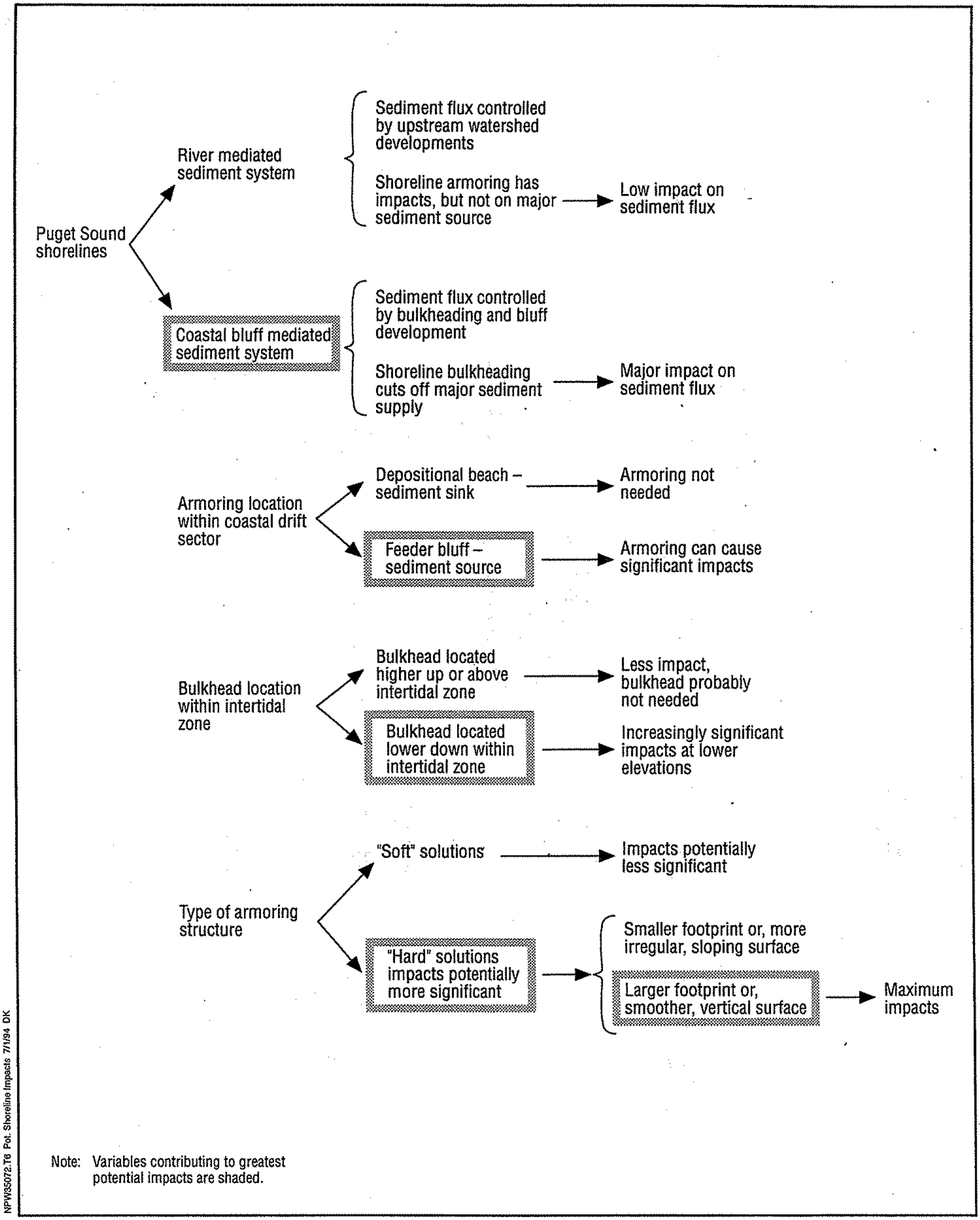


Figure 6-3
Potential Shoreline Impacts Vary with Landscape Position and Armoring Type

- Compare armored and unarmored beach habitats (habitat complexity, LOD, organic inputs, etc.)

- Document beach sediment temperature in shaded/unshaded conditions

- Document leaf fall, insect "fall out," and other organic or nutrient inputs to developed versus undeveloped shoreline sites

- Document shoreline sediment sources versus local beach erosion rates.

6. There is a critical need for the public at large to better understand the possible roles of shoreline armoring and bluff development practices on the overall health and biological productivity of Puget Sound. Public lectures, news articles, informative posters, scientific and popular publications all provide complimentary mechanisms to disseminate better understanding. Puget Sound is a unique resource with values and benefits well beyond its immediate shores; much that has been discussed herein is also closely related to increasing public interest and concerns regarding watershed management and regional fisheries resources.

sea100291A5.wp5

7.0 References Cited

Albright, R., R. Hirschi, R. Vanbianchi, and C. Vita. Coastal Zone Atlas of Washington: Land Cover/Land Use Narratives. Vol. I: Urban, Agricultural, Nonforested Uplands, Forest, Water (Pp. 1-447); Vol. II: Wetlands, Exposed and Other Lands, Appendices (Pp. 448-887). State of Washington Department of Ecology, Olympia, Washington. 1980.

Associated Rockery Contractors (ARC). *Standard Rock Wall Construction Guidelines*. Woodinville, Washington. 11 pp. December 1992.

Bauer, W. Marine Shore Resource Analysis: Shoreline Dynamics. Shoreline Environments for Puget Sound Conference. Sponsored by Washington Dept. of Ecology, Shorelands and Coastal Zone Management Program. Seattle, Washington. 17 pp. October 1991.

Brenner, R. P. A Hydrological Model Study of a Forested and Cutover Slope. Bulletin of Hydrological Science. Vol. 18(26), pp. 125-143. 1973.

Brody, J. (ed.). Hood Canal; Splendor at Risk. Published by The Sun Newspaper, Bremerton, Washington. 264 pp. 1991.

Burns, R. *The Shape and Form of Puget Sound*. Puget Sound Books, University of Washington Press, Seattle. 100 pp. 1985.

Calvert County Cliff Policy Task Force (CCCPTF). Recommendations to the Board of County Commissioners for the Preservation of and Development Adjacent to Calvert Cliffs. CCCPTF, Prince Fredrick, Maryland. 18 pp. October 1993.

Canning, D. J. *Sea Level Rise in Washington State: State-of-the-Knowledge, Impacts and Potential Policy Issues*. Shorelands and Coastal Zone Management Program, Washington Department of Ecology. Olympia. 1990.

__________________. *Shoreline Bluff and Slope Stability*. Shorelands Technical Advisory Paper No. 2, Shorelands and Coastal Zone Management Program, Washington Department of Ecology. March 1991.

Canning, D.J., and H. Shipman. Washington State Coastal Erosion Management Strategy. Coastal Zone 93, New Orleans, Louisiana. 1993.

Culliton, T.J., J.J. McDonough III, D.G. Remer, and D.M. Lott. *Building Along America's Coasts*. National Oceanographic and Atmospheric Administration, Rockville, Maryland. 1992.

Department of the Navy Design Manual 7.1: *Soil Mechanics*. NAVFAC DM 7.1. May 1982.

Downing, J. *The Coast of Puget Sound, Its Processes and Development*. Puget Sound Books, University of Washington Press, Seattle. 126 pp. 1983.

Dunagan, C. Logging: Rising from Toppled Trees. Chapter 6(1), pp. 59-63. In Brody, J. (ed.), Hood Canal: Splendor at Risk. Published by The Sun Newspaper, Bremerton, Washington. 1991.

Dunagan, C. Oysters: To Protect the Canal... and Oysters (p. 115-118), In, Brody, J. (ed.). Hood Canal: Splendor at Risk. The Sun Newspaper, Bremerton, Washington. 1991.

Easterbrook, D. J. and D. A. Rahm. *Landforms of Washington, The Geologic Environment*. Union Printing Company, Bellingham, Washington. 1970.

Edil, T. B. *Control of Coastal Landslides*. Proceedings of the International Symposium on Landslides, Volume 3, New Delhi, India. 1980.

Edil, T. B. and P. J. Bosscher. *Lakeshore Erosion Processes and Control*. Proceedings of the Nineteenth Annual Conference of the International Erosion Control Association, New Orleans, Louisiana. February 1988.

Edil, T. B. and L.E. Vallejo. *Mechanics of Coastal Landslides and the Influence of Soil Parameters*. Engineering Geology, Volume 16, pgs. 83-96, Elsevier Scientific Publishing Company, Amsterdam. 1980.

Egan, T. The Good Rain: Across Time and Terrain in the Pacific Northwest. Random House, New York. Vintage Books. 254 pp. 1990.

Endo, T. and T. Tsuruta. The Effect of Tree Roots Upon the Shearing Strength of Soil. Annual Reports of the Hokkaido Branch, Tokyo Forest Experiment Station. Vol. 18, pp. 168-179. 1969.

Environmental Protection Agency. Guidance Specifying Management Measures for Sources of Nonpoint Pollution in Coastal Waters. USEPA, Office of Water, Washington, D.C. Report No. 840-B-92-002. 1993.

Forman, R.T.T. and M. Godron. Landscape Ecology. John Wiley & Sons, New York. 620 pp. 1986.

Franklin, J. F. and C. T. Dyrness. Natural Vegetation of Oregon and Washington. U.S. Forest Service (1973) reprinted by Oregon State University Press. 452 pp. 1988.

Gabriel, A. O. *An Evaluation of Coastal Hazard Management Programs in the Puget Sound Lowland*. Master of Science Thesis, Western Washington University, Bellingham, Washington. 1988.

Gedney, D. S. and W. G. Weber. *Design and Construction of Soil Slopes*. Landslides, Analysis and Control, Special Report 176, Transportation Research Board, National Academy of Sciences. 1978.

Gray, D. H. and A. T. Leiser. Biotechnical Slope Protection and Erosion Control. Van Nostrand Reinhold Company, Inc. New York. 271 pp. 1982.

Hemphill Consulting Engineers. *The Engineering Method for Rockery Design*. Bellevue, Washington. 22 pp. Undated.

Henderson, K. and D. Owens. Increasing Oceanfront Setbacks to Manage High Density Development Along North Carolina's Coast. Division of Coastal Management, North Carolina Dept. of Environment, Health and Natural Resources, Raleigh, N. Carolina. 8 pp. December 1983.

Herdendorf, C. H. Guide to Lake Erie Bluff Stabilization. Ohio State University, Sea Grant Program. Guide Series OHSU-GS-7. 20 pp. 1984.

Hunt, R. E. *Geotechnical Engineering Investigation Manual*. McGraw-Hill Book Company, New York, New York. 1984.

Hunt, R. E. *Geotechnical Engineering Techniques and Practices*. McGraw-Hill Book Company, New York, New York. 1986.

Hutchinson, J. N. 1973. The response of London Clay cliffs to differing rates of toe erosion. *Geologia Applicata e Idrogeologia*. Vol. VIII (1), pp. 221-239.

Johnson, A. W. and J. M. Stypula. (eds.) Guidelines for Bank Stabilization Projects in the Riverine Environments of King County. King County, Dept. of Public Works, Surface Water Management Division, Seattle, Washington. 1993.

Kamphuis, J. W. Recession Rate of Glacial Till Bluffs. American Society of Civil Engineers. Journal of Waterway, Port, Coastal and Ocean Engineering. Vol. 113(1), pp. 60-73. 1987.

Keuler, R.F. Coastal Zone Processes and Geomorphology of Skagit County, Washington. Master of Science Thesis, Western Washington University, Bellingham, Washington. 135 pp. June, 1979.

Kockelman, W. J. *Some Techniques for Reducing Landslide Hazards*. Bulletin of the Association of Engineering Geologists, Volume XXIII, Number 1. February 1986.

Koloski, J. W., S. D. Schwartz, and D. W. Tubbs. *Geotechnical Properties of Geologic Materials*. Engineering Geology in Washington, Volume 1, Washington Division of Geology and Earth Resources, Bulletin 78, pp. 19-26. 1989.

Komar, P. D. Beach Processes and Sedimentation. Prentice-Hall, Inc. New Jersey. 429 pp. 1976.

Kreutzwiser, R.D. and A.O. Gabriel. Managing for sustainable development and use of the Long Point Sandy Barrier. Report to the Laidlaw Foundation. Department of Geography, University of Guelph, Guelph, Ontario. 69 pp. September 1993.

Kropp, Alan, presenter. *Repair of Landslides*. Notes from 8th National Short Course on Slope Stability and Landslides, Tacoma, Washington. September, 1988.

Kruckeberg, A. R. The Natural History of Puget Sound Country. University of Washington Press. Seattle, Washington. 469 pp. 1991.

McCabe, G.H. and K.F. Wellman. *Policy Alternatives for Coastal Erosion Management*. Prepared for CH2M HILL and Washington Dept. of Ecology. Prepared by Battelle Seattle

Research Center. Report No. PNL-8548, BHARC-800/93/004. Seattle, Washington. 86 pp. July 1993.

__________________. *Regional Approaches to Address Coastal Erosion Control Issues.* Prepared for CH2M HILL and Washington Dept. of Ecology. Prepared by Battelle Seattle Research Center. Report No. BSRC-800/94/011. Seattle, Washington. 44 pp. April 1994.

McKee, B., *Cascadia: The Geologic Evolution of the Pacific Northwest.* McGraw-Hill Book Company, New York. 1972.

Menashe, E. Vegetation Management: A guide for Puget Sound Bluff Property Owners. Shorelands and Coastal Zone Management Program. Washington Department of Ecology, Olympia. Publication 93-31. 46 pp. 1993.

Miller, R. D. Map Showing Relative Slope Stability in Part of West-Central King County, Washington. U.S. Geological Survey, Miscellaneous Geological Investigations, Map I-852A. 1973.

Morrison, Steven W., J. Keltman, and D. Haug. *Inventory and Characterization of Shoreline Armoring, Thurston County, Washington, 1977-1993.* Prepared by Thurston Regional Planning Council for the Washington Department of Ecology, Olympia, Washington. 1993.

Myers, R. D. Slope Stabilization and Erosion Control Using Vegetation: A Manual of Practice for Coastal Property Owners. Shorelands and Coastal Zone Management Program. Washington Department of Ecology, Olympia. Publication 93-30. 42 pp. 1993.

Nairn, R. An Ecosystem Approach to Shoreline Treatment (EAST). *Great Lakes Report.* Littoral. p. 3-4. March 1994.

Nordstrom, K.F. *Estuarine Beaches*. Elsevier Science Publishing Co., Inc., New York. 1992.

Peck, R. B., W. F. Hanson, and T. H. Thornburn. *Foundation Engineering*. John Wiley & Sons, Inc., New York, New York. 1974.

Puget Sound Water Quality Authority (PSWQA). Population and Land Use (p. 14-15); Shellfish (p. 29-30); and Shellfish Protection (p. 50-51). In State of the Sound, 1992 Report. Olympia, Washington. 71 pp. 1992.

Puget Sound Water Quality Authority. Sound's Future Hinges on Effective Growth Plans. *Sound Waves*. Vol. 9(2), p. 1. PSWQA, Olympia, Washington. May/June 1994a.

Puget Sound Water Quality Authority. Fresh Approach to On-Site Sewage Problems. *Sound Waves*. Vol. 9(2), p. 5. PSWQA, Olympia, Washington. May/June 1994b.

Rogers, J. D. *Recent Developments in Landslide Mitigation Techniques*. Article 10, 8th National Technical Short Course, University of Wisconsin, Madison: Slope Stability and Landslides. Held in Tacoma, Washington. September 1988.

Royster, D. L. *Landslide Remedial Measures*. Bulletin of the Association of Engineering Geologists, Volume XVI, Number 2, pp. 301-352. Spring, 1979.

Ruotsala, A. A. A Beach Processes Field Guide for the Pacific Northwest. Privately produced with assistance from University of Washington Sea Grant Program. 322 pp. 1979.

Sargeant, D. Pollution Gains Upper Hand in Lower Hood Canal. p. 3-4. In Shellfish Quarterly, Washington Coastal Currents. Washington Department of Ecology, Olympia, Washington. Vol. XVII (10), p. 3-4. April 1993.

Schwartz, M. L. and R. S. Wallace. Quantification of Net Share-Drift Rates in Puget Sound and the Strait of Juan de Fuca. Washington Department of Ecology, Olympia. WDOE 87-10. 41 pp. 1986.

Seattle Water Pollution Control Department (SWPCD). Biofiltration Swale Performance, Recommendations, and Design Considerations. Municipality of Metropolitan Seattle, Water Pollution Control Department. Seattle, Washington. Publication No. 657 (October 15, 1992). 1992.

Sharpe, C. F. S. Landslides and Related Phenomena: A Study of Movements of Soil and Rock. Columbia University Press, New York. 137 pp. 1938.

Shipman, H. *Vertical Land Movements in Coastal Washington: Implications for Relative Sea Level Changes*. Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia. 1989.

__________________. "Potential application of the Coast Barrier Resources Act to Washington State." *Proceedings, Coastal Zone 93, Eighth Symposium on Coastal and Ocean Management*. July 19-23, 1993, New Orleans, Louisiana, American Society of Civil Engineers, New York. 1993.

Slade, D.C. *et al.* Putting the Public Trust Doctrine to Work. Prepared for Connecticut Department of Environmental Protection, Coastal Resources Management Division. 361 pp. 1990.

Soil Conservation Service (SCS). Soil Bioengineering for Upland Slope Protection and Erosion Reduction. Chapter 18, U.S. Department of Agriculture, Soil Conservation Service, Engineering Field Handbook (210-EFH, 10/92). SCS, Washington, D.C. 53 pp. 1992.

Southeastern Wisconsin Regional Planning Commission (SEWRPC). *A Lake Michigan Shoreline Erosion Management Plan for Northern Milwaukee County, Wisconsin.* Community Assistance Planning Report Number 155. Waukesha, Wisconsin. December 1988.

Stembridge, Jr., J.E. Beach Protection Properties of Accumulated Driftwood. American Society of Civil Engineers, New York. Coastal Structures '79. Vol. II, pp. 1052-1068. 1979.

Sunamura, T. A Wave Tank Experiment on the Erosional Mechanism at a Sea Cliff Base. Earth Surface Processes. Vol. 7, pp. 333-343. 1982.

__________________. Process of Sea Cliff and Platform Erosion. Pp. 233-266, In Komar, P.D. (ed.) Handbook of Coastal Processes and Erosion. CRC Press, Boca Raton, Florida. 1983.

Tainter, S. P. Bluff Slumping and Stability: A Consumers Guide. Michigan Sea Grant Program, Project R/CE-4, Publications Office, Ann Arbor, Michigan. Report No. MICHU-SG-82-902. 65 pp. 1982.

Taylor, D. W. Fundamentals of Soil Mechanics. John Wiley & Sons, New York. 700 pp. 1984.

Terich, T. A. *Living with the Shore of Puget Sound and the Georgia Strait.* Sponsored by the National Audubon Society. Duke University Press. Durham, North Carolina. 165 pp. 1987.

Thorsen, G. W. *Soil Bluffs + Rain = Slide Hazards.* Washington Geologic Newsletter, Volume 15, Number 3, Washington State Department of Natural Resources, Division of Geology and Earth Resources. July 1987.

__________________. *Landslide Provinces in Washington.* Engineering Geology in Washington, Volume 1, Washington Division of Geology and Earth Resources, Bulletin 78, pp. 71-89. 1989.

Tubbs, D. W. *Landslides and Associated Damage During Early 1972 in Part of West-Central King County, Washington.* U.S. Geological Survey, Miscellaneous Geological Investigations, Map I-852B. 1974a.

__________________. *Landslides in Seattle.* State of Washington, Department of Natural Resources. Informational Circular 52. 15 pp. 1974b.

__________________. *Causes, Mechanisms, and Prediction of Landslides in Seattle.* Doctor of Philosophy Thesis, University of Washington. 75 pp. plus Appendices. 1975.

Tubbs, D. W. and T. Dunne. *Geologic Hazards in Seattle.* A field guide for the Geological Society of America Annual Meeting. 1977.

Tubbs, D. W., T. Dunne, and R. W. Sternberg. Earth Sciences Component, pp. 15-46, In Discovery Park Inventory and Natural History Report. Institute for Environmental Studies, University of Washington, Seattle. 1974.

U. S. Army Corps of Engineers. *Shore Protection Manual. Vols. 1-3.* U.S. Government Printing Office, Washington, D.C. 1973.

U. S. Army Corps of Engineers (USACOE). Elliott Bay Small Craft Harbor, Final Federal Environmental Impact Statement, NEPA. Seattle District Office. USACOE, Seattle, Washington. 281 pp. January, 1987.

University of Wisconsin. Eight National Technical Short Course, University of Wisconsin, Madison: Slope Stability and Landslides. Held in Tacoma, Washington. September 12-15, 1988. Short Course Notes.

Urban Forestry Services. Report to CH2M HILL on Tree Cutting Evaluation. April 1992.

Varnes, D. J. *Slope Movement Types and Processes*. Landslides, Analysis and Control, Special Report 176, Transportation Research Board, National Academy of Sciences. 1978.

Wallace, R. S. Quantification of Net Share-Drift Rates in Puget Sound and the Strait of Juan de Fuca, Washington. J. Coastal Research. 4(3):395-403. 1988.

Washington State. Testing the Joint Aquatic Resource Permits Application (JARPA). Prepared by State Departments of Fisheries, Wildlife and Ecology, the USACOE, and representatives of county and city governments. Focus. Olympia, Washington. 30 pp. February 1994.

Washington State Department of Ecology (Ecology). Coastal Zone Atlas of Washington. Washington State Dept. of Ecology, Olympia, Washington. Vols. 1-12. 1977-1980.

__________________. Stormwater Management Manual for the Puget Sound Basin (the Technical Manual). Washington State Dept. of Ecology, Olympia, Washington. Report No. 91-75 (February 1992). 1992.

__________________. Coordinating Wetlands Requirements Under the Shoreline Management Act and the Growth Management Act. Shorelands Growth Management Project, Shorelands and Coastal Zone Management Program, Dept. of Ecology, Olympia, Washington. 14 pp. plus Appendices. 1993.

Watts, J.G. *Physical and Biological Impacts of Bulkheads on North Carolina's Estuarine Shoreline*. Division of Coastal Management, North Carolina Dept. of Environment, Health and Natural Resources, Raleigh, N. Carolina. 39 pp. July 1987.

White, G., *et al.* Natural Hazard Management in Coastal Areas. U.S. Department of Commerce, Washington, D.C. 1976.

Wilcock, P. R., D. S. Miller, and R. T. Kerhin. 1993. Calvert Cliffs Slope Erosion Project, Phase II Final Report: Processes and Controls of Coastal Slope Erosion (Phase I Final Report, 1992, 88 pp.). Maryland Dept. Natural Resources, Coastal and Watershed Resources Division, Baltimore, Maryland. 145 pp.

sea10028406.wp5

Appendix A

Example Homeowner Questionnaires

DIAGNOSING COASTAL EROSION

Before designing a coastal erosion structure or system, before selecting the type of erosion control structure desired, in fact, before even determining whether an erosion control structure is desirable for a specific site and problem, it's important to identify the exact causes of the erosion. Professional assistance may be necessary and may be available from your local Soil Conservation District.

The following checklist, adapted from a Cornell University Cooperative Extension publication, will enable a simple do-it-yourself evaluation of most shoreline erosion, and a preliminary determination as to the primary cause(s) or the erosion, if any. It cannot be stressed enough, however, that coastal erosion control engineering and design are complex and difficult, and the potential impacts far-reaching.

Three major causes of coastal erosion are wave action, surface runoff, and groundwater seepage. Bulkheading and other forms of shoreline hardening can be effective only against wave action. A predominance of "yes" answers in any section is a good indication that that particular cause of erosion may be one, if not the primary, cause of erosion.

Wave Action

1. Is the site a headland that juts out, unprotected, into the water?
2. Is there a long fetch (stretch of open water) in front of the site over which the wind can blow and generate waves?
3. Does the site face prevailing wind and waves?
4. a) Is there a beach along this section of shoreline?
   b) If yes, is the beach often covered by waves, particularly during storms?
   c) If yes, can you see a decrease in the size of the beach after it has been covered by storm waves?
5. If the shoreline is a bluff, is there evidence of wave action such as undercutting of the slope during storms?
6. Is the site subject to flooding during storms?
7. Is there an existing erosion control structure at the site or at an adjacent site which is being flanked, that is, is erosion is cutting around the ends of the structure?

Surface Runoff

1. Is the face of the slope unvegetated and unprotected from the action of rain and flowing water?
2. During a rainfall, can you see a sheetlike flow of water over the surface of the slope?
3. a) Are there rills (tiny channels) cut into the surface of the slope?
   b) Are there gullies (larger channels) cut into the surface of the slope?
4. a) Does the lawn (or other large, flat area) at the site slope toward the face of the bluff?
   b) Is the runoff from that area allowed to flow uncontrolled over the face of the slope?
5. a) Does the runoff from the roof of any building on the site run directly off the roof and over the face of the slope?
   b) Does any driveway or parking lot runoff go directly over the face of the slope?
   c) Is there any lawn sprinkling or irrigation taking place at the top of the slope?

Source: Canning (1991)

Groundwater Seepage

1. a) After a rainfall or during the winter or spring, can you see seep zones (dark, wet-looking layers of soil) along the face of the bluff?
   b) If yes, are they still there after the rest of the slope has dried up?
2. a) Is there active slumping or landsliding taking place on the bluff?
   b) Are there any mudflows or springs along the face of the bluff?
3. a) Does the runoff from any roof drains discharge into the soil at the top of the bluff?
   b) Does the driveway of parking lot runoff soak into the soil at the top of the bluff?
   c) Is there any lawn sprinkling or irrigation taking place at the top of the bluff?
   d) Is there a septic system leach field near the top of the bluff?

COASTAL PROPERTY OWNER CHECKLIST

WHAT LANDFORM(S) ARE LOCATED ON MY PROPERTY? (check glossary definitions)

- ☐ Low Bluff (for this publication, ≤ 10 feet)
- ☐ High Bluff (for this publication, > 10 feet)
- ☐ Low Cliff (not generally applicable to this publication)
- ☐ High Cliff (not generally applicable to this publication)
- ☐ Low Bank (for this publication, ≤ 10 feet)
- ☐ High Bank (for this publication, > 10 feet)
- ☐ Beach with Backshore Berms of Sand/Gravel/Cobbles (marine/estuarine)
- ☐ Wetlands (check with the County Planning Office)

PROPERTY DESCRIPTION AND OBSERVATIONS

_____ What is the elevation of the house above the high tide water surface?
_____ What is the average angle of the slope face?
_____ Do waves reach the toe of the slope?
_____ What are the diameters of beach sediments around the slope toe? (e.g. sand/gravel/cobbles)
_____ Has the slope face been recontoured or filled?
_____ What is soil material type(s) of the slope?

FACTORS INFLUENCING SLOPE EROSION AND STABILITY

- **SURFACE WATER RUNOFF, WIND AND FROST WEDGING**

Can the effects of surface water runoff be visually identified?

- ☐ Rainfall impact erosion
- ☐ Soil rills and gullies
- ☐ Winter freeze-thaw evidence
- ☐ Wind erosion
- ☐ Pipe discharge erosion

What does your property contribute to runoff?

- ☐ Significant upland impervious surface
- ☐ Drainage pipe discharge onto slope
- ☐ Sprinkling/irrigation/hot tub releases
- ☐ Other ______________________________

- **GROUNDWATER**

Is there evidence of groundwater in the slope?

- ☐ Seepage or damp surfaces seen on the slope face
- ☐ Active or historical landslides

What are your contributions to groundwater in the slope?

- ☐ Water infiltration areas (roof and curtain drains)
- ☐ Septic system
- ☐ Irrigation systems

- **VEGETATION**

_____ Is there vegetation on or adjacent to the slope?

If yes, where is it and what are the species.

____

____

If no, is there evidence of past vegetation? What happened to it and what were the species? (check other properties)

____

____

_____ Is there evidence of vegetation movement down the slope?

- **MARINE WATERS**

_____ Is there a noticeable beach width above the high water line?
_____ Are wave energies eroding the toe of the slope?
_____ Are there coastal erosion control structures along the beach of your or neighboring properties? (e.g. bulkheads)
_____ If yes, are these structures causing erosion?
_____ Is your property flood prone?

- **SLOPE USE**

How do you use the slope?

- ☐ Access to the beach (trail/road/stairs/other)
- ☐ Vegetation removal for view maintenance
- ☐ Horticultural/garden areas
- ☐ Waste/debris fills
- ☐ Natural greenbelt including slope crest

Source: Myers (1993)

Menashe (1993): Questions to Answer Before You Begin

The key to maintaining a stable bluff lies in recognizing the natural forces at work on your site. We have discussed the major processes that contribute to unstable situations and the factors that need to be considered. Obviously, some properties and bluff sites are difficult or impossible to develop while maintaining stability. It is important to recognize these sites and to avoid the expense and frustration of attempting to develop them. If you are considering the purchase of bluff property, these questions will be valuable guidelines for what to avoid. If you already own a problem site, the questions below will serve as a checklist to help you make decisions.

- Is the bluff presently stable.
- Are there signs of past instability (landslides)?
- Can you determine when the last one occurred?
- Is the bluff toe subject to wave attack?
- If subject to wave attack, what is the nature and frequency of such action?
- Is the shoreline accreting or eroding?
- If eroding, what is the rate of bluff retreat?
- Would a greater setback of structures from the edge be practical?
- What materials comprise the bluff?
- What is the stratigraphic sequence of the sediments making up the bluff?
- What are the soil moisture and groundwater conditions?
- Is there surface water drainage over the bluff on or adjacent to the property?
- What is the angle of the bluff?
- What vegetation is present?
- Is the property large enough for your purposes (i.e., required setback, driveway, septic, yard, and home)?
- Can the property be developed successfully without initiating or aggravating erosion?

Some of these questions cannot be answered adequately by the homeowner and require the help of a geotechnical expert.

sea10028F7B.wp5

a king county development assistance bulletin 16

Shoreline erosion control:

Puget Sound and Lakes Washington and Sammamish

This Bulletin provides information to help property owners assess beach and bluff erosion problems, outlines regulations regarding construction of shoreline erosion control structures such as bulkheads, and discusses the permits required.

INTRODUCTION

Shoreline erosion on Puget Sound and Lakes Washington and Sammamish is a problem encountered by many owners of waterfront property. In King County, shorelines are characterized by relatively narrow beaches adjacent to steep bluffs rising from a few feet to over a hundred feet above the water. The term "shoreline erosion" commonly includes erosion by waves and currents, which result in the loss of material from beaches and bluffs.

In King County, most material eroded from beaches and bluffs consists of sand, gravel, clay and till deposited by glaciers which last visited Western Washington about thirteen thousand years ago. The particle size of this material affects how easily it is eroded and determines its ultimate fate.

When fine grain particles such as silts and clays are eroded, they are held in suspension by the moving water and swept away. Sand is transported along the beach in the direction of prevailing winds, waves and currents. This helps maintain a sandy beach and builds accretion deposits such as spits and bars. Pebbles, cobbles (fist-size rocks), and boulders too large to be moved by the waves and currents remain on the beach, forming a "lag deposit" that is highly resistant to erosion.

The changing tides and winds affect wave erosion in that the water level moves up and down, subjecting parts of the beach to wave action at different times during the tidal cycle. A wide, well-maintained sand or gravel beach is good protection against wave erosion because wave energy is dissipated on the beach before it reaches the bluffs behind and because the upper part of the beach is subjected to wave action only during high tidal elevations and storm conditions.

The preparation of this document was financially aided by a grant from the Washington State Department of Ecology with funds obtained from the National Oceanic and Atmospheric Administration appropriated for Section 306 of the Coastal Zone Management Act of 1972.

ASSESSING THE PROBLEM

To help determine the nature of your own shoreline erosion problem, answer the following questions.

Questions

1. What is eroding? - the beach, the bluff or both?

2. How far back horizontally is your house (or the closest building) from the high water line? What is the vertical elevation between your house and high water?

3. What is the approximate rate of erosion? (You can keep track of the rate by periodically measuring the distance from a fixed object, (corner of a building, for example) to the top of the bluff.

4. Is the erosion more or less continuous at a constant rate, or is it sudden and severe (such as during a bad storm)?

5. What is the character of the beach surface? See Figure 1 for examples of sand, gravel, and hardpan beaches.

6. If the beach is sandy, how thick is the sand layer? (To measure this, drive a slender steel rod, such as a piece of concrete reinforcing bar, into the beach at several points. The rod should push easily through loose sand and gravel, but stop at a layer of hardpan or cobbles).

7. What is the bluff made of? See Figure 2 for examples of sand, clay and glacial till. One or more of these may be present in layers visible where vegetation is absent from the bluff.

8. What type of vegetation is present on the beach and bluff (trees, brush, vines, seaweed, beach grass, etc.)? Are there any bare landslide areas on the property or nearby?

9. Look at the surface drainage. Are open drain pipes, sewers, streams, or lawn and garden watering causing surface run-off problems?

   Has surface water run-off eroded gullies in the top or face of the bluff?

10. Think about ground water inside the bluff. Surface water can become ground water, causing problems within the bluff. Is there any ponding of water at the top or bottom of the bluff? Is water seepage visible on an exposed bluff face (sometimes at the boundary between clay and sand, where the sand is on top of the clay)?

Answers

1. Building a structure to control beach erosion when it's really the bluff that is eroding (or vice versa) may be avoided by knowing where the problem lies.

2.
3. The distance from the eroding beach or bluff to your house, and the rate of erosion are important in assessing the immediacy of the problem. A situation in which a stucture is not in immediate danger provides more time to evaluate the problem carefully than a situation in which the structure is in immediate danger.

4. Continuous beach erosion is different from a case in which beach erosion occurred all at once during a severe storm. In some cases beaches "heal" themselves after a bad storm; the sand may return in a few months, building the beach back to its former shape.

5.
6. The kind of material comprising the beach determines how easily the beach can be eroded. Sand is easily eroded, but hardpan or cobbles are extremely difficult to erode. A hardpan beach with a thin sand layer on top may have the sand eroded away, but in many cases the hardpan beneath won't be eroded significantly.

7. The material or materials comprising the bluffs help determine how easily this material can be eroded. Sand in a bluff, exposed at the water line, can be easily eroded, whereas till may be quite resistant to erosion. A clay layer, especially when combined with excess ground water can cause potential landslide problems that require special engineering consideration.

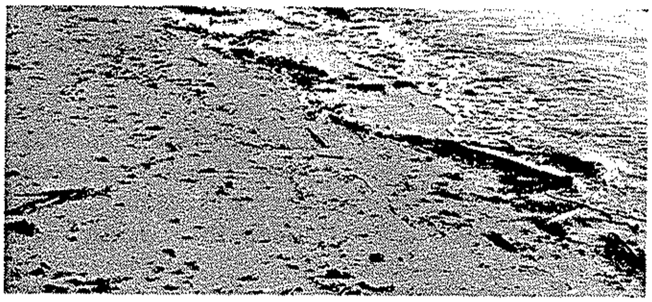
8. Vegetation is a stabilizing influence on beaches and bluffs. Large, mature trees indicate that a slope has not moved much recently. The absence of vegetation means erosion or movement has occurred recently.

9.
10. Surface and ground water are common causes of problems in bluffs. This is one type of problem that a bulkhead alone often cannot alleviate.

11. Is there any direct evidence of on-going erosion, such as cracks or fissures in the slope, piles of debris (rocks, sand, gravel, etc.) at the base of a bluff, leaning trees or exposed roots, cracked foundations, retaining walls or pavement, or wave-cut notches at the base of the bluff?

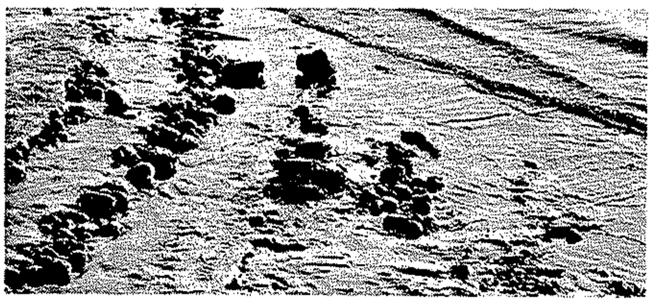
11. Such evidence of on-going erosion can help determine the nature and immediacy of the problem.

FIGURE 1



SANDY BEACH

GRAVEL BEACH

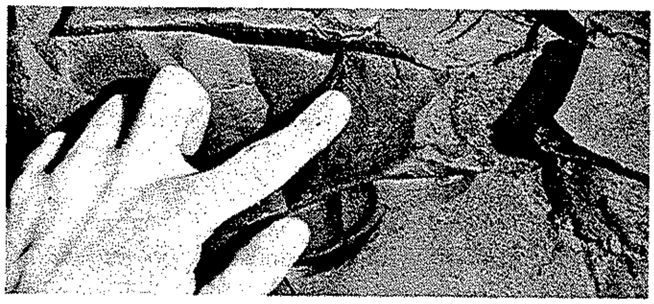


HARDPAN BEACH

FIGURE 2

SAND

GLACIAL TILL



CLAY

BE A BLUFF WATCHER

Because of the serious consequences of shoreline erosion and landslides, owners of waterfront property should develop a habit of watching and maintaining their beaches and bluffs. In much the same way as homeowners think about fire safety by taking care of hazards before they become a problem, owners of waterfront property can do certain things to reduce the likelihood of shoreline erosion and landslides, including:

- Maintain catch basins and surface drainage systems in good working condition.
- Don't let drain pipes or surface run-off spill down the unprotected face of a bluff.
- Use appropriate plantings whosé roots help stabilize bluffs.
- Keep fast-growing brush or trees on bluffs trimmed back to keep their weight from toppling them over.
- Use tight-line pipe for drainage to keep water from seeping into the ground through leaky pipe joints.
- Avoid making cuts and fills near bluffs or on steep slopes. This can lead to erosion or landslide problems.

EROSION CONTROL STRUCTURES

Before you decide to build a shoreline erosion control structure such as a bulkhead, get competent, professional advice about the causes of the problem from a licensed engineer or geologist. Bulkheads are expensive to build and don't always solve the problem. Professional engineering advice may save you time, money, and trouble by identifying the problem and recommending appropriate solutions.

SIDE EFFECTS OF BULKHEADS

A properly designed and constructed bulkhead may help control a shoreline erosion problem. But it can have some undesirable side effects. On Puget Sound, most of the sand making up local beaches comes from the gradual erosion of nearby bluffs. Bulkheads alter or restrict the natural supply of sand to the beaches. Without a continuing supply of sand, other beaches in the area may be eroded by waves and deposits of sand such as spits and bars which also depend on a continuing sand supply, may be endangered.

Because you might create other erosion problems for your neighbors by blocking natural sand supplies to a beach, consider non-structural alternatives to a bulkhead, that will not block sand supplies. Again, the services of a licensed professional engineer can be helpful in choosing non-structural methods for reducing or controlling an erosion problem.

REQUIRED PERMITS

Listed below are examples of some of the permits that may be required, should you decide to build a bulkhead:

- A Shoreline Substantial Development Permit.
- Building Permit.
- U.S. Army Corps of Engineers Section 10 Permit.

Application for the Building and Shoreline Permits may be made at the Building and Land Development Division at the address below. (Phone 296-6650). The U.S. Army Corps of Engineers Permit may be obtained from the Corps' Seattle District Office, 4735 E. Marginal Way So., Seattle, WA. (Phone: 764-3495).

RESTRICTIONS ON BULKHEADS

Bulkheads are not an outright permitted use in King County. Restrictions on bulkheads in King County include:

- A bulkhead is normally permitted only when necessary to protect legally established structures and public improvements, or to preserve important agricultural lands, as determined by King County Building and Land Development Division.
- Bulkheads on property without structures require a Shoreline Substantial Development Permit.
- The elevation of the toe of a bulkhead must be at or above the elevation of Mean Higher High Water in Puget Sound or Ordinary High Water in Lakes Washington and Sammamish, except when necessary to tie in with adjacent, legally constructed bulkheads or to replace an existing bulkhead installed no farther offshore than the original.
- Construction of a bulkhead for the purpose of creating landfill is prohibited.

For more detailed information call a Shoreline Planner at 296-6650.

PENALTIES AND LIABILITIES

It is important to obtain the necessary permits before beginning construction of a bulkhead or other shoreline erosion control structure. As part of their mandate to oversee construction in navigable waters, the U.S. Army Corps of Engineers periodically conducts aerial photographic surveys to check compliance with their regulations. Illegally constructed or otherwise nonconforming structures are spotted and appropriate action is taken.

Anyone found guilty of willfully violating the King County Code may be subject to a fine and/or County jail sentence. In addition, civil suits may be filed holding a violator responsible for any damages caused by such violation, even to the extent of restoring all affected areas to their previous natural state. Take time to know the law to protect yourself.

Note: BALD Development Assistance Bulletins and other written information should not be used as substitutes for codes and regulations. You should review all the details of your project to be sure they comply with the applicable codes and regulations.

Building and Land Development Division

3600 - 136th Place Southeast, Suite A
Bellevue, WA 98006-1400
Telephone (206) 296-6650

Know Your Situation

Some 80 percent of the Great Lakes shoreline is privately owned. About half the private shore which is susceptible to erosion is used for residences. This means the responsibility for controlling erosion is in your hands.

How do you approach an erosion problem?

First use the site assessment checklist to learn what is happening on your bluff site. By the time you have finished filling out the assessment sheet, you will know most of the relevant information for determining what erosion problems you have.

Then you can match the natural factors you are up against with your options in erosion protection.

Finally, when you've made a decision on what to do, you can make a detailed plan of how to go about it.

Assessing Your Property - A Checklist

WHAT IS YOUR BLUFF SITE LIKE?

Dimensions

____height above the water

____width of beach between water and bluff toe

____slope angle

Composition

Of what materials is the beach made?

____sand ____gravel ____cobbles

Of what materials is the bluff made?

____sand ____silt ____glacial till ____clay ____combinations

Make a diagram of your bluff showing the relative vertical location, depth, and thickness of the materials in the bluff.

Source: Tainter (1982)

Wave Action

___waves eroding the beach ___waves eroding the bluff toe

Are there any shore protection devices nearby?

___on your property ___on adjacent property

Are these devices protecting the beach?

Are neighbors having problems?

Surface Drainage

Is water running over the face of the bluff after rainfall or sprinkling?

What are your contributions to surface runoff?

___sprinkling ___downspouts/rain gutters

Subsurface Drainage

Do you have a septic system drain field?

Are there seep areas on the bluff face?

Are there wet areas?

Is the soil saturated during heavy rains?

Are any drains installed in the bluff? If so, do they operate correctly and is the drain outlet correctly situated to cause no further face or toe erosion?

Toe

___grasses ___shrubs ___trees

Face

___grasses ___shrubs ___trees

Top

___grasses or lawn ___green belt ___trees

___no roots exposed

___roots exposed

If there used to be vegetation on the toe, face, or top of the bluff, but it is no longer there, what happened to it?

4. **WHAT USES WILL YOU MAKE OF THE PROPERTY?**

Access to the beach

___foot path ___stairs ___roadways

A place from which to view the lake

Building site

5. **WHAT LOCAL, STATE, AND FEDERAL RESTRICTIONS APPLY TO YOUR PROPERTY?**

Once you have identified the type of property you have and the problems you may encounter, then you can determine how to handle your problems.

Appendix B

Geological Resource Materials Annotated By County

Geological Resource Materials

GENERAL RESOURCES

Canning, Douglas J., 1985, Shoreline bluff and slope stability--Technical management options: Washington Department of Ecology Shorelands Division Shorelands Technical Advisory Paper 2, 64 p.
Geographic: PUGET LOWLAND
Subject: LANDSLIDES AND SLOPE STABILITY/ENGINEERING GEOLOGY/SHORELINES

Canning, Douglas J., 1991, Shoreline bluff and slope stability--Management options: Washington Department of Ecology Shorelands Technical Advisory Paper 2, 56 p.
Geographic: PACIFIC COAST/PUGET LOWLAND
Subject: SHORELINES/LANDSLIDES AND SLOPE STABILITY

Galster, Richard W., 1987, A survey of coastal engineering geology in the Pacific Northwest: Association of Engineering Geologists Bulletin, v. 24, no. 2, p. 161-197.
Geographic: PUGET SOUND/STRAIT OF JUAN DE FUCA/PACIFIC COAST
Subject: SHORELINES/ENGINEERING GEOLOGY/GEOMORPHOLOGY/LANDSLIDES AND SLOPE STABILITY

Menashe, Elliott, 1993, Vegetative management--A guide for Puget Sound bluff property owners: Washington Department of Ecology Publication 93-31, 46 p.
Geographic: PUGET LOWLAND
Subject: SHORELINES - EROSION/LANDSLIDES AND SLOPE STABILITY - VEGETATIVE CONTROL

Mintz, D. W.; Babcock, R. S.; Terich, T. A., 1976, Potential land use problems of Puget Sound shore bluffs. IN Washington Division of Geology and Earth Resources, Engineering geologic studies: Washington Division of Geology and Earth Resources Information Circular 58, p. 21-33.
Geographic: PUGET LOWLAND
Subject: GEOLOGIC HAZARDS - LANDSLIDES /SHORELINES/COASTAL ZONE MANAGEMENT/LAND USE PLANNING

Myers Biodynamics, Inc., 1993, Slope stabilization and erosion control using vegetation--A manual of practice for coastal property owners: Washington Department of Ecology Publication 93-30, 42 p.
Geographic: PUGET LOWLAND
Subject: SHORELINES - EROSION/LANDSLIDES AND SLOPE STABILITY - VEGETATIVE CONTROL

Peck, Craig A., and Associates, 1976, Draft environmental impact statement for Seacliff, residential development: Whatcom County Planning Department, 1 v.
Geographic: WHATCOM CO./POINT ROBERTS, WASH.
Subject: ENVIRONMENTAL IMPACT STATEMENTS/STRATIGRAPHY/LANDSLIDES AND SLOPE STABILITY/SHORELINES/SOIL MECHANICS

Terich, Thomas A., 1987, Living with the shore of Puget Sound and the Georgia Strait: Duke University Press, 165 p.
Geographic: PUGET SOUND
Subject: SHORELINES/COASTAL ZONE MANAGEMENT/GEOLOGIC HAZARDS - COASTAL LANDSLIDES

AND FLOODING/LANDSLIDES AND SLOPE STABILITY/FLOODING

Washington Department of Ecology, 1977, Coastal zone atlas of Washington; volume 1, Whatcom County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.
Geographic: WHATCOM CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY/LITTORAL DRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT

Washington Department of Ecology, 1978, Coastal zone atlas of Washington; volume 2, Skagit County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.
Geographic: SKAGIT CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY/LITTORAL DRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT

Washington Department of Ecology, 1978, Coastal zone atlas of Washington; volume 3, San Juan County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.
Geographic: SAN JUAN CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY/LITTORAL DRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT

Washington Department of Ecology, 1979, Coastal zone atlas of Washington; volume 4, Island County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.
Geographic: ISLAND CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY/LITTORAL DRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT

Washington Department of Ecology, 1979, Coastal zone atlas of Washington; volume 5, Snohomish County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.
Geographic: SNOHOMISH CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY/LITTORAL DRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT

Washington Department of Ecology, 1979, Coastal zone atlas of Washington; volume 6, King County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.
Geographic: KING CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY/LITTORAL DRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT

Washington Department of Ecology, 1979, Coastal zone atlas of Washington; volume 7, Pierce County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.
Geographic: PIERCE CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY/LITTORAL DRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT

Washington Department of Ecology, 1980, Coastal zone atlas of Washington; volume 8, Thurston County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.
Geographic: THURSTON CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY/LITTORAL DRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT

Washington Department of Ecology, 1980, Coastal zone atlas of Washington; volume 9, Mason County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.
Geographic: MASON CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY/LITTORAL DRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT

Washington Department of Ecology, 1979, Coastal zone atlas of Washington; volume 10, Kitsap County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.
Geographic: KITSAP CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY/LITTORAL DRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT

Washington Department of Ecology, 1978, Coastal zone atlas of Washington; volume 11, Jefferson County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.
Geographic: JEFFERSON CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY/LITTORAL DRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT

Washington Department of Ecology, 1978, Coastal zone atlas of Washington; volume 12, Clallam County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.
Geographic: CLALLAM CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY/LITTORAL DRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT

Clallam County

Brown, R. D., Jr., 1970, Geologic map of the north-central part of the Olympic Peninsula, Washington: U.S. Geological Survey Open-File Report 70-43, 2 sheets, scale 1:62,500.

Geographic: CLALLAM CO.

Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Brown, Robert David, Jr.; Gower, Howard Dale; Snavely, Parke Detwiler, Jr., 1960, Geology of the Port Angeles-Lake Crescent area, Clallam County, Washington: U.S. Geological Survey Oil and Gas Investigation Map OM-203, 1 sheet, scale 1:62,500.

Geographic: CLALLAM CO./PORT ANGELES, WASH./LAKE CRESCENT

Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Frederick, J. E., 1979, Map showing natural land slopes, Port Townsend quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-A, 1 sheet, scale 1:100,000.

Geographic: PORT TOWNSEND QUADRANGLE/CLALLAM CO./JEFFERSON CO./ISLAND CO./SNOHOMISH CO./SKAGIT CO./SAN JUAN CO.

Subject: TOPOGRAPHY/GEOMORPHOLOGY

Halloin, Louis J., 1987, Soil survey of Clallam County area, Washington: U.S. Soil Conservation Service, 213 p., 67 plates.

Geographic: CLALLAM CO.

Subject: SOIL SURVEYS

Keuler, Ralph F., 1988, Map showing coastal erosion, sediment supply, and longshore transport in the Port Townsend 30- by 60-minute quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-E, 1 sheet, scale 1:100,000.

Geographic: PORT TOWNSEND QUADRANGLE/SKAGIT CO./ISLAND CO./JEFFERSON CO./CLALLAM CO.

Subject: SHORELINES/LITTORAL DRIFT/EROSION

Maytin, Iury L.; Gilkeson, Raymond A., 1961, State of Washington engineering soils manual--Soils of Clallam County: Washington State Institute of Technology Division of Industrial Research Bulletin 253, 130 p.

Geographic: CLALLAM CO.

Subject: SOILS/ENGINEERING GEOLOGY

Miller, Robert D.; Pessl, Fred, Jr., compilers, 1986, Map showing unconsolidated deposits grouped on the basis of texture, Port Townsend 30' x 60' quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-D, 1 sheet.

Geographic: PORT TOWNSEND QUADRANGLE/CLALLAM CO./JEFFERSON

CO./ISLAND CO./SKAGIT CO./SNOHOMISH CO.
Subject: SEDIMENTARY PETROLOGY/SOILS

Miller, R. D.; Safioles, S. A.; Pessl, Fred, Jr., 1985, Map showing relative slope stability in the Port Townsend 30' x 60' quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I- 1198-C, 1 sheet, scale 1:100,000.
Geographic: PUGET LOWLAND/SKAGIT CO./SNOHOMISH CO./ISLAND CO./SAN JUAN CO./CLALLAM CO./JEFFERSON CO./PORT TOWNSEND QUADRANGLE
Subject: LANDSLIDES AND SLOPE STABILITY

Noble, John Boardman, 1960, A preliminary report on the geology and ground- water resources of the Sequim-Dungeness area, Clallam County, Washington: Washington Division of Water Resources Water Supply Bulletin 11, 43 p., 3 plates.
Geographic: CLALLAM CO./SEQUIM, WASH./DUNGENESS, WASH.
Subject: AREAL GEOLOGY/HYDROLOGY - GROUND WATER/MAPS - GEOLOGIC/DRILLING LOGS

Othberg, K. L.; Palmer, Pamela, 1979, Preliminary surficial geologic map of part of the Gardiner quadrangle, Clallam County, Washington: Washington Division of Geology and Earth Resources Open-File Report 79-19, 3 p., 1 plate, scale 1:24,000.
Geographic: CLALLAM CO./GARDINER QUADRANGLE
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Othberg, K. L.; Palmer, Pamela, 1979, Preliminary surficial geologic map of the Dungeness quadrangle, Clallam County, Washington: Washington Division of Geology and Earth Resources Open-File Report 79-17, 3 p., 1 plate, scale 1:24,000.
Geographic: CLALLAM CO./DUNGENESS QUADRANGLE
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Othberg, K. L.; Palmer, Pamela, 1979, Preliminary surficial geologic map of the Sequim quadrangle, Clallam County, Washington: Washington Division of Geology and Earth Resources Open-File Report 79-18, 4 p., 1 plate, scale 1:24,000.
Geographic: CLALLAM CO./SEQUIM QUADRANGLE
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Othberg, K. L.; Palmer, Pamela, 1982, Preliminary surficial geologic map of the Carlsborg quadrangle, Clallam County, Washington: Washington Division of Geology and Earth Resources Open-File Report 79-20, 1 sheet, scale 1:24,000.
Geographic: CLALLAM CO./CARLSBORG QUADRANGLE
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Pessl, Fred, Jr.; Dethier, D. P.; Booth, D. B.; Minard, J. P., 1989, Surficial geologic map of the Port Townsend 30- by 60-minute quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-F, 1 sheet, scale 1:100,000, with 13 p. text.
Geographic: PORT TOWNSEND QUADRANGLE/SKAGIT CO./SNOHOMISH CO./ISLAND CO./SAN JUAN CO./CLALLAM CO./JEFFERSON CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Ritchie, A. M., 1958, Recognition and identification of landslides. In Eckel, E. B., editor, 1958, Landslides and engineering practice: Highway Research Board Special Report 29, p. 48-68.
Geographic: KING CO./CLALLAM CO.
Subject: LANDSLIDES AND SLOPE STABILITY/LANDSLIDE BIB/ENGINEERING GEOLOGY

U.S. Army Corps of Engineers, 1972, Erosion control, Ediz Hook, Port Angeles, Washington. In Schwartz, M. L., editor, 1972, Spits and bars: Dowden, Hutchinson and Ross Benchmark Papers in Geology, p. 401-438.
Geographic: EDIZ HOOK/CLALLAM CO.
Subject: SHORELINES/EROSION/COASTAL ZONE MANAGEMENT

Washington Department of Ecology, 1978, Coastal zone atlas of Washington; volume 12, Clallam County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.
Geographic: CLALLAM CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY /LITTORALDRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT

Whetten, J. T.; Carroll, P. I.; Gower, H. D.; Brown, E. H.; Pessl, Fred, Jr., 1988, Bedrock geologic map of the Port Townsend 30- by 60-minute quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-G, 1 sheet, scale 1:100,000.
Geographic: PORT TOWNSEND QUADRANGLE/SKAGIT CO./SNOHOMISH CO./ISLAND CO./JEFFERSON CO./SAN JUAN CO./CLALLAM CO./PUGET LOWLAND
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Island County

Anderson, H. W., Jr., 1968, Ground-water resources of Island County, Washington: Washington Department of Water Resources Water-Supply Bulletin 25, part 2, 317 p.
Geographic: ISLAND CO.
Subject: HYDROLOGY - GROUND WATER

Easterbrook, D. J., 1968, Pleistocene stratigraphy of Island County: Washington Department of Water Resources Water-Supply Bulletin 25, part 1, 34 p., 1 plate (in 4 parts).
Geographic: ISLAND CO./DOUBLE BLUFF DRIFT/WHIDBEY FORMATION/POSSESSIONDRIFT/QUADRA FORMATION/VASHON DRIFT/PARTRIDGE GRAVEL/EVERSON GLACIOMARINE DRIFT
Subject: QUATERNARY - PLEISTOCENE/STRATIGRAPHY/GLACIAL GEOLOGY/SEDIMENTARY PETROLOGY

Frederick, J. E., 1979, Map showing natural land slopes, Port Townsend quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-A, 1 sheet, scale 1:100,000.
Geographic: PORT TOWNSEND QUADRANGLE/CLALLAM CO./JEFFERSON CO./ISLAND CO./SNOHOMISH CO./SKAGIT CO./SAN JUAN CO.
Subject: TOPOGRAPHY/GEOMORPHOLOGY

Keuler, Ralph F., 1988, Map showing coastal erosion, sediment supply, and longshore transport in the Port Townsend 30- by 60-minute quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-E, 1 sheet, scale 1:100,000.
Geographic: PORT TOWNSEND QUADRANGLE/SKAGIT CO./ISLAND CO./JEFFERSON CO./ CLALLAM CO.
Subject: SHORELINES/LITTORAL DRIFT/EROSION

Miller, Robert D.; Pessl, Fred, Jr., compilers, 1986, Map showing unconsolidated deposits grouped on the basis of texture, Port Townsend 30' x 60' quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-D, 1 sheet.
Geographic: PORT TOWNSEND QUADRANGLE/CLALLAM CO./JEFFERSON CO./ISLAND CO./ SKAGIT CO./SNOHOMISH CO.
Subject: SEDIMENTARY PETROLOGY/SOILS

Miller, R. D.; Safioles, S. A.; Pessl, Fred, Jr., 1985, Map showing relative slope stability in the Port Townsend 30' x 60' quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I- 1198-C, 1 sheet, Miller, Robert D.; Pessl, Fred, Jr., compilers, 1986, Map showing unconsolidated deposits grouped on the basis of texture, Port Towscale 1:100,000.
Geographic: PUGET LOWLAND/SKAGIT CO./SNOHOMISH CO./ISLAND

CO./SAN JUAN CO./CLALLAM CO./JEFFERSON CO./PORT TOWNSEND QUADRANGLE
Subject: LANDSLIDES AND SLOPE STABILITY

Minard, James P., 1982, Distribution and description of geologic units in the Mukilteo quadrangle, Washington: U.S. Geological Survey Miscellaneous Field Studies Map MF-1438, 1 sheet, scale 1:24,000.
Geographic: ISLAND CO./MUKILTEO QUADRANGLE/SNOHOMISH CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Minard, James P., 1985, Geologic map of the Tulalip quadrangle, Snohomish County, Washington: U.S. Geological Survey Miscellaneous Field Studies Map MF- 1744, 1 sheet, scale 1:24,000.
Geographic: SNOHOMISH CO./ISLAND CO./TULALIP QUADRANGLE
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Ness, A. O.; Richins, C. G., 1958, Soil survey of Island County, Washington: U.S. Soil Conservation Service Series 1949, no. 6, 58 p., 16 plates.
Geographic: ISLAND CO.
Subject: SOILS

Pessl, Fred, Jr.; Dethier, D. P.; Booth, D. B.; Minard, J. P., 1989, Surficial geologic map of the Port Townsend 30- by 60-minute quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-F, 1 sheet, scale 1:100,000, with 13 p. text.
Geographic: PORT TOWNSEND QUADRANGLE/SKAGIT CO./SNOHOMISH CO./ISLAND CO./ SAN JUAN CO./CLALLAM CO./JEFFERSON CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Washington Department of Ecology, 1979, Coastal zone atlas of Washington; volume 4, Island County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.
Geographic: ISLAND CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY/LITTORAL DRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT

Jefferson County

Birdseye, R. U., 1976, Geologic map of east-central Jefferson County, Washington: Washington Division of Geology and Earth Resources Open-File Report 76-26, 1 sheet, scale 1:24,000.
Geographic: JEFFERSON CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Birdseye, R. U., 1976, Relative slope stability in east-central Jefferson County, Washington: Washington Division of Geology and Earth Resources Open-File Report 76-27, 1 sheet, scale 1:24,000.
Geographic: JEFFERSON CO.
Subject: LANDSLIDES AND SLOPE STABILITY

Carson, R. J., 1976, Relative slope stability of the Brinnon area, Jefferson County, Washington: Washington Division of Geology and Earth Resources Open-File Report 76-15, 1 sheet, scale 1:24,000.
Geographic: JEFFERSON CO./BRINNON AREA.
Subject: LANDSLIDES AND SLOPE STABILITY

Frederick, J. E., 1979, Map showing natural land slopes, Port Townsend quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-A, 1 sheet, scale 1:100,000.
Geographic: PORT TOWNSEND QUADRANGLE/CLALLAM CO./JEFFERSON CO./ISLAND CO./SNOHOMISH CO./SKAGIT CO./SAN JUAN CO.
Subject: TOPOGRAPHY/GEOMORPHOLOGY

Galster, Richard W.; Ekman, Mark, 1977, Field trip 5--Coastal engineering geology, northern Olympic Peninsula. In Association of Engineering Geologists, Guidebook to field trips; 1977 National Meeting, Seattle, Washington: Association of Engineering Geologists, p. 115-133.
Geographic: JEFFERSON CO./CLALLAM CO./DUNGENESS SPIT/EDIZ HOOK.
Subject: GUIDEBOOKS/SHORELINES/LITTORAL DRIFT/ENGINEERING GEOLOGY

Gayer, M. J., 1976, Slope stability map of northeastern Jefferson County, Washington: Washington Division of Geology and Earth Resources Open-File Report 76-22, 1 sheet, scale 1:24,000.
Geographic: JEFFERSON CO.
Subject: LANDSLIDES AND SLOPE STABILITY

Grimstad, Peder; Carson, Robert J., 1981, Geology and ground-water resources of eastern Jefferson County, Washington: Washington Department of Ecology Water-Supply Bulletin 54, 125 p., 3 plates.
Geographic: JEFFERSON CO.

Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/HYDROLOGY - GROUND WATER

Hanson, K. L., 1976, Geologic map of the Uncas-Port Ludlow area, Jefferson County, Washington: Washington Division of Geology and Earth Resources Open-File Report 76-20, 1 sheet, scale 1:24,000.
Geographic: JEFFERSON CO./UNCAS-PORT LUDLOW AREA.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Hanson, K. L., 1976, Slope stability map of the Uncas-Port Ludlow area, Jefferson County, Washington: Washington Division of Geology and Earth Resources Open-File Report 76-18, 1 sheet, scale 1:24,000.
Geographic: JEFFERSON CO./UNCAS-PORT LUDLOW AREA.
Subject: LANDSLIDES AND SLOPE STABILITY

Keuler, Ralph F., 1988, Map showing coastal erosion, sediment supply, and longshore transport in the Port Townsend 30- by 60-minute quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-E, 1 sheet, scale 1:100,000.
Geographic: PORT TOWNSEND QUADRANGLE/SKAGIT CO./ISLAND CO./JEFFERSON CO./ CLALLAM CO.
Subject: SHORELINES/LITTORAL DRIFT/EROSION

McCreary, F. R., 1975, Soil survey of Jefferson County area, Washington: U.S. Soil Conservation Service,
100 p., 70 plates.
Geographic: JEFFERSON CO.
Subject: SOILS

Miller, R. D.; Safioles, S. A.; Pessl, Fred, Jr., 1985, Map showing relative slope stability in the Port Townsend 30' x 60' quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198- C, 1 sheet, scale 1:100,000.
Geographic: PUGET LOWLAND/SKAGIT CO./SNOHOMISH CO./ISLAND CO./SAN JUAN CO./ CLALLAM CO./JEFFERSON CO./PORT TOWNSEND QUADRANGLE.
Subject: LANDSLIDES AND SLOPE STABILITY

Pessl, Fred, Jr.; Dethier, D. P.; Booth, D. B.; Minard, J. P., 1989, Surficial geologic map of the Port Townsend 30- by 60-minute quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-F, 1 sheet, scale 1:100,000, with 13 p. text.
Geographic: PORT TOWNSEND QUADRANGLE/SKAGIT CO./SNOHOMISH CO./ISLAND CO./SAN JUAN CO./CLALLAM CO./JEFFERSON CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Washington Department of Ecology, 1978, Coastal zone atlas of Washington; volume 11, Jefferson County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.
Geographic: JEFFERSON CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY/LITTORAL DRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT

Yount, J. C.; Minard, J. P.; Dembroff, G. R., 1993, Geologic map of surficial deposits in the Seattle 30' x 60' quadrangle, Washington: U.S. Geological Survey Open-File Report 93-233, 2 sheets, scale 1:100,000.
Geographic: KING CO./KITSAP CO./SNOHOMISH CO./SEATTLE QUADRANGLE/ISLAND CO./JEFFERSON CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/STRATIGRAPHY

King County

King County Parks, Planning, and Resources Department, 1990, Sensitive areas map folio--King County, December 1990: King County Parks, Planning, and Resources Department, 1 v.

Geographic: KING CO.

Subject: GEOLOGIC HAZARDS/LAND USE PLANNING /WETLANDS /FLOODS /EROSION /LANDSLIDES AND SLOPE STABILITY /EARTHQUAKES AND SEISMOLOGY/COAL MINE SUBSIDENCE

Woodward, D. G., 1992, Evaluation of the ground-water resources of southwestern King County. In Wayenberg, J. A.; Renslow, V. F., compilers, Summary of water-resources activities of the U.S. Geological Survey in Washington--Fiscal year 1991: U.S. Geological Survey Open-File Report 92-92, p. 27.

Geographic: KING CO.

Subject: HYDROLOGY - GROUND WATER

Yount, J. C.; Minard, J. P.; Dembroff, G. R., 1993, Geologic map of surficial deposits in the Seattle 30' x 60' quadrangle, Washington: U.S. Geological Survey Open-File Report 93-233, 2 sheets, scale 1:100,000.

Geographic: KING CO./KITSAP CO./SNOHOMISH CO./SEATTLE QUADRANGLE/ISLAND CO./JEFFERSON CO.

Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/STRATIGRAPHY

Booth, D. B., 1991, Geologic map of Vashon and Maury Islands, King County, Washington: U.S. Geological Survey Miscellaneous Field Studies Map MF-2161, 1 sheet, scale 1:24,000, with 6 p. text.

Geographic: KING CO./VASHON ISLAND/MAURY ISLAND

Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Friedman-Thomas, Rachel; Minton, Gary, 1988, Erosion control--What is the state of the art? In Washington State Puget Sound Water Quality Authority, Proceedings--First annual meeting on Puget Sound research: Puget Sound Water Quality Authority, v. 2, p. 718-722.

Geographic: KING CO.

Subject: ENGINEERING GEOLOGY - EROSION/SOIL EROSION CAUSED BY DEVELOPMENT

Galster, R. W.; Laprade, W. T., 1991, Geology of Seattle, Washington, United States of America: Association of Engineering Geologists Bulletin, v. 28, no. 3, p. 235-302, 1 plate..

Geographic: SEATTLE, WASH./KING CO.

Subject: AREAL GEOLOGY/ENGINEERING GEOLOGY/MAPS - GEOLOGIC/EARTHQUAKES AND SEISMOLOGY/GLACIAL GEOLOGY

Grant, W. P.; Perkins, W. J.; Youd, T. L., 1992, Evaluation of liquefaction potential, Seattle, Washington: U.S. Geological Survey Open-File Report 91-441-T, 44 p., 1 plate.

Geographic: SEATTLE, WASH./KING CO.
Subject: EARTHQUAKE-INDUCED LIQUEFACTION/AREAL GEOLOGY/MAPS - GEOLOGIC/ENGINEERING GEOLOGY - SOIL MECHANICS

King County Department of Community and Environmental Development, 1975, Vashon-Maury Island--Physical characteristics and shoreline inventory: King County Department of Community and Environmental Development, 63 p.
Geographic: KING CO./VASHON ISLAND/MAURY ISLAND
Subject: SHORELINES/LAND USE PLANNING

King County Parks, Planning, and Resources Department, 1990, Sensitive areas map folio--King County, December 1990: King County Parks, Planning, and Resources Department, 1 v.
Geographic: KING CO.
Subject: GEOLOGIC HAZARDS/LAND USE PLANNING /WETLANDS /FLOODS /EROSION /LANDSLIDES AND SLOPE STABILITY/EARTHQUAKES AND SEISMOLOGY/COAL MINE SUBSIDENCE

Liesch, B. A.; Price, C. E.; Walters, K. L., 1963, Geology and ground-water resources of northwestern King County, Washington: Washington Division of Water Resources Water-Supply Bulletin 20, 241 p., 3 plates.
Geographic: KING CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/HYDROLOGY - GROUND WATER

Livingston, V. E., Jr., 1971, Geology and mineral resources of King County, Washington: Washington Division of Mines and Geology Bulletin 63, 200 p., 8 plates.
Geographic: KING CO.
Subject: AREAL GEOLOGY/MINERAL RESOURCES/MAPS - GEOLOGIC

McGavock, Edwin H., 1990, Evaluation of ground-water resources in southwest King County. In Wayenberg, J. A., editor, Summary of water-resources activities of the U.S. Geological Survey in Washington--Fiscal year 1989: U.S. Geological Survey Open-File Report 90-180, p. 43.
Geographic: KING CO.
Subject: HYDROLOGY - GROUND WATER

Miller, R. D., 1973, Map showing relative slope stability in part of west- central King County, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-852-A, 1 sheet, scale 1:48,000.
Geographic: KING CO.
Subject: LANDSLIDES AND SLOPE STABILITY

Minard, James P., 1982, Landslides mapped in Seattle, Washington [abstract]: U.S. Geological Survey Professional Paper 1275, p. 222-223.
Geographic: SEATTLE, WASH./KING CO.

Subject: LANDSLIDES AND SLOPE STABILITY

Minard, James P., 1983, Geologic map of the Edmonds East and part of the Edmonds West quadrangles, Washington: U.S. Geological Survey Miscellaneous Field Studies Map MF-1541, 1 sheet, scale 1:24,000.
Geographic: KING CO./SNOHOMISH CO./EDMONDS EAST QUADRANGLE/EDMONDS WEST QUADRANGLE
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Yount, J. C.; Minard, J. P.; Dembroff, G. R., 1993, Geologic map of surficial deposits in the Seattle 30' x 60' quadrangle, Washington: U.S. Geological Survey Open-File Report 93-233, 2 sheets, scale 1:100,000.
Geographic: KING CO./KITSAP CO./SNOHOMISH CO./SEATTLE QUADRANGLE/ISLAND CO./JEFFERSON CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/STRATIGRAPHY

Reichert, W. H., 1978, Annotated guide to sources of information on the geology, minerals, and ground-water resources of the Puget Sound region, Washington, King County section; with supplemental references by D. D. Dethier: Washington Division of Geology and Earth Resources Information Circular 61, 63 p.
Geographic: KING CO.
Subject: AREAL GEOLOGY/MINERAL RESOURCES/HYDROLOGY - GROUND WATER/ BIBLIOGRAPHY

Ritchie, A. M., 1958, Recognition and identification of landslides. In Eckel, E. B., editor, 1958, Landslides and engineering practice: Highway Research Board Special Report 29, p. 48-68.
Geographic: KING CO./CLALLAM CO.
Subject: LANDSLIDES AND SLOPE STABILITY/LANDSLIDE BIB/ENGINEERING GEOLOGY

Smith, Mackey, 1975, Preliminary surficial geologic map of the Edmonds East and Edmonds West quadrangles, Snohomish and King Counties, Washington: Washington Division of Geology and Earth Resources Geologic Map GM-14, 1 sheet, scale 1:24,000.
Geographic: SNOHOMISH CO./KING CO./EDMONDS EAST QUADRANGLE/EDMONDS WEST QUADRANGLE
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Snyder, D. E.; Gale, P. S.; Pringle, R. F., 1973, Soil survey of King County area, Washington: U.S. Soil Conservation Service, 100 p., 22 plates.
Geographic: KING CO.
Subject: SOILS

Tubbs, D. W., 1974, Landslides and associated damage during early 1972 in part of west-central King County, Washington: U.S. Geological Survey Miscellaneous Investigations

Series Map I-852-B, 1 sheet, scale 1:48,000.
Geographic: KING CO.
Subject: LANDSLIDES AND SLOPE STABILITY/GEOLOGIC HAZARDS - LANDSLIDES

Tubbs, D. W., 1974, Landslides in Seattle: Washington Division of Geology and Earth Resources Information Circular 52, 15 p.
Geographic: KING CO./SEATTLE, WASH.
Subject: LANDSLIDES AND SLOPE STABILITY

Tubbs, D. W.; Dunne, Thomas, 1977, Geologic hazards in Seattle--A field guide for the Geological Society of America Annual Meeting, 1977: Geological Society of America, 37 p.
Geographic: SEATTLE, WASH./KING CO.
Subject: GEOLOGIC HAZARDS/LANDSLIDES AND SLOPE STABILITY

Waldron, H. H., 1961, Geology of the Poverty Bay quadrangle, Washington: U.S. Geological Survey Open-File Report 61-167, 2 sheets. (Published as USGS map GQ- 158.)
Geographic: KING CO./PIERCE CO./POVERTY BAY QUADRANGLE
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Waldron, H. H., 1967, Geologic map of the Duwamish Head quadrangle, King and Kitsap Counties, Washington: U.S. Geological Survey Geologic Quadrangle Map GQ- 706, 1 sheet, scale 1:24,000.
Geographic: DUWAMISH HEAD QUADRANGLE/KING CO./KITSAP CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Waldron, H. H.; Leisch, B. A.; Mullineaux, D. R.; Crandell, D. R., 1961, Preliminary geologic map of Seattle and vicinity: U.S. Geological Survey Open- File Report 61-168, 3 sheets. (Published as USGS map I-354.)
Geographic: KING CO./SEATTLE, WASH.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Walsh, Timothy J., 1987, Geologic map of the south half of the Tacoma quadrangle, Washington: Washington Division of Geology and Earth Resources Open-File Report 87-3, 10 p., 1 plate, scale 1:100,000.
Geographic: TACOMA QUADRANGLE/THURSTON CO./PIERCE CO./KING CO./MASON CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Walsh, Timothy J.; Korosec, Michael A.; Phillips, William M.; Logan, Robert L.; Schasse, Henry W., 1987, Geologic map of Washington--Southwest quadrant: Washington Division of Geology and Earth Resources Geologic Map GM-34, 2 sheets, scale 1:250,000, with 28 p. text.
Geographic: SOUTHWESTERN WASHINGTON/GRAYS HARBOR CO./MASON CO./THURSTON CO./PIERCE CO./KING CO./KITTITAS CO./PACIFIC CO./LEWIS CO./YAKIMA CO./KLICKITAT CO./SKAMANIA CO./CLARK CO./COWLITZ CO./

WAHKIAKUM CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Washington Department of Ecology, 1979, Coastal zone atlas of Washington; volume 6, King County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.
Geographic: KING CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY/LITTORAL DRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT

Washington Surveying and Rating Bureau, 1966, Seattle and vicinity, Washington earthquake map, showing general areas of filled or unstable ground: Washington Surveying and Rating Bureau, 1 sheet, scale 1:48,000, with 1 p. text.
Geographic: SEATTLE, WASH./KING CO.
Subject: EARTHQUAKES AND BUILDING/SOIL MECHANICS

Yount, J. C., 1982, Earthquake hazards Puget Sound, Washington. In Jacobson, M. L.; Rodriguez, T. R.; Seiders, W. H., compilers, Summaries of technical reports, Volume XIV: U.S. Geological Survey Open-File Report 82-840, p. 70-71.
Geographic: PUGET LOWLAND/SEATTLE, WASH./KING CO.
Subject: EARTHQUAKE INDUCED LANDSLIDES/GEOLOGIC HAZARDS/AREAL GEOLOGY/ SEISMOLOGY/LANDSLIDES AND SLOPE STABILITY/EARTHQUAKES

Yount, James C., 1983, Geologic units that likely control seismic ground shaking in the greater Seattle area. In Yount, J. C.; Crosson, R. S., editors, Proceedings of workshop XIV, Earthquake hazards of the Puget Sound region, Washington: U.S. Geological Survey Open-File Report 83-19, p. 268-279.
Geographic: KING CO./SEATTLE, WASH.
Subject: SEISMOLOGY/AREAL GEOLOGY

Kitsap County

Garling, M. E.; Molenaar, Dee; and others, 1965, Water resources and geology of the Kitsap Peninsula and certain adjacent islands: Washington Division of Water Resources Water-Supply Bulletin 18, 309 p., 5 plates.

Geographic: KITSAP CO./MASON CO./PIERCE CO./PUGET LOWLAND/KITSAP PENINSULA

Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/HYDROLOGY - GROUND WATER

Hansen, A. J., Jr.; Bolke, E. L., 1980, Ground-water availability on the Kitsap Peninsula, Washington: U.S. Geological Survey Open-File Report 80-1186, 70 p.

Geographic: KITSAP PENINSULA/KITSAP CO./PIERCE CO.

Subject: HYDROLOGY - GROUND WATER

McMurphy, C. J., 1980, Soil survey of Kitsap County area, Washington: U.S. Soil Conservation Service,
127 p., 31 plates.

Geographic: KITSAP CO.

Subject: SOILS

Othberg, K. L., 1975, Geologic interpretive map showing areas of unstable slopes, Kitsap County, Washington: Washington Division of Geology and Earth Resources Open-File Report 75-7, 11 sheets, scale 1:24,000.

Geographic: KITSAP CO.

Subject: LANDSLIDES AND SLOPE STABILITY/MAPS - GEOLOGIC

Sceva, Jack E., 1956, Geology and ground-water resources of Kitsap County, Washington: Annotated Bibliography of Economic Geology 1954, v. 27, no. 2, p. 289.

Geographic: KITSAP CO.

Subject: HYDROLOGY - GROUND WATER

Sceva, Jack Edward, 1957, Geology and ground-water resources of Kitsap County, Washington: U.S. Geological Survey Water-Supply Paper 1413, 178 p., 3 plates.

Geographic: KITSAP CO.

Subject: AREAL GEOLOGY/HYDROLOGY - GROUND WATER/MAPS - GEOLOGIC

Smith, Mackey, 1974, Poulsbo slide: Washington Geologic Newsletter, v. 2, no. 3, p. 7.

Geographic: KITSAP CO./POULSBO, WASH.

Subject: LANDSLIDES AND SLOPE STABILITY

Smith, Mackey; Carson, R. J., 1977, Relative slope stability of the southern Hood Canal area, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-853-F, 1 sheet, scale 1:62,500.

Geographic: MASON CO./KITSAP CO./HOOD CANAL
Subject: LANDSLIDES AND SLOPE STABILITY

Washington Department of Ecology, 1979, Coastal zone atlas of Washington; volume 10, Kitsap County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.

Geographic: KITSAP CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY/LITTORAL DRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT

Yount, J. C.; Minard, J. P.; Dembroff, G. R., 1993, Geologic map of surficial deposits in the Seattle 30' x 60' quadrangle, Washington: U.S. Geological Survey Open-File Report 93-233, 2 sheets, scale 1:100,000.

Geographic: KING CO./KITSAP CO./SNOHOMISH CO./SEATTLE QUADRANGLE/ISLAND CO./JEFFERSON CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/STRATIGRAPHY

Mason County

Carson, R. J., 1975, Slope stability map of north-central Mason County, Washington: Washington Division of Geology and Earth Resources Open-File Report 75-4, 1 sheet, scale 1:62,500.

Geographic: MASON CO.
Subject: LANDSLIDES AND SLOPE STABILITY

Carson, R. J., 1976, Geologic map of north-central Mason County, Washington: Washington Division of Geology and Earth Resources Open-File Report 76-2, 1 sheet, scale 1:62,500.

Geographic: MASON CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Garling, M. E.; Molenaar, Dee; and others, 1965, Water resources and geology of the Kitsap Peninsula and certain adjacent islands: Washington Division of Water Resources Water-Supply Bulletin 18, 309 p., 5 plates.

Geographic: KITSAP CO./MASON CO./PIERCE CO./PUGET LOWLAND/KITSAP PENINSULA
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/HYDROLOGY - GROUND WATER

Molenaar, Dee; Noble, J. B., 1970, Geology and related ground- water occurrence, southeastern Mason County, Washington: Washington Department of Water Resources Water-Supply Bulletin 29, 145 p., 2 plates.

Geographic: MASON CO.
Subject: HYDROLOGY - GROUND WATER/AREAL GEOLOGY/MAPS - GEOLOGIC

Ness, A. O.; Fowler, R. H., 1960, Soil survey of Mason County, Washington: U.S. Soil Conservation Service Series 1951, no. 9, 76 p., 24 plates.

Geographic: MASON CO.
Subject: SOILS

Smith, Mackey; Carson, R. J., 1977, Relative slope stability of the southern Hood Canal area, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-853-F, 1 sheet, scale 1:62,500.

Geographic: MASON CO./KITSAP CO./HOOD CANAL
Subject: LANDSLIDES AND SLOPE STABILITY

Walsh, Timothy J., 1987, Geologic map of the south half of the Tacoma quadrangle, Washington: Washington Division of Geology and Earth Resources Open-File Report 87-3, 10 p., 1 plate, scale 1:100,000.

Geographic: TACOMA QUADRANGLE/THURSTON CO./PIERCE CO./KING CO./MASON CO.

Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Walsh, Timothy J.; Korosec, Michael A.; Phillips, William M.; Logan, Robert L.; Schasse, Henry W., 1987, Geologic map of Washington--Southwest quadrant: Washington Division of Geology and Earth Resources Geologic Map GM-34, 2 sheets, scale 1:250,000, with 28 p. text.

Geographic: SOUTHWESTERN WASHINGTON/GRAYS HARBOR CO./MASON CO./THURSTON CO./PIERCE CO./KING CO./KITTITAS CO./PACIFIC CO./LEWIS CO./YAKIMA CO./KLICKITAT CO./SKAMANIA CO./CLARKCO./COWLITZ CO./WAHKIAKUM CO.

Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Washington Department of Ecology, 1980, Coastal zone atlas of Washington; volume 9, Mason County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.

Geographic: MASON CO.

Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY/LITTORAL DRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT

Pierce County

Anderson, W. W.; Ness, A. O.; Anderson, A. C., 1955, Soil survey of Pierce County, Washington: U.S. Soil Conservation Service Soil Survey Series 1939, no. 27, 88 p.
Geographic: PIERCE CO.
Subject: SOIL SURVEYS

Garling, M. E.; Molenaar, Dee; and others, 1965, Water resources and geology of the Kitsap Peninsula and certain adjacent islands: Washington Division of Water Resources Water-Supply Bulletin 18, 309 p., 5 plates.
Geographic: KITSAP CO./MASON CO./PIERCE CO./PUGET LOWLAND/KITSAP PENINSULA
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/HYDROLOGY - GROUND WATER

Smith, Mackey, 1976, Relative slope stability of Gig Harbor Peninsula, Pierce County, Washington: Washington Division of Geology and Earth Resources Geologic Map GM-18, 1 sheet, scale 1:31,680.
Geographic: PIERCE CO./GIG HARBOR PENINSULA
Subject: LANDSLIDES AND SLOPE STABILITY

Smith, Mackey, 1976, Surficial geology of northeast Tacoma, Pierce County, Washington: Washington Division of Geology and Earth Resources Open-File Report 76-9, 1 sheet, scale 1:24,000.
Geographic: TACOMA, WASH./PIERCE CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Smith, Mackey, 1977, Geologic map of the city of Tacoma, Pierce County, Washington: Washington Division of Geology and Earth Resources Open-File Report 77-9, 1 sheet, scale 1:24,000.
Geographic: PIERCE CO./TACOMA, WASH.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Waldron, H. H., 1961, Geology of the Poverty Bay quadrangle, Washington: U.S. Geological Survey Open-File Report 61-167, 2 sheets. (Published as USGS map GQ- 158.)
Geographic: KING CO./PIERCE CO./POVERTY BAY QUADRANGLE
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Waldron, Howard Hamilton, 1961, Geology of the Poverty Bay quadrangle, Washington: U.S. Geological Survey Geologic Quadrangle Map GQ-158, 1 sheet, scale 1:24,000.
Geographic: POVERTY BAY QUADRANGLE/KING CO./PIERCE CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Walsh, Timothy J., 1987, Geologic map of the south half of the Tacoma quadrangle, Washington: Washington Division of Geology and Earth Resources Open-File Report 87-3, 10

p., 1 plate, scale 1:100,000.
Geographic: TACOMA QUADRANGLE/THURSTON CO./PIERCE CO./KING CO./MASON CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Walsh, Timothy J.; Korosec, Michael A.; Phillips, William M.; Logan, Robert L.; Schasse, Henry W., 1987, Geologic map of Washington--Southwest quadrant: Washington Division of Geology and Earth Resources Geologic Map GM-34, 2 sheets, scale 1:250,000, with 28 p. text.
Geographic: SOUTHWESTERN WASHINGTON/GRAYS HARBOR CO./MASON CO./ THURSTON CO./PIERCE CO./KING CO./KITTITAS CO./PACIFIC CO./LEWIS CO./YAKIMA CO./KLICKITAT CO./SKAMANIA CO./CLARK CO./COWLITZ CO./WAHKIAKUM CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Washington Department of Ecology, 1979, Coastal zone atlas of Washington; volume 7, Pierce County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.
Geographic: PIERCE CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY/LITTORAL DRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT

Zulauf, A. S., 1979, Soil survey of Pierce County area, Washington: U.S. Soil Conservation Service, 131 p.
Geographic: PIERCE CO.
Subject: SOILS

San Juan County

Cowan, D. S.; Whetten, J. T.; Brown, E. H., 1977, Geology of the southern San Juan Islands. IN Brown, E. H.; Ellis, R. C., editors, Geological excursions in the Pacific Northwest; Geological Society of America annual meeting, 1977: Western Washington University, p. 309-338.
Geographic: SAN JUAN ISLANDS/FIDALGO FORMATION/SAN JUAN CO.
Subject: AREAL GEOLOGY/GUIDEBOOKS

Danner, Wilbert Roosevelt, 1962, Guidebook for geological field trips, San Juan Island, Washington State: University of British Columbia Department of Geology Report 1, 25 p., 2 plates.
Geographic: SAN JUAN ISLAND/SAN JUAN CO.
Subject: GUIDEBOOKS/AREAL GEOLOGY

Dietrich, W. E., 1975, Surface water resources of San Juan County. IN Russell, R. H., editor, Geology and water resources of the San Juan Islands, San Juan County, Washington: Washington Department of Ecology Water-Supply Bulletin 46, p. 59-125.
Geographic: SAN JUAN CO./SAN JUAN ISLANDS
Subject: HYDROLOGY

Eddy, P. A., 1975, Quaternary geology and ground-water resources of San Juan County, Washington. IN Russell, R. H., editor, Geology and water resources of the San Juan Islands, San Juan County, Washington: Washington Department of Ecology Water-Supply Bulletin 46, p. 21-39.
Geographic: SAN JUAN CO./SAN JUAN ISLANDS
Subject: AREAL GEOLOGY/QUATERNARY/HYDROLOGY - GROUND WATER

Frederick, J. E., 1979, Map showing natural land slopes, Port Townsend quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-A, 1 sheet, scale 1:100,000.
Geographic: PORT TOWNSEND QUADRANGLE/CLALLAM CO./JEFFERSON CO./ISLAND CO./SNOHOMISH CO./SKAGIT CO./SAN JUAN CO.
Subject: TOPOGRAPHY/GEOMORPHOLOGY

Miller, R. D.; Safioles, S. A.; Pessl, Fred, Jr., 1985, Map showing relative slope stability in the Port Townsend 30' x 60' quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-C, 1 sheet, scale 1:100,000.
Geographic: PUGET LOWLAND/SKAGIT CO./SNOHOMISH CO./ISLAND CO./SAN JUAN CO./CLALLAM CO./JEFFERSON CO./PORT TOWNSEND QUADRANGLE
Subject: LANDSLIDES AND SLOPE STABILITY

Pessl, Fred, Jr.; Dethier, D. P.; Booth, D. B.; Minard, J. P., 1989, Surficial geologic map of

the Port Townsend 30- by 60-minute quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-F, 1 sheet, scale 1:100,000, with 13 p. text.
Geographic: PORT TOWNSEND QUADRANGLE/SKAGIT CO./SNOHOMISH CO./ISLAND CO./SAN JUAN CO./CLALLAM CO./JEFFERSON CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Russell, R. H., editor, 1975, Geology and water resources of the San Juan Islands, San Juan County, Washington: Washington Department of Ecology Water-Supply Bulletin 46, 171 p., 3 plates.
Geographic: SAN JUAN CO./SAN JUAN ISLANDS
Subject: AREAL GEOLOGY/HYDROLOGY/MAPS - GEOLOGIC

Schlots, Fred E.; Ness, Arnold O.; Rasmussen, Jack J.; McMurphy, Carl J.; Main, Lauren L.; Richards, Ralph J.; Starr, Warren A.; Krashevski, Stephen H., 1962, Soil survey of San Juan County, Washington: U.S. Soil Conservation Service Series 1957, no. 15, 73 p., 36 plates.
Geographic: SAN JUAN CO.
Subject: SOILS

Washington Department of Ecology, 1978, Coastal zone atlas of Washington; volume 3, San Juan County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.
Geographic: SAN JUAN CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY/LITTORAL DRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT

Skagit County

Artim, E. R.; Wunder, J. M., 1976, Preliminary geologic map of the La Conner quadrangle in Skagit County, Washington: Washington Division of Geology and Earth Resources Open-File Report 76-1, 1 sheet, scale 1:24,000.
Geographic: SKAGIT CO./LA CONNER QUADRANGLE
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Dethier, David P.; Whetten, John T., 1981, Preliminary geologic map of the Mount Vernon 7 1/2 minute quadrangle, Skagit County, Washington: U.S. Geological Survey Open-File Report 81-105, 9 p., 1 sheet, scale 1:24,000.
Geographic: SKAGIT CO./MOUNT VERNON QUADRANGLE
Subject: MAPS - GEOLOGIC/AREAL GEOLOGY

Frederick, J. E., 1979, Map showing natural land slopes, Port Townsend quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-A, 1 sheet, scale 1:100,000.
Geographic: PORT TOWNSEND QUADRANGLE/CLALLAM CO./JEFFERSON CO./ISLAND CO./SNOHOMISH CO./SKAGIT CO./SAN JUAN CO.
Subject: TOPOGRAPHY/GEOMORPHOLOGY

Heller, P. L., 1979, Map showing landslides and relative slope stability of Quaternary deposits of the lower Skagit and Baker Valleys, north Cascades, Washington: U.S. Geological Survey Open-File Report 79-963,
30 p., 2 plates, scale 1:62,500.
Geographic: SKAGIT VALLEY/BAKER VALLEY/SKAGIT CO.
Subject: LANDSLIDES AND SLOPE STABILITY/QUATERNARY

Heller, P. L., 1979, Map showing surficial geology of parts of the lower Skagit and Baker Valleys, north Cascades, Washington: U.S. Geological Survey Open-File Report 79-964, 16 p., 1 plate, scale 1:62,500.
Geographic: SKAGIT CO./SKAGIT VALLEY/BAKER VALLEY
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/QUATERNARY

Heller, Paul L., 1981, Small landslide types and controls in glacial deposits-- Lower Skagit River drainage, northern Cascade Range, Washington: Environmental Geology, v. 3, no. 4, p. 221-228.
Geographic: SKAGIT CO./SKAGIT RIVER BASIN/BAKER RIVER BASIN
Subject: LANDSLIDES AND SLOPE STABILITY/GLACIAL GEOLOGY

Heller, Paul L.; Dethier, David P., 1981, Surficial and environmental geology of the lower Baker valley, Skagit County, Washington: Northwest Science, v. 55, no. 2, p. 145-155.
Geographic: SKAGIT CO./BAKER VALLEY/BAKER RIVER BASIN
Subject: AREAL GEOLOGY/LANDSLIDES AND SLOPE STABILITY

Keuler, Ralph F., 1988, Map showing coastal erosion, sediment supply, and longshore transport in the Port Townsend 30- by 60-minute quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-E, 1 sheet, scale 1:100,000.

Geographic: PORT TOWNSEND QUADRANGLE/SKAGIT CO./ISLAND CO./JEFFERSON CO./CLALLAM CO.

Subject: SHORELINES/LITTORAL DRIFT/EROSION

Miller, R. D.; Safioles, S. A.; Pessl, Fred, Jr., 1985, Map showing relative slope stability in the Port Townsend 30' x 60' quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-C, 1 sheet, scale 1:100,000.

Geographic: PUGET LOWLAND/SKAGIT CO./SNOHOMISH CO./ISLAND CO./SAN JUAN CO./CLALLAM CO./JEFFERSON CO./PORT TOWNSEND QUADRANGLE

Subject: LANDSLIDES AND SLOPE STABILITY

Ness, A. O.; Buchanan, D. E.; Richins, C. G., 1960, Soil survey of Skagit County, Washington: U.S. Soil Conservation Service Series 1951, no. 6, 91 p., 40 plates.

Geographic: SKAGIT CO.

Subject: SOILS

Pessl, Fred, Jr.; Dethier, D. P.; Booth, D. B.; Minard, J. P., 1989, Surficial geologic map of the Port Townsend 30- by 60-minute quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-F, 1 sheet, scale 1:100,000, with 13 p. text.

Geographic: PORT TOWNSEND QUADRANGLE/SKAGIT CO./SNOHOMISH CO./ISLAND CO./SAN JUAN CO./CLALLAM CO./JEFFERSON CO.

Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Washington Department of Ecology, 1978, Coastal zone atlas of Washington, volume 2, Skagit County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.

Geographic: SKAGIT CO.

Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY/LITTORAL DRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT

Wunder, J. M., 1976, Preliminary geologic map of the Utsalady quadrangle, Skagit and Snohomish Counties, Washington: Washington Division of Geology and Earth Resources Open-File Report 76-10, 1 sheet, scale 1:24,000.

Geographic: SKAGIT CO./SNOHOMISH CO./UTSALADY QUADRANGLE

Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Snohomish County

Capps, Gerald; Simmons, J. D.; Videgar, F. D., 1973, Preliminary report on the geology of southern Snohomish County, Washington: Washington Division of Geology and Earth Resources Open-File Report 73-1, 11 p.,
2 plates.
Geographic: SNOHOMISH CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Debose, Alfonso; Klungland, Michael W., 1983, Soil survey of Snohomish County area, Washington: U.S. Government Printing Office, 197 p., 59 plates.
Geographic: SNOHOMISH CO.
Subject: SOILS

Frederick, J. E., 1979, Map showing natural land slopes, Port Townsend quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-A, 1 sheet, scale 1:100,000.
Geographic: PORT TOWNSEND QUADRANGLE/CLALLAM CO./JEFFERSON CO./ISLAND CO./ SNOHOMISH CO./SKAGIT CO./SAN JUAN CO.
Subject: TOPOGRAPHY/GEOMORPHOLOGY

Miller, R. D.; Safioles, S. A.; Pessl, Fred, Jr., 1985, Map showing relative slope stability in the Port Townsend 30' x 60' quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-C, 1 sheet, scale 1:100,000.
Geographic: PUGET LOWLAND/SKAGIT CO./SNOHOMISH CO./ISLAND CO./ SAN JUAN CO./CLALLAM CO./JEFFERSON CO./PORT TOWNSEND QUADRANGLE
Subject: LANDSLIDES AND SLOPE STABILITY

Minard, J. P., 1980, Distribution and description of the geologic units in the Stanwood quadrangle, Washington: U.S. Geological Survey Open-File Report 80-464, 6 p., 1 plate, scale 1:24,000.
Geographic: STANWOOD QUADRANGLE/SNOHOMISH CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Minard, J. P., 1980, Distribution and description of the geologic units in the Tulalip quadrangle, Washington: U.S. Geological Survey Open-File Report 80-465, 6 p., 1 sheet, scale 1:24,000.
Geographic: TULALIP QUADRANGLE/SNOHOMISH CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Minard, James P., 1981, Distribution and description of the geologic units in the Everett quadrangle, Washington: U.S. Geological Survey Open-File Report 81- 248, 5 p., 1 sheet, scale 1:24,000.

Geographic: SNOHOMISH CO./EVERETT QUADRANGLE
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Minard, James P., 1982, Distribution and description of geologic units in the Mukilteo quadrangle, Washington: U.S. Geological Survey Miscellaneous Field Studies Map MF-1438, 1 sheet, scale 1:24,000.
Geographic: ISLAND CO./MUKILTEO QUADRANGLE/SNOHOMISH CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Minard, James P., 1985, Geologic map of the Stanwood quadrangle, Snohomish County, Washington: U.S. Geological Survey Miscellaneous Field Studies Map MF- 1741, 1 sheet, scale 1:24,000.
Geographic: SNOHOMISH CO./STANWOOD QUADRANGLE
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Minard, James P., 1985, Geologic map of the Tulalip quadrangle, Snohomish County, Washington: U.S. Geological Survey Miscellaneous Field Studies Map MF- 1744, 1 sheet, scale 1:24,000.
Geographic: SNOHOMISH CO./ISLAND CO./TULALIP QUADRANGLE
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Newcomb, Reuben C., 1952, Ground-water resources of Snohomish County, Washington: U.S. Geological Survey Water-Supply Paper 1135, 133 p.
Geographic: SNOHOMISH CO.
Subject: HYDROLOGY - GROUND WATER/AREAL GEOLOGY/MAPS - GEOLOGIC

Pessl, Fred, Jr.; Dethier, D. P.; Booth, D. B.; Minard, J. P., 1989, Surficial geologic map of the Port Townsend 30- by 60-minute quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-F, 1 sheet, scale 1:100,000, with 13 p. text.
Geographic: PORT TOWNSEND QUADRANGLE/SKAGIT CO./SNOHOMISH CO./ISLAND CO./ SAN JUAN CO./CLALLAM CO./JEFFERSON CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Smith, Mackey, 1975, Preliminary surficial geologic map of the Edmonds East and Edmonds West quadrangles, Snohomish and King Counties, Washington: Washington Division of Geology and Earth Resources Geologic Map GM-14, 1 sheet, scale 1:24,000.
Geographic: SNOHOMISH CO./KING CO./EDMONDS EAST QUADRANGLE/EDMONDS WEST QUADRANGLE
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Smith, Mackey, 1976, Preliminary surficial geologic map of the Mukilteo and Everett quadrangles, Snohomish County, Washington: Washington Division of Geology and Earth Resources Geologic Map GM-20, 1 sheet, scale 1:24,000.
Geographic: SNOHOMISH CO./MUKILTEO QUADRANGLE/EVERETT QUADRANGLE
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Washington Department of Ecology, 1979, Coastal zone atlas of Washington; volume 5, Snohomish County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.
Geographic: SNOHOMISH CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY/LITTORAL DRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT

Weber, Paul R., 1977, Landslides in Puget Sound glacial sediments. In Canadian Geotechnical Society, 30th Canadian geotechnical conference (proceedings); "Geotechnical aspects of glacial deposits": Canadian Geotechnical Society, p. VIII-26 - VIII-46.
Geographic: KING CO./SNOHOMISH CO.
Subject: QUATERARY/GLACIAL GEOLOGY/LANDSLIDES AND SLOPE STABILITY/ SEDIMENTS

Wunder, J. M., 1976, Preliminary geologic map of the Utsalady quadrangle, Skagit and Snohomish Counties, Washington: Washington Division of Geology and Earth Resources Open-File Report 76-10, 1 sheet, scale 1:24,000.
Geographic: SKAGIT CO./SNOHOMISH CO./UTSALADY QUADRANGLE
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Yount, J. C.; Minard, J. P.; Dembroff, G. R., 1993, Geologic map of surficial deposits in the Seattle 30' x 60' quadrangle, Washington: U.S. Geological Survey Open-File Report 93-233, 2 sheets, scale 1:100,000.
Geographic:KING CO./KITSAP CO./SNOHOMISH CO./SEATTLE QUADRANGLE/ISLAND CO./JEFFERSON CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/STRATIGRAPHY

Thurston County

Artim, E. R., 1976, Slope stability map of Thurston County, Washington: Washington Division of Geology and Earth Resources Geologic Map GM-15, 1 sheet, scale 1:125,000.
Geographic: THURSTON CO.
Subject: LANDSLIDES AND SLOPE STABILITY

Noble, J. B.; Wallace, E. F., 1966, Geology and ground-water resources of Thurston County, Washington; Volume 2: Washington Division of Water Resources Water-Supply Bulletin 10, v. 2, 141 p., 5 plates.
Geographic: THURSTON CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/HYDROLOGY - GROUND WATER

Pringle, Russell F., 1990, Soil survey of Thurston County, Washington: U.S. Soil Conservation Service,
283 p., 49 plates.
Geographic: THURSTON CO.
Subject: SOIL SURVEYS

Wallace, Eugene Francis; Molenaar, Dee, 1961, Geology and ground-water resources of Thurston County, Washington, volume 1: Washington Division of Water Resources Water Supply Bulletin 10, v. 1, 254 p.,
2 plates.
Geographic: THURSTON CO.
Subject: AREAL GEOLOGY/HYDROLOGY - GROUND WATER/DRILLING LOGS

Walsh, Timothy J., 1987, Geologic map of the south half of the Tacoma quadrangle, Washington: Washington Division of Geology and Earth Resources Open-File Report 87-3, 10 p., 1 plate, scale 1:100,000.
Geographic: TACOMA QUADRANGLE/THURSTON CO./PIERCE CO./KING CO./MASON CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Walsh, Timothy J.; Korosec, Michael A.; Phillips, William M.; Logan, Robert L.; Schasse, Henry W., 1987, Geologic map of Washington--Southwest quadrant: Washington Division of Geology and Earth Resources Geologic Map GM-34, 2 sheets, scale 1:250,000, with 28 p. text.
Geographic: SOUTHWESTERN WASHINGTON/GRAYS HARBOR CO./MASONCO./THURSTON CO./PIERCE CO./KING CO./KITTITAS CO./PACIFIC CO./LEWIS CO./YAKIMA CO./KLICKITAT CO./SKAMANIA CO./CLARK CO./COWLITZ CO./WAHKIAKUM CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Washington Department of Ecology, 1980, Coastal zone atlas of Washington; volume 8, Thurston County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.
Geographic: THURSTON CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY/LITTORAL DRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT

Whatcom County

Cline, D. R., 1974, A ground-water investigation on the Lummi Indian Reservation, Washington: U.S. Geological Survey Open-File Report 74-1016, 66 p.
Geographic: WHATCOM CO./LUMMI INDIAN RESERVATION
Subject: HYDROLOGY - GROUND WATER

Easterbrook, D. J., 1973, Environmental geology of western Whatcom County, Washington: Western Washington State College Department of Geology, 78 p.
Geographic: WHATCOM CO.
Subject: AREAL GEOLOGY/GEOLOGIC HAZARDS/ENGINEERING GEOLOGY

Easterbrook, D. J., 1976, Geologic map of western Whatcom County, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-854-B, 1 sheet, scale 1:62,500.
Geographic: WHATCOM CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC

Easterbrook, D. J., 1976, Map showing engineering characteristics of geologic materials, western Whatcom County, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-854-D, 1 sheet, scale 1:62,500.
Geographic: WHATCOM CO.
Subject: ENGINEERING GEOLOGY/SOIL MECHANICS

Easterbrook, D. J., 1976, Map showing slope stability in western Whatcom County, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I- 854-C, 1 sheet, scale 1:62,500.
Geographic: WHATCOM CO.
Subject: LANDSLIDES AND SLOPE STABILITY

Goldin, Alan, 1992, Soil survey of Whatcom County area, Washington: U.S. Soil Conservation Service, 481 p., 54 plates.
Geographic: WHATCOM CO.
Subject: SOIL SURVEYS

Newcomb, R. C.; Sceva, J. E.; Stromme, Olaf, 1949, Ground-water resources of western Whatcom County, Washington: U.S. Geological Survey Open-File Report 50- 7, 134 p., 2 plates.
Geographic: WHATCOM CO.
Subject: HYDROLOGY/AREAL GEOLOGY/MAPS - GEOLOGIC

Peck, Craig A., and Associates, 1976, Draft environmental impact statement for Seacliff, residential development: Whatcom County Planning Department, 1 v.
Geographic: WHATCOM CO./POINT ROBERTS, WASH.
Subject: ENVIRONMENTAL IMPACT

STATEMENTS/STRATIGRAPHY/LANDSLIDES AND SLOPE STABILITY/SHORELINES/SOIL MECHANICS

Phillabaum, S. D.; Schwartz, M. L., 1974, A geomorphic shoreline inventory with management considerations for Whatcom County, Washington: Shore and Beach, v. 42, no. 1, p. 21-24.
Geographic: WHATCOM CO.
Subject: SHORELINES/COASTAL ZONE MANAGEMENT

Poulson, E. N.; Flannery, R. D., 1953, Soil survey of Whatcom County, Washington: U.S. Soil Conservation Service Soil Survey Series 1941, no. 7, 153 p., 6 plates.
Geographic: WHATCOM CO.
Subject: SOILS

Terich, T. A., 1977, Coastal processes of the Whatcom County mainland: Washington Division of Geology and Earth Resources Open-File Report 77-1, 36 p.
Geographic: WHATCOM CO.
Subject: SHORELINES/COASTAL ZONE MANAGEMENT

Washington Department of Ecology, 1977, Coastal zone atlas of Washington; volume 1, Whatcom County: Washington Department of Ecology, 1 v., maps, scale 1:24,000.
Geographic: WHATCOM CO.
Subject: AREAL GEOLOGY/MAPS - GEOLOGIC/SAND/GRAVEL/LANDSLIDES AND SLOPE STABILITY/LITTORAL DRIFT/SHORELINES/LAND USE PLANNING/COASTAL ZONE MANAGEMENT