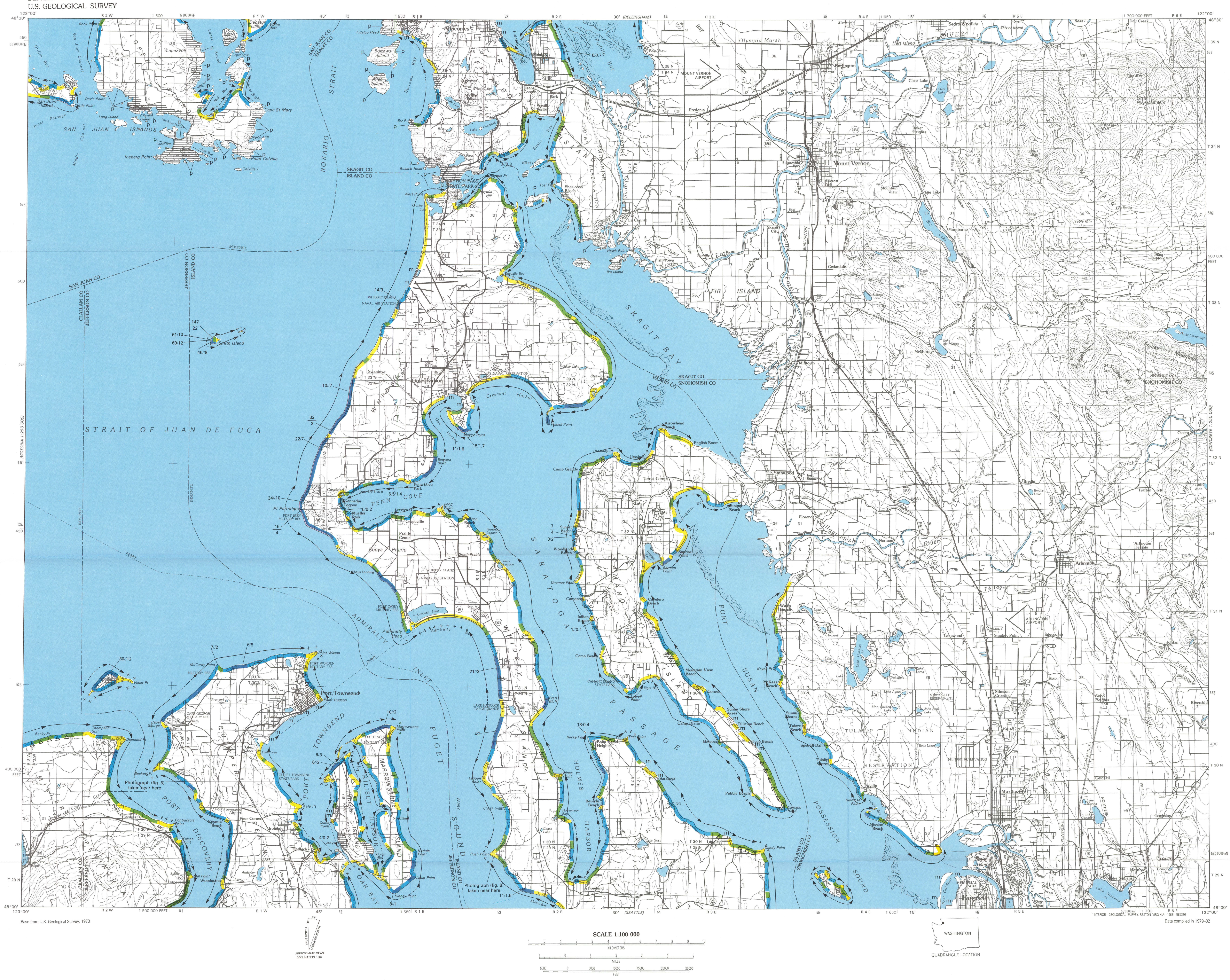

SCALE 1:100 000

CONTOUR INTERVAL 50 METERS
NATIONAL GEODETIC VERTICAL DATUM OF 1929

QUADRANGLE LOCATION

EXPLANATION

- ZONE OF SUBSTANTIAL WAVE EROSION AND EROSION-INDUCED LANDSLIDES
- ZONE OF RELATIVELY SLOW WAVE EROSION—Relatively frequent but small landslides common
- APPROXIMATELY NEUTRAL COASTAL SEGMENT—Little or no net erosion or deposition
- DEPOSITIONAL BEACH

△ △ △ ZONE OF SUBSTANTIAL SEDIMENT LOSS FROM BLUFFS—Caused by large sporadic landslides (little or no direct wave erosion)

DIRECTION OF LONG-TERM NET-SEDIMENT TRANSPORT
- Unimpeded
- Sediment volume and (or) rate of movement impeded by natural or manmade conditions

NULL (NODAL) ZONE—Zone where sediment being transported along shore diverges into two adjacent littoral cells on a net long-term basis

CONVERGENT ZONE—Zone where sediment from two drift cells meets

EROSION RATES—First or upper number shows rate of bluff retreat, in centimeters per year. Second or lower number shows volume of bluff material lost, in cubic meters per meter of shoreline per year

10/5 Average erosion rate based on an accurately known retreat distance and at least 20 years of record

10//5 Minimum erosion rate; true rate is likely to be greater. Rate is averaged over at least 20 years of record

$\frac{10}{5}$ Average erosion rate based on less than 20 years of record. Rate shown may be representative of a long-term average but has an equal chance of being less or greater than the long-term average

ROCKY COAST—No beaches or appreciable longshore sediment transport unless specifically indicated with map symbols

p POCKET BEACH ON ROCKY COAST

m MODIFIED SHORELINE—Consisting of dredge spoils, artificial fill, jetties, docks, seawalls, or dikes. No appreciable longshore transport unless otherwise indicated on map

DELTAIC AND ESTUARINE TIDAL FLATS—Composed of mud and muddy sand. The seaward margin shown on the map is the minus 1-meter depth contour (generalized), which is also the edge of the exposed tidal flat during very low tides. Net transport is shown only where beaches border the muddy flats along the landward edge; more commonly, fringing marshes rather than beaches are present

INTRODUCTION

The inland marine waters of northwest Washington (fig. 1), including the Strait of Juan de Fuca, Puget Sound, and the waters of the San Juan Islands, contain approximately 3,000 km of coast (Washington Department of Ecology, 1977), a length approximately equal to the rest of the Pacific coast of Washington, Oregon, and California. Within these inland waters, an extreme range of coastal conditions exists, varying from high rocky cliffs subject to 15-plus-ft storm waves and swell from the north Pacific Ocean to sheltered muddy embayments and salt marshes, where even gale-force winds produce no more than tiny ripples on the water surface.

Despite the coast's length and diversity, very little study of physical coastal processes was done in the Puget Sound region prior to 1977. Since that time, the Washington Department of Ecology (1977) has published a coastal zone atlas, each volume showing certain conditions along the shoreline of individual counties. Keuler (1978; 1979) assessed coastal conditions and processes in Skagit County, including a study of coastal erosion rates, which had not been done previously in the Puget Sound region.

This report describes selected physical processes and conditions along approximately 600 km of the inland marine coast in the Port Townsend quadrangle (fig. 1). Topics include: patterns of coastal erosion and deposition, the first subregional assessment of erosion rates and their variability, coastal sediment sources, longshore-transport patterns, and some potential geologic hazards. The coast of the Port Townsend quadrangle is well suited for a subregional study because it contains virtually every type of coastal setting found in the Puget Sound region. These include: high- and low-energy rocky shores (both with cliffs and without), high- and low-energy shores with bluffs composed of unconsolidated deposits, deltas and their associated muddy tidal flats, sandy tidal flats, embayments, salt marshes, and a wide variety of depositional beaches.

Accurate information on coastal processes, such as erosion rates and sediment-movement patterns, can be very difficult to obtain. Yet it is precisely this type of information that is needed to make informed decisions on the uses and limitations of coastal areas, whether the user is a homeowner, developer, or local government. This map is one in a series of studies done by the U.S. Geological Survey to present earth-science information and interpretations to assist land-use planning, resource development, and environmental protection in the Puget Sound region.

COASTAL SEDIMENT SOURCES AND TEXTURES

On most coasts, the important sources of active sediment supply usually are major rivers, local streams, and eroding coastal bluffs; in special situations beach sediment can be supplied from other sources such as material previously deposited on the nearshore sea bed that is being transported back onshore. Our studies of coastal sediment supply and movement attempt to assess the relative importance of each of these potential sources.

MAJOR RIVERS

On a worldwide basis, rivers are the most common source of sediment in coastal systems (Komar, 1976, p. 325). Detailed observations and comparisons of the sizes and volumes of coastal sediment made during this study indicate that the Puget Sound region is somewhat unusual because a very high percentage of all coastal sediment is supplied by bluff erosion. The beaches in this study area are coarse-grained mixtures of sand, pebbles, cobbles, and boulders. Moreover, the beaches typically are poorly supplied with sediment which is indicated by their thinness. Along many kilometers of coast, it is common to find the underlying wave-cut platform a meter, or less, below the beach surface. The coarse beach texture and thin sediment cover are in distinct contrast to the large volume of sandy sediment that is being delivered to, and deposited at, the mouths of the major rivers draining the Cascade and Olympic Mountain Ranges. Beaches that are directly adjacent to the river deltas have a high sand content (100 percent sand in some locations), reflecting the abundant available supply. One typical example of this sediment-texture contrast is found in northern Port Susan at the Stillaguamish delta. Livingston Bay, Juniper Beach, and Warm Beach, which adjoin the delta, all have sand beaches; however, the sandy river sediment disappears very rapidly away from the river mouth. Only 2 km away, at Kayak Point and Barnum Point, beach texture ranges from pebbly at the former to bouldery at the latter, indicating that the sediment source is not the adjacent river. This type of sediment distribution, also seen at other deltas in the central and northern Puget lowland, indicates that the basins associated with the deep fjordlike marine channels of glacial origin trap much of the sand from major rivers and effectively prevent its redistribution along the coast.

LOCAL STREAMS

A second potential source for beach sediment is the smaller local streams originating in the uplands directly adjacent to the coast. The geographic distribution and flow volume of these streams indicate that they are not large enough or numerous enough to contribute a significant percentage of the total sediment budget on most coastal segments in the Port Townsend quadrangle. Many coastal segments have no streams at all; for example, a 40-km stretch from Admiralty Bay to Deception Pass (northwestern Whidbey Island) has no streams extending to the saltwater shoreline. In other coastal segments where streams do reach tidewater, the discharge is so small (commonly less than 0.14 m³/s [5 ft³/s]; Cummans, 1977) that sediment quantities and sizes suitable for beach material are not being delivered to the coast.

BLUFFS

In the absence of sediment from both major rivers and smaller streams, the beaches of the Port Townsend quadrangle are primarily supplied from the only other easily available source—the relatively erodable bluffs composed of unconsolidated deposits of glacial and nonglacial origin. Because many of the bluff-forming materials are glacial deposits containing boulders, cobbles, pebbles, and sand, it is not surprising that most beaches are composed of varying proportions of these same sediment sizes. With the exception of fine-grained sand, silt, and clay (which are winnowed out by waves), the beach textures along most coastal segments mainly reflect the coarse fractions of the glacial deposits being eroded there. On coastal segments where the bluffs are composed of predominantly fine-grained nonglacial deposits (typically with a high silt or clay content), many thousands of cubic meters of material are eroded from bluffs each year but this produces only a small contribution to beach sediment. Silt and clay are too fine to remain in the relatively high-energy nearshore and intertidal zones, but rather are transported offshore by currents and deposited in quieter water.

SEDIMENT DELIVERY FROM BLUFFS

A number of different processes are involved in delivering material from bluffs to the coastal sediment system. Field study indicates that a direct wave attack, which produces bluff-face failure by undercutting at the bluff toe (fig. 2), is the most effective sediment-producing mechanism along most segments of shoreline bluffs. Evidence of other processes affecting these steep, unvegetated bluffs, such as rain wash and freeze-thaw activity, is found occasionally. However, these processes appear to make only a minor contribution along most coastal segments where wave attack not only produces direct erosion during storms, but leaves bluffs oversteepened. Oversteepening produces soil falls, slumps, and raveling during the weeks, months, and years between major storms.

Within some coastal segments, landslide zones largely unrelated to recent marine erosion are the primary sources of beach sediment. The location of these zones commonly is dependent on heavy ground-water seepage emerging from bluffs composed of deposits with very different permeability (for example, glacial outwash sand overlying dense silt). Such conditions have been consistently found to produce landslides at inland settings in the Puget Sound region (Tubbs, 1974; Heller, 1981). These zones typically occur where the bluff face is well vegetated with trees and there is little or no wave erosion at the bluff toe. Being heavily vegetated, these slide-prone segments of shoreline present a deceptive appearance that belies their role as producers of coastal sediment. Individual slides or even entire zones may have a variety of different landforms associated with the landsliding. Two slide settings found in the Port Townsend quadrangle that are capable of delivering a large volume of sediment to the beach in a single slope failure are: (1) large amphitheaterlike bowls (fig. 3) that funnel landslide debris to the beach through narrow chutes, and (2) failures that begin as arcuate slump blocks at or near the bluff top and then break up into debris while moving downslope (fig. 4). Landslides from individual sites in these settings commonly involve 1,000 m³ of material per event, and slides of 3,000–4,000 m³ to 10,000 m³ are not unusual. One recent slide included more than 20,000 m³ (fig. 4), and revegetated slide scars of a comparable size are seen at several places in the Port Townsend quadrangle. Because the net sediment volume being transported along the shore is less than 3,000 m³/year within most shoreline segments, the volume of debris produced by such large but sporadic failures can be the principal sediment-supply source along some coastal segments. Large slides usually involve more than one geologic unit; typically both fine- and coarse-grained deposits contribute debris. Therefore, at each landslide, a varying percentage of the debris will be in a suitable size range for beach material (sand to cobbles). The well-vegetated landslide zones are noted on the map with a special symbol to indicate their deceptive but important role as sediment-producing zones.

COASTAL SEDIMENT TRANSPORT

THE TRANSPORT CELL

Sediment being transported along the coast does not form an endless conveyor-beltlike system. Rather, due to obstructions such as embayments, headlands, and sharp bends in the shoreline, the coastal sediment-transport system is naturally fragmented into separate compartments. These compartments operate independently, each having its own sources of sediment, transport pathway, net transport direction, and areas of sediment deposition, although minor sediment leakage can occur between compartments. Such independent compartments or subsystems have variously been called littoral drift cells, longshore-transport cells, regional sediment compartments, and shore-drift sectors. In this report, the terms "drift cell" and "transport cell" will be used interchangeably.

Along parts of the world's coasts, littoral-transport cells can be 100 km long or more; along the 600 km of coast in the Port Townsend quadrangle there are many individual cells, few being more than 15 km in length and some being only about 1 km long. Because they are supplied mainly by bluff erosion, drift cells in the Puget Sound region typically have their beginnings along zones where erosion, and therefore sediment supply, is greatest. However, these same zones are subject to very active longshore sediment transport; so despite a continuing sediment supply from the adjoining bluffs, the beaches in these zones are largely stripped of easily transported particle sizes (sand and pebbles). The common result is a beach that consists of a broad, wave-cut platform (fig. 2) with only a thin cover of coarse sediment (cobbles and boulders). Farther downdrift, in the central portion of the drift cell, bluff erosion typically is slower because enough sediment is transported from the beginning of the cell so that the beach is capable of providing partial protection for the bluffs. At the cell terminus, sediment accumulates in the form of depositional beaches such as spits and barrier beaches, and (or) as broad sandy tidal flats. This simplified picture of drift-cell operation has literally hundreds of localized variations and exceptions, but the features described above are so common in the Port Townsend quadrangle that they nevertheless are useful for a basic understanding of longshore sediment movement in any local drift cell.

SEDIMENT TRANSPORT PROCESSES

The most common misconception of coastal processes is one that attributes sediment movement on local beaches to currents in general, and frequently to tidal currents. The technical arguments are beyond the scope of this report but it is worth noting that a high percentage of all beach sediment, especially coarse-grained sand, pebbles, and cobbles, which comprise the sediments of Puget Sound beaches, move (by rolling, sliding, and bouncing) as the direct result of waves breaking and running up onto the beach.

Sediment is rarely, if ever, transported directly and rapidly from its origin (for example, an eroding bluff) to a depositional beach some distance away. Instead, a specific particle may spend years following a complex and random transport history that includes: (1) longshore movement which frequently reverses direction as wave direction changes from day to day, (2) many transits up and down the beach as the beach scours and rebuilds under changing wave conditions, and (3) temporary storage in berms or nearshore bars whose formation and destruction are due to short-term cycles (commonly winter-summer) of scour and rebuilding (fig. 5). As a result, many thousands of cubic meters of sediment may be moved about constantly, but only a small percentage of that total will be moved to its ultimate deposition site at the cell terminus during any single time span (day, week, year, etc.). That small percentage of the total sediment that is permanently transported to the cell terminus constitutes the *net-transport volume*; that is, it is the net result of all the moving sediment in the cell which is gradually edging its way toward the terminus on a long-term basis. Similarly, the direction in which the sediment moves along the shore from its source to cell terminus is called *the net long-term transport direction*, frequently shortened to *net-transport direction or net-drift direction*.

METHODS USED TO DETERMINE TRANSPORT PATTERNS

A variety of methods can be used to assess both short-term and net long-term sediment-transport directions along a coast. For coastal management and planning, the net long-term transport pattern is of primary interest because the frequently reversing sediment movement over short periods of days, months, or seasons individually have almost no effect downdrift. Rather, it is the reduction or blockage of sediment supply on a long-term basis (years) that leads to problems and unforeseen consequences such as increased erosion down-drift. Methods commonly employed for assessments of net transport direction include: (1) computations based on wave energy from various directions by using records of winds that produce the waves, (2) use of artificial or naturally occurring tracer sediment, (3) analysis of large-scale coastal landforms, such as growth direction of spits, and (4) study of small-scale landforms and longshore beach-sediment variations. Each of these methods has strengths and weaknesses, and a method that is useful for one type of coast may yield poor results elsewhere. In this study, all four techniques were used; the latter two (large- and small-scale landforms and sediment variations) produce the most reliable results on the intricately embayed coast of the Puget Sound region (Keuler, 1980) and, therefore, were used most extensively.

From analysis of mean annual wind directions, velocities, and fetch (the exposure of open water over which the wind blows to generate waves), only a generalized, though still useful, understanding of sediment transport directions can be gained. In the Puget Sound region, this method is partly limited by the lack of wind-recording stations in some areas and by the difficulty of accurately analyzing the effects of restricted and intersecting fetches. In some areas, the results are unreliable because of local topography, bays, and channels. These features funnel wind differently from the larger-scale windflow and provide localized wind shelter, so that wind records of a station even a few kilometers away cannot be used with confidence.

The use of natural tracers (unique rocks and minerals) is usually not possible in this region because of the mixing of rock types that has occurred in the widespread glacial deposits. Placing and tracking artificial tracer sediment would be too time consuming for a regional study, although in a few localities rubble discarded along the shore (such as bricks and asphalt) provides useful, though originally unintended, sources of artificial tracers.

Large-scale landforms and their erosion or growth patterns (such as spits) provide a reliable indicator of the net-transport direction; however, because spits are areas of sediment deposition, they occur mainly at or near a drift cell's terminus where transported sediment is most abundant. Therefore, these landforms yield little or no information about the location of the cell's beginning nor about the sediment source(s) active within the cell. Small-scale features, such as offset stream mouths, sediment accumulation at groins, and asymmetric cuspate spits also reflect the net-transport direction, and are used to map the longshore extent of drift cells associated with the large-scale features.

Many variations in beach sediment have been found along coasts; however, not all longshore sediment variations are necessarily linked to net-transport direction. To use such sediment variations as an indicator of net-transport direction, sedimentologic data must be gathered from many different "test" drift cells where net transport direction can be independently determined. If such testing can establish a solid link between transport direction and some sediment variation, then the procedure can be reversed and the sediment variation used as a drift-direction indicator elsewhere in the region where similar conditions exist. In the Puget Sound region, such a link has been established for several types of longshore sediment variations (Keuler, 1979, 1980). One example, found in many local drift cells, is a regular decrease in the size of pebbles and cobbles from a cell's beginning to its terminus. This variation and others were used in the Port Townsend quadrangle to help define drift-cell limits and net-transport directions.

SEDIMENT TRANSPORT VOLUMES

Accurate knowledge of the annual average-net-sediment volume moving through each drift cell would be ideal for assessing potential problems from proposed shoreline projects (for example, frequent dredging due to deposition, or downdrift beach starvation and erosion). Unfortunately, an accurate estimate of net-sediment-transport volume for each drift cell is very difficult to obtain. As an alternative, an estimate can be made of the range of typical net-transport rates for drift cells in the north-central Puget Sound region. Typical net-transport rates for low-energy (sheltered) cells and moderate-energy (partly sheltered) cells are of particular interest because these two wave-energy settings are the most common along the majority of the coast in the study area.

Several different kinds of coastal sites, both manmade and natural, can be used as indicators of the net-transport rate. Such sites include: (a) piers and jetties where transport is partly or completely blocked, causing sediment to accumulate over a period of years, (b) boat channels (for example, marina entrances) that trap transported sediment and must be dredged periodically, (c) coastal segments where known or estimated long-term erosion rates allow a reasonable estimate of the total sediment supply going into a drift cell, and (d) the rate at which large landslide deposits (of an approximately known volume) on a beach are transported away. Sediment-transport calculations from such sites in the Port Townsend quadrangle and nearby areas indicate that most moderate- and low-energy drift cells have a net-transport rate of less than 3,000 m³/yr (4,000 yd³/yr). Many low-energy cells are well under 3,000 m³/yr, some with a transport rate of less than 1,000 m³/yr. Transport rates for moderate- and low-energy cells can overlap because wave energy is only one of several major factors that help determine net-transport volume.

A further indication that transport rates in typical drift cells are likely to be no higher than 3,000 m³/yr can be found by comparison with a cell that is both well supplied with sediment and has moderate-to-high wave energy available for transport. Such conditions exist along western Whidbey Island facing the Strait of Juan de Fuca and Admiralty Inlet. Unpublished dredging records available at the U.S. Army Corps of Engineers office (Seattle) show that the ferry channel at Admiralty Head has been trapping sediment at a consistent rate of about 5,000–5,400 m³/yr (6,500–7,000 yd³/yr) since the late 1940's. The channel is deep enough that it traps virtually all the sediment reaching it, and is located adjacent to the drift-cell terminus so that the trapped material should represent the total net-transport volume moved through the cell. Therefore, if the net-transport rate is only about 5,000 m³/yr in this cell where sediment supply and wave energy are favorable for a large net-transport volume, then a substantially lesser amount (less than 3,000 m³/yr) is probably typical of many other drift cells where conditions are less conducive to high rates of longshore transport.

The sediment-transport rates given above are much lower (5–10 times lower) than the amounts given in the Coastal Zone Atlas of Washington (Washington Department of Ecology, 1977). It gives net-transport rates along typical shoreline segments in low-to-moderate wave-energy zones as being 10,000–25,000 yd³/yr (7,600–19,000 m³/yr). There are several reasons for this large discrepancy, but the primary reason is that, in the Atlas, computed amounts of sediment transport for each shore segment are based on the amount of incoming wave energy from various directions. This computational method uses as two of its basic assumptions, (a) the sediment consists of medium-fine-grained sand, and (b) an abundant sediment supply is available on the beaches to be transported. Neither of these assumptions is met for the coarse-grained, sediment-deficient beaches that exist along most of the coast in the northern Puget Sound region. Thus far, no reliable method has been found to convert the volumes derived from such hypothetical calculations into the actual net-transport volume.

COASTAL EROSION

Although a high percentage of the bluff-rimmed coast in the Port Townsend quadrangle is eroding, the amount of erosion varies considerably from one shoreline segment to another in terms of bluff-retreat rates, volume of bluff sediment lost, and longshore extent of eroding zones. Additionally, at any specific site, the timing of erosion can vary greatly from an easily measureable loss one year to little or no erosion over several years.

RATES OF BLUFF RETREAT AND VOLUME LOSS

Rates of erosion are symbolized on the map by a set of two numbers,

such as 15/3, 10//2, or $\frac{9}{4}$

In each of these three formats the first or upper number indicates the average linear-retreat rate, in centimeters per year. This is the distance per year that either the upper bluff edge or the lower toe has been receding landward. The second number shows the average yearly volume of bluff material lost for each one-meter-long unit of shoreline at that site; thus the second number expresses the erosion in cubic meters per meter of shoreline per year. The linear-retreat rate (first number) is best suited for assessing potential erosion hazards to existing structures near the bluff and for planning setback distances for new facilities. However, because bluff heights differ greatly from one site to the next, the linear-retreat rate does not allow a complete comparison of erosion between sites. Nor does the linear rate provide any direct information about the volume of sediment supplied to the beach system. For information of this type, the volume loss (second number) is more useful. An example of this difference between linear erosion and volume of erosion is at Indian Island, on the southwest part of the map. On the north tip of the island, a high bluff has been receding at 9 cm/yr; the volume lost is about 3 m³/m/yr. In contrast, at a nearby site, where Indian Island faces Kilisut Harbor, erosion also is 9 cm/yr, but because the bluff is low, the same retreat rate produces a volume loss of only 0.3 m³/m/yr (one-tenth the volume of the first site). Knowledge of the bluff-volume loss can also be used for making estimates of linear erosion at some sites where no erosion data exists.

When linear bluff-retreat rates are compared from different parts of the map area, the fastest rates (greater than 30 cm/yr) occur mainly in the Strait of Juan de Fuca where the wave energy is highest. Beyond that, no regional pattern is apparent; many areas, regardless of wave energy, have linear retreat rates in the range of 6 to 15 cm/yr. However, when erosion from different areas is compared on the basis of bluff-volume loss, an erosion pattern closely linked to wave energy becomes obvious. The Strait of Juan de Fuca (moderate-to-high wave energy) consistently shows bluff-volume loss rates greater than 4 m³/m/yr, especially in the range of 6 to 12 m³/m/yr. In partly sheltered areas (moderate wave energy) such as Admiralty Inlet, Port Townsend Bay, and Saratoga Passage erosion rates of 1 to 3 m³/m/yr are commonly found. The sheltered, low wave-energy areas such as Kilisut Harbor, Holmes Harbor, and the inner parts of Penn Cove usually lose less than 1 m³/m/yr.

LONGSHORE DISTRIBUTION OF ERODING ZONES

In addition to the erosion variability in zones of different wave energy, there commonly is a marked difference in erosion rates along the length of drift cells. Bluffs at a drift-cell beginning nearly always have the highest rates of volume loss and are the principal zone of sediment supply for the cell. As a result, these bluffs typically are steep to very steep, largely to completely unvegetated, and may even have wave-undercut notches at the bluff toe (fig. 2). On the map, these zones are indicated by a dark-blue color band. In the central part of the cell, the beaches provide some protection for bluffs. Here it is common to find a steep, wave-cut scarp at base of the bluff, but a less steep upper bluff partially or completely covered with vegetation (fig. 6), thus indicating a slower rate of wave erosion. The light-blue color indicates the longshore extent of such zones. In the downdrift part of the cell, nearest the terminal depositional beach, the beach is capable of providing nearly complete protection for bluffs. Here bluffs are totally vegetated, commonly with mature trees. If a wave-cut scarp at the bluff toe is present at all, it is very low (less than a meter) and largely inactive; wave erosion occurs very infrequently. These shoreline segments are approximately in equilibrium, neither significantly eroding nor accreting. They function mainly as neutral conduits for the longshore movement of sediment and are indicated with a green color band on the map.

The foregoing description of a slower rate of erosion in the downdrift direction can be visualized on the map by observing that many drift cells show a fairly consistent, though not exclusive, pattern of the blue colors at and near the cell beginning. The middle of most cells consists of mostly light blue with some dark blue and also some green; near the cell terminus the green color is prevalent. Because most local drift cells are short, it is rare to find enough sites within a cell to confirm this erosion pattern with actual measured long-term rates. However, in one of the longest cells in the map area (21 km), from Point Partridge to Deception Pass (northwestern Whidbey Island), a series of measured sites clearly show a downdrift pattern of decreasing erosion that ranges from approximately 10 m³/m/yr at the cell beginning to 3 m³/m/yr near the cell terminus.

OTHER FACTORS CONTROLLING EROSION

Although much of the distribution of eroding zones and erosion rates can be explained by a combination of the regional wave-energy pattern and the pattern of decreasing erosion through the length of a drift cell, there remain many localized variations and exceptions. Clearly the effects of other factors are superimposed on the two large-scale patterns discussed above. Localized sheltering is one of these important additional factors. For example, at headlands that extend from an otherwise fairly straight shoreline segment, erosion commonly is enhanced on the side facing the highest wave energy. In contrast, the opposite side usually has less erosion because of the extra shelter that would not exist if the shoreline were straight. Similar effects are seen in the vicinity of small depositional beaches that are located within the middle of some drift cells.

A second factor that alters erosion patterns is manmade modifications of the coast. Examples are numerous, but the most common are groins, jetties, docks, and marina channels that stop or impede the longshore movement of the sediment. Immediately downdrift from these obstructions, the beaches commonly are deprived of their normal sediment supply and do not protect the shore as well as they would with a complete supply, thus increased erosion results. Manmade modifications of one coastal site can also produce changes along the entire length of a drift cell rather than just immediately downdrift. For example, if a shoreline project completely blocks longshore sediment movement, then beaches and bluffs along the portion of the cell downdrift from the obstruction may erode to replace sediment previously supplied from updrift areas. Similarly, if a major sediment source at the beginning of a cell becomes artifically protected from erosion, then the entire cell may become sediment deficient. Parts of a cell that are presently neutral (shown in green) are particularly susceptible to change because they are in a delicate balance between erosion and deposition under present conditions. The balance is maintained only because the sediment that is constantly being transported from the neutral zone toward the cell terminus is replaced with an equal amount of new sediment from updrift.

Another factor that can be locally important in determining erosion rates is resistance to erosion of different geologic materials. Keuler (1979) showed that rock erodes 10 to 100 times more slowly than unconsolidated deposits in the northern Puget lowland. Even within unconsolidated deposits some lithologic units can be slightly more resistant than others (dense glacial till, for example). Such differences are commonly revealed by small offsets or jogs in fairly straight segments of eroding bluffs where the bluff composition changes from one material to another. Despite such offsets, large and consistent differences in susceptibility to erosion among unconsolidated materials is not generally supported by observations made during this study. These observations were: (a) where offsets do occur, they rarely exceed a few meters, (b) not all offsets are associated with changes in material type, and (c) there are literally hundreds of sites along eroding bluffs where transitions from one material type to another occur but no offset whatever exists. Therefore, variations in erosion resistance among unconsolidated deposits are small enough that any differences that exist are easily masked by other factors. In Europe, McGreal (1979) reported similar results; he found that the type of glacial deposit had only a small effect on rates of erosion, indicating that internal strength (resistance to erosion) was not a primary control of the overall rate.

Table 1.—*Comparison of short-term erosion rates to the long-term average rate at one well-documented site at Maylor Point in Saratoga Passage*

Period	Erosion (meters)	Years	Average short-term erosion rates (cm/yr) (rounded to the nearest centimeter)
Short-term erosion rates			
1944–54	0.48	10	5
1954–58	1.83	4	46
1958–60	0	2	0
1960–81	3.27	21	16
Long-term erosion rate			
Period	Erosion (meters)	Years	Average long-term erosion rate (cm/yr) (rounded to nearest centimeter)
1944–81	5.58	37	15

EROSION RATES AND THEIR VARIABILITY

Even a casual observer of the coast is aware that unusually high waves and very high tides occur rather infrequently. Because bluff erosion is closely linked to the simultaneous occurrence of both factors, erosion also is sporadic through time. Trying to express this sporadic process by using a long-term average rate can be both useful and at the same time misleading. An average rate has value for long-term planning such as for the location of roads, buildings, and other facilities. However, this average can be misleading in that it obscures the year-to-year variability of the actual erosion process and may lead people to falsely assume that they need to plan on losing only an average amount of bluff each year. In fact, the opposite usually is true. It is very common to find the greatest loss of bluff material occurring during (or soon after) individual severe storms or unusually stormy winters. Then, little or no erosion may occur until the next severe storm event(s), regardless of whether the next storm occurs 1, 5, or 8 years thereafter.

At one well-documented site, erosion rates were compared for both a long-term (37 years) average rate and the rates over shorter time periods (table 1). It is instructive to note in this erosion record that all three periods of 10 years or less show rates very different from the long-term average. During one period, bluff retreat was 5 cm/yr (three times lower than the average), in another period it was 46 cm/yr (three times higher than the average), and during one period no erosion was evident. In contrast, during the longer period of 21 years from 1960–81, the rate was 16 cm/yr, quite close to the long-term average of 15 cm/yr. When all sites where both short- and long-term records exist are compared and analyzed, a pattern emerges that is very similar to the one described above. Time periods of 10 years or less commonly show great variability, with rates ranging from as little as 20 percent of the long-term average to as much as 200 to 300 percent higher than average. The variability is not as great for rates based on more than 10 years but less than 15 years of record, but still may be plus-or-minus 40 to 50 percent different from the long-term average. Because of this short-term variability, erosion rates displayed on the map are separated into short- and long-term categories with rates based on more than 20 years of record being considered as fairly reliable, and probably near the long-term average. Similar conclusions were reached by the Great Lakes Basin Commission in analyzing erosion variability through time; they recommend that time intervals greater than 15 years (at a minimum) should be used to insure that the calculated erosion rate will be similar to the long-term mean for any particular site (Erosion/Hazard Management Subcommittee, 1978, p. 54).

At sites where only a short-term record is available (10 to 15 years or less), the measured rate might, coincidentally, be similar to the long-term average, but it also has an equal chance of being either much higher or much lower. Conversely, at sites on the map where a long-term average is shown, it should be understood that during short periods of a few years the actual rate likely will fluctuate markedly above and below the average rate.

DATA COLLECTION AND MAP PRESENTATION

All the erosion rates gathered for this study are based on actual field measurements of objects whose position relative to both the original and present bluff face could be determined. Some natural objects such as very large prominent boulders were used, but most objects were manmade and included roads, buildings, fence lines, and survey monuments. Where such reference objects are located on a beach, erosion measurements are based on the distance to the toe of the eroding bluff. Where an object is on top of a bluff, the measured distance is to the upper edge of the bluff scarp.

ACCURACY AND LIMITATIONS

The total amount of bluff retreat can be determined quite accurately (plus-or-minus a few centimeters) at sites where the original distance is known from a previous field measurement. Such accuracy is possible when the distance from the bluff edge to a survey monument has been previously recorded by surveyors. These sites are particularly valuable if the time span involved is 20 to 40 years or more because the erosion rate derived from the new measurement is likely to be representative of a long-term average rather than a short-term fluctuation. On the map, erosion rates from sites where both accuracy and time factors are favorable are displayed with a single diagonal bar (for example, 20/6).

At sites where the time span is more than 20 years, but the bluff-retreat distance is less accurately known, two diagonal bars are used (for example, 20//6). At such sites, the erosion rate shown is a minimum, and the true long-term average is likely to be greater. A variety of circumstances can require that a minimum loss or conservative estimate be used. If a survey monument or structure is completely lost to erosion at some time between two visits to a site, then only the loss of the original distance between the monument and the bluff can be positively known. The amount of additional erosion landward of where the monument stood usually cannot be reconstructed without additional information.

The third display format, one number above the other (for example, $\frac{20}{6}$, indicates that the time period over which the measurement is based is too short to be certain that the rate is representative of the long-term average, regardless of how accurately the eroded distance is known.

As shown in the map explanation, the shoreline color bands on the map indicate the erosional and depositional condition of different coastal segments. There are, however, two limitations in this display format. First, the smallest length of coast that can be adequately delineated as a separate element on the map (2 mm) is equivalent to 200 m on the ground. Therefore, within a zone having a uniform color band, there can be individual short segments (less than 200 m) that are different from the pattern shown. Because of this scale limitation, the map should not be used as a substitute for a field check when a specific site is under investigation. The second limitation is that the map, of necessity, must show one color band ending and another color beginning at a specific point along the coast. Yet in nature there commonly is not that sharp a boundary between two zones; rather, such transitions tend to be gradual. The longshore extent of the color bands therefore reflects the author's best judgment of where conditions have changed enough that one type of coastal setting has become predominant over an adjacent type.

INDIRECT ESITMATES OF BLUFF RETREAT RATES

Ideally, knowledge of long-term erosion rates for every coastal segment would be very useful for assessing potential erosion-related problems. Practically, this is hardly possible because of limitations imposed by time, money, and lack of sites with objects on which to base accurate measurements.

Despite these limitations, erosion data shown on the map can be used to indirectly estimate the range of probable linear-retreat rates for many localities that lack a measurement site. Indirect estimates can be made by taking advantage of a tendency for the volume of erosion at measured sites within a given area to be similar. For example, at most measured sites in Admiralty Inlet where there is substantial erosion, bluff-volume losses are 2 to 3 m³/m/yr. Therefore, it would be reasonable to expect that a site within this area with similar exposure to waves and displayed with the same color band (dark blue) as the measured sites is also losing material at a similar rate. By determining the bluff height at the site in question, the graph in figure 7 can then be used to find the range of long-term linear-retreat rates that are probable for the site. A hypothetical example using a volume loss of 2 to 3 m³/m/yr and a bluff height of 10 m is shown (fig. 7). No such indirect estimates are shown on the map; only measured rates are shown.

COASTAL HAZARDS

The coastal zone, with its waves, currents, bluffs, and nearly continual change, comprises areas with obvious hazards to man's activities and also areas where hazards exist but are less obvious. In the Port Townsend quadrangle, obvious hazards exist along eroding zones and landslide-prone bluffs. In terms of the length of coastline involved, such hazards are the predominant types found in the study area; however, hazards are not confined only to such zones. Depositional beaches and other low-lying areas, even though they constitute a small percentage of the coast, tend to be more densely populated. Therefore, the special, less obvious hazards existing there affect at least as many people as the hazards along steep bluffs.

Table 2 lists the most common coastal settings in the Port Townsend quadrangle, their typical hazards, causative factors, and possible mitigating measures. As the table shows, the principal hazards along bluffs all relate to loss of bluff-edge material by either direct wave erosion or by landsliding. On depositional beaches and other low-lying areas, the hazards are much more diverse in origin and in their effects. They include flooding, wave damage, temporary erosion during storms, subsidence, and soil liquefaction (loss of bearing strength during earthquakes). Within this range of possible hazards, coastal flooding (and its associated effects) is by far the most common. Widespread inundation of depositional beaches in the central-northern Puget Sound region occurred at least three times between 1975 and 1983. The most notable was December 15, 1977, when very low barometric pressure produced an unusually high tide, 1.2 to 1.5 m (4 to 5 ft) higher than mean high-tide level and about 0.6 m (2 ft) higher than had been predicted for that day. Fortunately, strong winds and high waves did not accompany that high water level or damage could have been extraordinary; instead, damage was largely confined to nonviolent inundation by saltwater.

Figure 8 shows damage to beach-front homes from waves and wave-driven debris (logs and sediment) during a 1979 storm that coincided with a tide that, while high, was not extraordinarily high. Much more severe damage, including homes that were almost completely destroyed by waves and logs, occurred in a nearby area only 4 years earlier. The relatively frequent occurrence of such damage is due to a combination of natural and man-related factors. In the Puget Sound region, the highest predicted tides each year are concentrated almost entirely during the winter months (Nov. to Feb.), when storms bringing low barometric pressure and high winds are also common. Therefore, the damage-producing combination of natural factors (tidal and meteorological) is present every winter, although their precise coincidence at a specific time may not occur each year. For example, high winds may occur during a day with a predicted very high tide, but the winds may arrive a few hours before or after the maximum tide, causing no widespread damage.

The damage from coastal flooding and waves could be greatly reduced and, in many instances, completely eliminated if building and land-use practices took into account the natural processes of the coastal environment. Thus far, making allowances for natural processes has been relatively infrequent in the Puget Sound region. Among the most effective mitigating strategies is the location of buildings well landward of the zone where logs and sediment were deposited by previous storms. This zone, which becomes part of the active beach during storms, typically has its highest concentration of storm-deposited logs and sediment just landward of the normal beach; from there, the concentration of such material decreases landward over a span of several tens of meters. Recognition and avoidance of this zone was not employed at the site of beach-front homes damaged during a 1979 storm (fig. 8). A second technique that can be very effective in avoiding damage from waves, logs, sediment, and flooding is the elevation of structures on foundations of concrete or wood piles, instead of using a ground-level foundation as is commonly used at inland locations. Damage of the type seen in figure 8 could become rare, instead of common, if natural processes of the coastal environment are understood and planned for in using coastal areas.

Table 2.—*Principal coastal settings and associated natural hazards in the Port Townsend quadrangle*

Coastal setting	Typical hazard(s)	Natural factors contributing to hazard	Manmade factors contributing to hazard	Possible Mitigating measures[1]
Unconsolidated bluffs regularly subjected to wave erosion	Bluff retreat endangering homes and bluff-top facilities Erosion induced landslides	Erosion more likely and rapid in zones of high wave energy Erosion more likely and rapid near drift-cell beginnings Majority of bluffs within the drift cell composed of fine-grained materials (silt and clay) from which erosion produces little useable beach sediment to help protect bluffs	Shoreline construction which might impede or completely block longshore sediment movement Extensive network of shore-defense structures within a drift cell which prevent renewal of beach sediment supply by halting erosion	Setbacks from bluff edge Construction techniques that allow building to be easily removed or relocated Shore-defense structures to slow erosion
Unconsolidated bluffs vegetated and subjected to little or no wave erosion	Mass movements (slumps, slides, debris-flows)	Bluff contains impermeable deposits (silt-clay) beneath or within more permeable deposits (sand-gravel) allowing buildup of pore pressure in the sediment Surface-water gullies Perched ground water and (or) spring issuing from bluff face	Addition of excess water from septic systems, lawn watering, surface runoff diversion Vegetation removal Cutting into bluff toe or excavating bluff face Loading unstable bluff edge with buildings	Setbacks from bluff edge Pump or drain excess ground water
Depositional beaches	Saltwater flooding Houses battered by waves, wave-driven logs, and sediment Shore-defense structures and beach-front amenities undermined by wave scouring and temporary removal of sediment during storms Land subsidence due to sediment compaction or flowage	Unusually high tides Unusually high-water levels due to low barometric pressure Storm waves and high-water levels due to storm surge Various combinations of the above three factors Earthquakes	Building in the zone that becomes part of the active beach during storms or very high tides Improper design or location of shore-defense structures (enhances wave scouring and removal of beach sediment)	Locate buildings well landward of natural storm deposits (drift logs and sediment) Elevate buildings on piles Shore-defense structures help in certain conditions
Deltas and coastal marshes	Saltwater flooding River flooding Land subsidence due to sediment compaction or flowage Underwater landsliding from deltas	Saltwater flooding factors same as for depositional beaches Deltaic and marsh sediments low in bearing strength and susceptible to mechanical failure (sediments typically are uncompacted, water saturated, and rich in organic materials and (or) gas Earthquakes	Building on improperly compacted artificial fill or dredge spoils River dredging and channelizing oversteepen underwater slopes	Elevate structures Careful engineering of structures and foundations

[1]A mitigating measure that can be used at any hazardous site is the option of leaving it undeveloped. This choice might be exercised by an individual owner, commercial firm, or government agency because of perceived risks, cost, or land-use regulations.

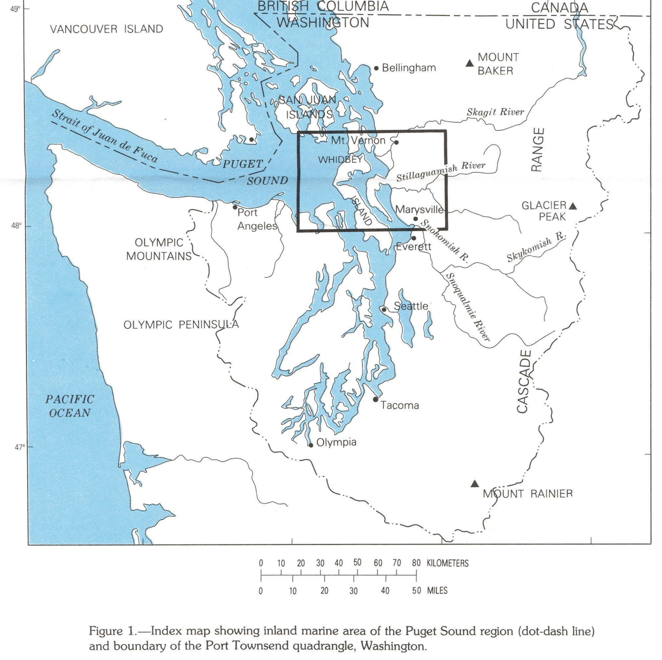

Figure 1.—Index map showing inland marine area of the Puget Sound region (dot-dash line) and boundary of the Port Townsend quadrangle, Washington.

Figure 2.—Bluff maintained in near-vertical condition by substantial wave erosion. Vertical profile, wave-cut notch at bluff toe, and partly exposed wave-cut platform with sparse cobble cover (foreground) are typical of drift-cell beginnings in Puget Sound region. Even more cobble-littered platform is exposed at site during lower tides. Photograph taken 2 mi west of Rocky Point, Miller Peninsula, just west of study area.

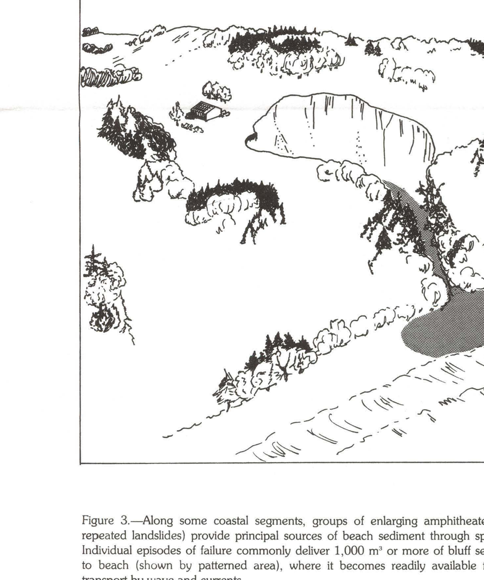

Figure 3.—Along some coastal segments, groups of enlarging amphitheaters (formed by repeated landslides) provide principal sources of beach sediment through sporadic failures. Individual episodes of failure commonly deliver 1,000 m³ or more of bluff sediment directly to beach (shown by patterned area), where it becomes readily available for sorting and transport by wave and currents.

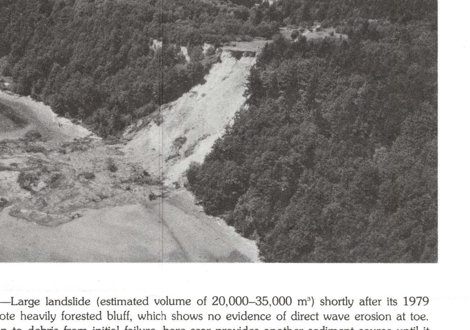

Figure 4.—Large landslide (estimated volume of 20,000–35,000 m³) shortly after its 1979 failure. Note heavily forested bluff, which shows no evidence of direct wave erosion at toe. In addition to debris from initial failure, bare scar provides another sediment source until it becomes revegetated. Large debris fan, as seen here, typically requires 3 to 6 years to be completely removed by waves in the Puget Sound region. Note houses in center left of photograph for scale. Photograph taken along southeast coast of Whidbey Island, just south of the study area.

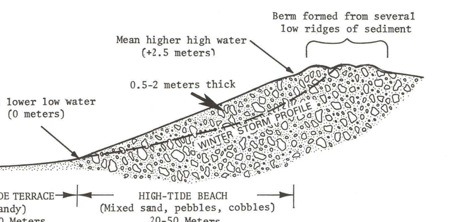

Figure 5.—Diagrammatic sketch of typical intertidal zone showing portion of the high-tide beach that is most subject to alternate scour and rebuilding under changing wave conditions. In the Port Townsend quadrangle, scour during winter storms may temporarily remove a layer of sediment as much as 2 m thick, although 1 m and less is more common. Additionally, the mean higher high-water line may be displaced landward 3 to 4 m and occasionally more than 10 m.

Figure 6.—Coastal features typical of central portion of drift cells: (a) steep wave-cut scarp (here about 4 m high) maintained at bluff toe by slow erosion; (b) less steep, vegetated upper bluff (intersects wave-cut scarp in top-center of photograph); and (c) beach sediment that consists of mixed sand, pebbles, and cobbles. Compare features with those in figure 2.

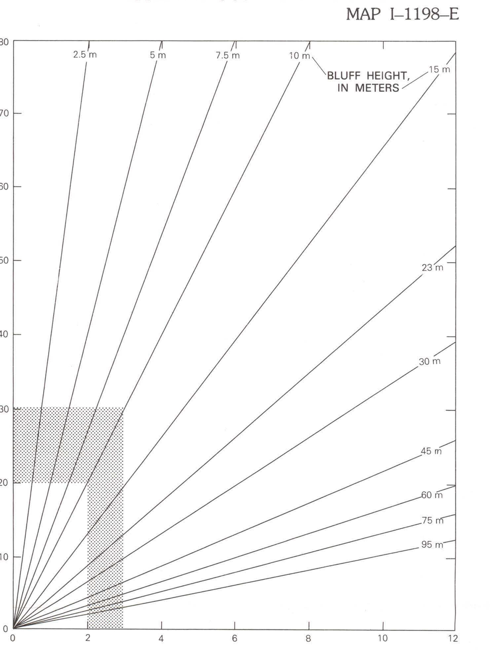

Figure 7.—Long-term averages of bluff volume eroded, bluff-face retreat, and bluff height. Hypothetical example (shaded area) shows probable linear-retreat rate of 20 to 30 cm/yr for site with 10-m-high bluff, located in area where measured sites lose bluff material at rate of 2 to 3 m³/m/yr. (See text for more detailed explanation.)

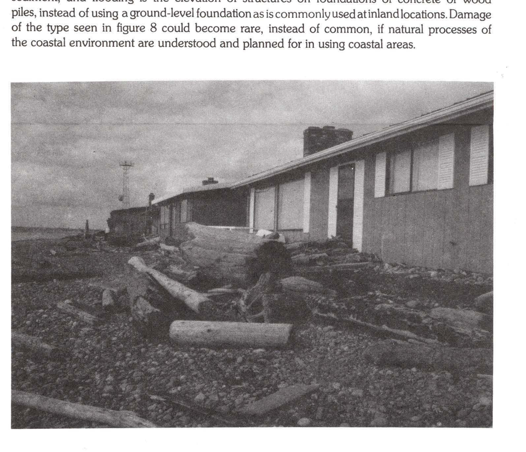

Figure 8.—Beach-front homes damaged by waves and wave-driven logs during 1979 storm that coincided with high tide. Not obvious from photograph are other items that were destroyed, such as porches, patios, barbecues, small boats, and launching structures. At this site, zone commonly affected by storm-deposited materials extends at least another 15 m landward of houses. Therefore, houses are actually built on part of beach, although part that is not active on daily or even annual basis.

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MAP SHOWING COASTAL EROSION, SEDIMENT SUPPLY, AND LONGSHORE TRANSPORT IN THE PORT TOWNSEND 30- BY 60-MINUTE QUADRANGLE, PUGET SOUND REGION, WASHINGTON

By

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1988

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