Marine Shoreline Sediment Survey and Assessment

Thurston County, Washington

February 4, 2005

Prepared for

Thurston Regional Planning Council
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Executive Summary

Executive Summary

Introduction

In Puget Sound, forage fish are a significant part of the prey base for marine mammals, sea birds, and fish populations, including salmonid species. There are six main species of forage fish in Puget Sound: herring (*Clupea harengus pallasi*), northern anchovy (*Engraulis mordax*), Pacific sardine (*Sardinops sagax*), surf smelt (*Hypomesus pretiosus*), longfin smelt (*Spirinchus thaleichthys*), and Pacific sand lance (*Ammodytes hexapterus*) (Bargmann 1998). Within the context of the Pacific salmon recovery, all forage fish species play an important role. However, of these six forage fish species, only surf smelt and Pacific sand lance spawn on the beach area (upper intertidal zone, approximately between MTL and MHHW). Consequently, only spawning habitat for these two species has been analyzed and discussed in this report.

This study is an assessment of beach and sediment characteristics, sediment sources, and sediment transport factors influencing surf smelt and Pacific sand lance habitat along marine shorelines of Thurston County. The principal focus of the study was to evaluate how shoreline armoring, particularly vertical bulkheads, influences forage fish habitat by altering beach morphology, substrate characteristics, and the supply and transport of sediment. This document describes the study objectives, theoretical and empirical background information, study approach and methods, results, and conclusions. The document also lays out a basic framework for prioritizing habitat preservation and restoration along the Thurston County marine shoreline.

Background

In order to properly characterize the beach sediment characteristics, sediment transport, and sediment budgets influencing surf smelt and Pacific sand lance spawning habitat along the marine shoreline of Thurston County, it is important to describe what is known about these species' biology and habitat and to describe the general coastal geomorphology and physical processes that influence sediment transport and beach characteristics. The ecological functions associated with the spawning habitat for these species depend on complex interactions that occur within nearshore habitat areas. Therefore, physical and biological processes that shape and control nearshore habitats and species assemblages were also characterized.

The background information included a general description of 1) a typical nearshore ecosystem; 2) the biology and life history of surf smelt and Pacific sand lance; 3) their spawning habitat within the nearshore zone; and 4) the theoretical and empirical background information on the general geomorphology and physical processes influencing sediment transport and overall beach morphology.

Methods

An essential part of this study was the development of a sampling protocol for an assessment of sediment and beach characteristics along the marine shoreline of Thurston County (Herrera 2003). The sampling protocol was developed in coordination with the Thurston Regional Planning Council, and was reviewed by the Thurston County Nearshore Technical Committee.

This study consisted of two general approaches: 1) a GIS analysis of existing aerial photographs and digital elevation data to identify sediment sources and sinks, impacts of bulkheads on upper beach areas, and long-term erosion and aggradation trends on the Thurston County shoreline; and 2) field surveys of representative beach profiles to document and categorize the various geomorphic beach characteristics present, to identify the effect of bulkheads on sediment characteristics and erosion, and to aid in identification of sediment sources and sinks.

A preliminary field investigation was performed on June 16, 2003, to test potential sampling protocols and to select representative beach sample sites. The major field phase of the study was performed between August 25 and August 28, 2003. In addition, field verification of beach profile data and of the results of the GIS analysis was performed at selected beach sites in September 2003. Thurston County's marine shoreline was analyzed using 29 paired beach sampling sites consisting of unarmored and armored sites (a total of 58 beach sampling locations), with five or more pairs sampled in each of the five inlets to provide statistical power.

In addition to the 29 paired beach sampling sites, three beach sites were surveyed at stream delta or drift cell confluences to determine accretion characteristics at these discrete sites in order to assess the relative importance of fluvial inputs from small streams. Six mass wasting sites were surveyed in the field to verify the GIS and digital elevation model map analysis performed for this study.

All sampling locations were georeferenced using a Trimble® GeoExplorer3 handheld global positioning system (GPS) unit (resolution +/- 6 – 16 feet). At these sites, the accuracy of existing site information (e.g., drift cells, habitat, bluff geology) was verified, and the GIS-based predictions of mass wasting potential were evaluated. Potential preservation and restoration sites were then evaluated in the field.

GPS and depth sounder methods were used to compare present-day bathymetry to historical information.

Results

The following GIS layers were produced and delivered to the Thurston Regional Planning Council in ESRI shapefile format:

- Bathymetry.shp – Depths from four transects conducted in Thurston County corrected to MLLW and to NAVD88. Includes approximate 1930s depths from georeferenced U.S. Coast and Geodetic Survey maps.

- Bulkhead_areas.shp – Interpolated area of upper beach lost to bulkhead construction. Modern shoreline mapping data provided by Thurston County (GIS shapefile) were copied and modified to estimate natural or preconstruction shoreline, where bulkheads have been built on beaches. Shorelines in areas without bulkheads were used to estimate the bulkhead footprint area. This information was used to estimate the total area of habitat lost.

- Landslide_erode.shp – Areas with landslides and erosion were identified using aerial and oblique photos and lidar-derived shaded relief maps and were digitized over aerial photos and lidar shaded relief maps.

- Manmade_structures.shp – Structures that block sediment transport along drift cells were digitized using vertical and oblique aerial photographs (TGDC 2000; Ecology 2000, respectively).

- Shore_additions.shp – Areas where the wetted shoreline was artificially increased between 1944 and 2001.

- Shore_reductions.shp – Areas where the wetted shoreline was artificially reduced between 1944 and 2001. This shapefile also includes filled inlets.

- Transect.shp – Locations of 29 paired transects established on the Thurston County shoreline. Appendix D contains illustrations of the transects and Appendix E and the shapefile contain a summary of the data collected at each transect.

- Thurston_Shoreline_Geology.shp – Polygon shapefile of surficial geology along the Thurston County shoreline digitized from the Coastal Zone Atlas of Washington published by the Washington State Department of Ecology in 1980.

- Prioritization.shp – Reaches along the Thurston County shoreline that meet specific preservation or restoration criteria derived in this study. Reaches were designated high priority when the majority of the criteria were met.

- Preservation sites.shp – Specific sites with unique habitat-related characteristics that should be preserved or restored.

Table ES-1 provides a summary of the differences observed between unarmored and armored (typically bulkhead or rock revetment) for 29 transect pairs that were surveyed in this study.

Table ES-1. Summary of beach differences between unarmored and armored (bulkhead or rock revetment) for 29 transect pairs.

	Percentage of Transects with Driftwood Present Near Site	Presence of Shade Area on Upper Beach	Average Width of Beach between MTL and MHHW (feet)	Average Width of Beach Usable for Spawning Habitat (sand and gravel) (feet)	Average Height of Top of Beach Above MLLW (feet)	Average Percentage of Beach Surface Coarsening along Transect Between -2 and MHHW	Percentage of Transects With Exposed Beach Platform [a]
Armored beaches	3%	45%	37.5	33.2	14.0	26%	10%
Unarmored beaches	79%	90%	43.4	39.3	15.5	25%	17%
Statistically significant	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**No**	**No**

[a] Beaches where underlying bedrock is exposed.

Statistical analyses were performed to compare habitat and geomorphic attributes for paired unarmored and armored beaches. Specifically, a Wilcoxon rank sum test (Zar 1984) was used to evaluate whether there were significant ($\alpha = 0.05$) differences in the following attributes across paired linear transects for all major Thurston County inlets combined ($n = 29$) and individual inlets having sufficient data ($n > 4$):

- Width of beach between MTL and MHHW
- Width of habitat, or beach that is predominantly sand or gravel, between MTL and MHHW
- Beach slope between MTL and MHHW
- Percentage of the beach that exhibits beach surface coarsening between MTL and MHHW
- Top of beach height relative to MLLW.

Results from the statistical tests showed that both beach width and the width of habitat were significantly shorter between MTL and MHHW in front of bulkheads or other armoring structures when the data from all inlets were analyzed (see Table 4-2). Additionally, top of beach height was shown to be significantly lower in front of bulkheads or other armoring when data from all of the inlets were analyzed. Between MTL and MHHW, the percentage of beach surface coarsening (due to the presence of overlying sediments with a relatively large median grain size [D50, i.e., the size for which 50 percent of the material is finer]) and the slope of the beach were not shown to be significantly different between unarmored and armored beaches. For individual inlets, the top of beach height was shown to be significantly lower for armored beaches within Henderson Inlet.

Habitat and geomorphic attributes that were measured on a nominal scale (presence or absence) were also compared between paired unarmored and armored beaches using the McNemar's test (Zar 1984). The attributes tested included the presence/absence of beach surface coarsening, presence/absence of beach platform exposure, presence/absence of barnacles, and presence/ absence of shade (Table ES-2). These tests showed that there was a significantly ($\alpha = 0.05$) higher number of unarmored beaches with shade relative to armored beaches.

Table ES-2. Statistical analysis of habitat and geomorphic attributes for paired unarmored and armored based on a NcNemar's test.

Attribute	χ^2 Value	p-Value [a]
Presence/Absence of Beach Surface Coarsening	3.13	0.0771
Presence/Absence of Beach Platform Exposure	0.57	0.4497
Presence/Absence of Shade	6.75	**0.0094**
Presence/Absence of Barnacles on Wood Debris	0.50	0.4795

[a] Values in bold indicate there was significant difference between unarmored and armored beaches for the indicated attribute ($\alpha = 0.05$).
Source: Zar 1984.

Initial analyses showed no statistically significant difference in beach surface substrate type between the unarmored and the armored shorelines. However, there does appear to be a slight, statistically nonsignificant shift from sand to gravel and (to a smaller degree) to cobble at armored areas.

Discussion

The elevation of shoreline armoring most directly determines both its direct physical impacts on the beach and the availability of suitable forage fish spawning habitat. Weggel (1988) classified seawalls into six types based on their location within the water column (Table ES-3).

Table ES-3. Seawall classification according to Weggel (1988).

Seawall Type	Seawall Type Description
Type 1	Base of seawall is located landward of the level of maximum wave setup and runup during times of maximum tide and storm surge.
Type 2	Base of seawall is located above water level that occurs at time of maximum combined tide and storm surge, but below level of maximum combined wave setup and runup.
Type 3	Base of seawall is above the maximum predicted tides excluding meteorological effects, but below storm surge plus tide level.
Type 4	Base of seawall is located within normal tide range, and thus the base is under water during part of the normal tidal cycle.
Type 5	Base of seawall is located seaward of the mean lower low water shoreline; it is subject to breaking and broken waves.
Type 6	Base of seawall is located in water so deep that incident waves do not normally break before reaching it.

Almost all of the observed bulkheads in this study were between MTL and MHHW, meaning that they were of Type 4, with the base of the bulkhead under water during part of the normal tidal cycle. This means that the existing bulkheads directly limit the availability of spawning habitat. For future bulkheads, a requirement for the elevation to be above the maximum predicted tides excluding meteorological effects (Type 2), or above the level of maximum combined setup and runup (Type 3), would eliminate this direct effect. Waves would still runup to meet the bulkhead, but the toe would not generally be under water.

In the long term, the availability of spawning habitat will be determined by the available sediment supply. Future changes to the sediment supply are likely to be varied, depending on land use and on direct actions at the shoreline (construction or removal of armoring). From a qualitative perspective it appears that a decrease in sediment supply will likely continue to occur, unless reasonable planning-level precautions are taken.

Restoration of the Deschutes River as an estuary has the potential to make a significant contribution to the sediment supply along the western shore of Budd Inlet, although very careful analysis and design for the restoration would be needed, and any changes would likely require decades to be fully established. Other fluvial sediment sources are likely to remain essentially constant, in that no major dam construction or removal efforts are anticipated and current stormwater management requirements do not allow developments to introduce significant changes to river and stream hydrology.

The following sections describe the present state of the marine shoreline of Thurston County in terms of the current condition of the beaches and the sediment supply.

Totten Inlet

Totten Inlet is not severely erosional; the beaches in front of bulkheads are not significantly narrower than other beaches. The sediment supply is approximately evenly divided between the fluvial supply (primarily Skookum, Kennedy, and Schneider Creeks) and landslides (including bluff erosion). There is no strong evidence that sediment is being lost offshore into the inlet. A relatively small portion of the Totten Inlet shoreline is armored (19 percent).

The sediment deficit appears to be relatively small, on the order of 4,000 cubic yards per year of sand-size and coarser sediments, and could be offset by a program of beach nourishment.

Squaxin Passage

The north-facing beaches of Squaxin Passage receive the highest wave energy in Thurston County. The majority of this reach, (i.e., 71 percent) is armored, and the area continues to erode as evidenced by the high proportion of exposed footings on bulkheads in this area.

Encroachment of bulkheads onto the beach is a significant issue. Because of the high wave energy and relatively large wave runup, the unarmored beach reaches an elevation 5 feet or more

above MHHW. Therefore, bulkheads that have been constructed with their toes at MHHW immediately encroach some tens of feet onto the beach.

Another impact of the high wave energy in this area is the relatively high rate of alongshore transport. Thus, sediment added to beaches in this area rapidly moves north and away, past Steamboat Island and therefore limits beach nourishment opportunities implemented without structural elements such as groins or offshore reefs/berms to retain littoral sediment.

Eld Inlet

Eld Inlet is similar to Totten Inlet in that the sediment supply is approximately evenly divided between the fluvial supply (Perry and McLane Creeks) and landslides (including bluff erosion). There is more shoreline erosion in Eld Inlet compared to Totten Inlet, and the level of armoring is greater (36 percent in Eld Inlet compared to 19 percent in Totten Inlet).

It appears likely that there is some loss of sediment offshore into Eld Inlet. This is based upon the high level of shoreline erosion observed in Eld Inlet compared to the other identified sources and sinks. Shoreline erosion in Eld Inlet is likely to lead to more shoreline armoring, and therefore Eld Inlet should be targeted for improved bulkhead siting and more complex bulkhead structures that dissipate wave energy and trap sediment.

Budd Inlet

Budd Inlet is the only inlet in Thurston County that is fed by a large river, the Deschutes. More sediment is transported by the Deschutes River than by any other stream in Thurston County except for the Nisqually River; this sediment is now trapped in Capitol Lake.

Budd Inlet is the most heavily developed and most heavily armored of the four inlets. Forty five percent is armored, including 71 percent of the western side of the inlet. The amount of measured erosion is surprisingly small given the level of development. The transect studies showed average beach narrowing of 2 feet in front of armored shorelines. However, particularly on the western, more developed side of Budd Inlet, beaches are narrow and are cut off below MHHW and generally do not provide desirable spawning habitat for forage fish.

These observations are representative of a sediment-starved system backed by a relatively unerosive perimeter (west shoreline). Along the western part of Budd Inlet, it appears that there is little bluff or backshore erosion even in unarmored areas.

Dana Passage

Dana Passage is similar to Squaxin Passage, although it is less erosional.

Henderson Inlet

Uniquely, among the four inlets in Thurston County, Henderson Inlet traps some sediment from outside the inlet due to littoral drift. The drift direction directly northwest of the inlet along Dana Passage is to the south, into the inlet. Henderson Inlet also appears to be the most rapidly eroding of the four inlets and is similar to the much more exposed Dana Passage. For example, bulkhead footings were observed to be exposed at all of the bulkhead transects in Dana Passage. This suggests that significant amounts of sediment are being lost offshore. Unlike Budd Inlet and Totten Inlet, Henderson Inlet appears to be actively "filling-in".

Nisqually Reach

There is no one predominant drift direction along the Thurston County portion of the Nisqually Reach, suggesting that much of the beach sediment in this area is locally sourced from bluffs. Field observations suggest that this reach is more erosional than indicated by the statistical analysis of beach profile performed in this study. Hardpan and other qualitative evidence of erosion was observed in several transects, and 40 percent of the reach is armored.

Conclusions

Development along the marine shoreline of Thurston County has led to extensive shoreline armoring, dominated by vertical concrete bulkheads. Less than half of the county shoreline associated with gravel and sand beaches remains unarmored.

Quantitative evidence gathered in this investigation clearly demonstrates that armoring (bulkheads) has reduced, both directly and indirectly, the upper tidal zone beach habitat used by forage fish to spawn along the Thurston County marine shoreline. The greatest effect occurs in the upper-most portion of the shoreline between MHW and MHHW. Armoring can invoke physical changes to beaches that would otherwise not occur. Armoring affects sediment recruitment by decreasing or obstructing sediment input from actively eroding bluffs and landslides.

Key Findings

Following are several key findings of this study regarding the geomorphic characteristics of the marine shoreline in Thurston County.

1. Shorelines with armoring, particularly bulkheads, differ significantly from unarmored shorelines with regards to the following characteristics:

    - Reduced beach area and thereby reduced forage fish spawning habitat in the upper tidal zone

    - Reduced local sediment recruitment potential

- Lowered elevation profile of beaches
- Reduced area of sand and small gravel in relation to beach width
- Lack of wood debris either from adjacent riparian areas or offshore
- Reduced shade/cover along upper beach

2. No significant differences were found between unarmored and armored shorelines with regards to the following characteristics:

   - Beach slope
   - Substrate grain size, although a statistically non-significant coarsening was observed along armored shorelines, which warrants further investigation

3. The following trends were observed regarding the geomorphology of Thurston County shorelines:

   - Coastal bluff height tends to increase from south to north, as does the frequency of landsliding
   - Shoreline armoring has had the likely effect of stopping landslides and may reduce upland inputs of sediments over years or decades, but not over the long term
   - There is a general coarsening of beach sediments from south to north in Totten, Eld, and Henderson Inlets, which generally reflects an increasing potential wave energy from south to north

4. Development of a general sediment budget for each inlet within the marine shoreline of Thurston County's marine shoreline indicates the following:

   - Landslides and larger rivers both provide a potentially significant source of sediment.
   - Small, typically unnamed creeks do not and have not historically provided a significant source of sediment.
   - If the sediment transported by the Deschutes River could be delivered to the littoral system of Budd Inlet through restoring Capitol Lake to an estuary, the nearshore environment of the western shore of Budd Inlet could be significantly improved. Careful study would be needed to determine whether this is possible, given the present morphology and south-directed shore drift in the area.

- Most of the sediment sourced in Thurston County is eventually delivered out of the inlets to the north and into the deep channels to the north of Thurston County. A significant fraction of the sediment, particularly in Eld and Henderson Inlets, is being lost offshore within the inlet.

5. The loss of upper beach habitat is more pronounced as the percentage of shoreline armoring increases.

6. Preservation of unarmored shorelines will minimize further impacts to upper beach habitat.

7. Restoration action should focus on evaluating potential solutions for reducing upper beach loss along armored shorelines by increasing the elevation at which bulkheads are built and roughening the structures to dissipate wave energy and trap sediment.

Data Gaps

This study identified several data gaps that include:

1. Repeated topographic surveys of beach profiles over time are needed to obtain more accurate estimates regarding the rate of beach erosion and accretion, including both seasonal and long-term effects. The profiles established in this study could provide a baseline for future surveys. However, it would be necessary to obtain explicit permission from landowners to set up a fixed survey marker in unarmored areas where the back beach may not be fixed.

2. Additional data collection is necessary to quantify the effect of bulkheads on wave reflection and whether these structures contribute actively to erosion of the upper beach. The repeated topographic surveys recommended in (1) above are a significant portion of this. More intensive direct studies of sediment transport at unarmored and armored shorelines, and in areas with and without wood debris should also be performed.

3. Statistically unbiased forage fish surveys are needed to better correlate fish utilization with the physical beach characteristics observed in this study. (Existing fish sampling was clearly biased based on beach substrate type.)

4. Role of wood on coastal beaches needs to be investigated, particularly within the context of forage fish spawning habitat maintenance. This should include the role of wood in trapping sediment and in dissipating wave energy for water levels at or above MHHW.

5. Measurements of bedload transport on the beach for various wave conditions are needed to better estimate sediment mobility of representative beach profiles and substrates.

6. The significance of alternative shoreline armoring techniques needs to be investigated through the use of prototype armoring structures (i.e., "prototype bulkheads"), in order to explore the maximum rehabilitation potential of the Thurston County marine shoreline.

7. The role of littoral drift in shoreline erosion requires additional investigation in which more sample sites are examined than were possible in this study.

Recommendations

A general protocol for prioritizing sites for preservation and restoration of forage fish habitat was developed specifically with regards to beach sediment and upper beach habitat. The first factor influencing upper beach environments consisting of coarse sediment (grain sizes equal and larger to sand) is the sediment supply to sustain these conditions. Sediment supply is provided by either local sources of coarse sediment such as bluffs, streams and rivers, or littoral drift that conveys supply reaches to the site in question. Since littoral drift and beach erosion are both directly affected by wave energy, site exposure and fetch should also be factored into an assessment of preservation or restoration. Sites lacking a major source of coarse sediment and wave energy offer limited opportunity for providing upper beach forage fish habitat. Such areas include much of the low-relief shorelines found at the southern ends of Totten, Eld, and Henderson Inlets. Priority sites will tend to be located in those shoreline areas toward the northern end of Thurston County that are characterized by high bluffs. These are sources of coarse sediment (e.g., glacial outwash and inter-glacial fluvial deposits) that are susceptible to mass wasting and high rates of littoral drift due to their exposure and fetch.

Much of the marine shoreline of Thurston County is erosional due to regional sediment starvation. This sediment starvation is believed to be partly natural and partly a result of human impacts including modifications to the Deschutes River and sediment impoundment behind bulkheads. The restoration and preservation opportunities identified in this report include the following:

- Reconnection of the natural sediment supply to the littoral zone, through reconnection of landslides and bluff failures to the beaches. A discussion regarding the potential removal of the Capitol Lake dam is included in this report.

- Pilot projects to improve sediment trapping and decrease the rate of erosion and littoral drift through placement of woody debris, alone or in conjunction with beach nourishment.

- Localized restoration and preservation actions to improve the quality of specific habitat areas through actions such as the reintroduction and preservation of riparian vegetation.

- Planning actions to diminish the regional impact of future development and shoreline protection in the area.

The results of this study suggest that riparian forests play an important role in providing shade and the recruitment of woody debris. Therefore, attention should be given to the proper management, preservation, and restoration of marine riparian forest areas along the marine shorelines of Thurston County because they support habitats that are heavily impacted by the construction of bulkheads and other human activities. Active programs to reforest impacted shorelines will enhance intertidal beach habitats for forage fish species. Improved shade and overhanging vegetation can be established even along armored shorelines through riparian reforestation and limiting tree clearing.

The potential for successful preservation and restoration varies by inlet and as a result of the differing sediment supply, wave energy, and development practices within each inlet. The following general guidance for the most suitable approach to preservation and restoration in each inlet is given.

- Totten Inlet is relatively non-erosive and relatively lightly developed: as a result, the level of shoreline armoring is also low. The focus in Totten Inlet should be on preservation actions, particularly through planning actions that limit new armoring. Beach nourishment could also be effective in restoring upper beach habitat, both locally and as a regional (inlet-wide) action.

- Squaxin Passage is very highly developed and receives the highest wave energy in Thurston County. The shoreline is very erosive and heavily armored. The shoreline is also susceptible to deep-seated landslides. These landslides have historically provided significant sediment to the littoral system. However, the sediment does not remain in Thurston County, it rapidly moves north and is lost offshore, past Steamboat Island.

  The focus in Squaxin Passage should be on slowing sediment transport, possibly through the introduction of woody debris, and on the reconnection of landslide-generated material to the littoral zone. Howver, given the high level of development, this area may not be cost-effective for restoration.

- Eld Inlet is more erosional than Totten Inlet, and the level of development and armoring is higher. Restoration and preservation actions should consider a combination of beach nourishment and slowing sediment transport.

The area to the north of Frye Cove is a significant source of sediment through landsliding. However, this sediment is relatively fine. This means that the coarse fraction is important in supplying sediment to the littoral system as a whole, so that the connection of the landslides to the littoral system should be preserved.

- The west shore of Budd Inlet is the most heavily developed and heavily armored shoreline within Thurston County, with the exception of Squaxin Passage. It appears that the bluffs in Budd Inlet are relatively unerosive and subsequently contribute little sediment to the beach. Unarmored and armored sites exhibit poor upper beach habitat conditions. The scope for local restoration is limited here.

  A regional restoration action with considerable potential for the west shore of Budd Inlet would be to open up Capitol Lake in such a way as to make the sediment supply from the Deschutes River available to the littoral zone of Budd Inlet. If this could be achieved, the nearshore environment of the western shore of Budd Inlet could be significantly improved. Careful study would be needed to determine the level of improvement, given the present morphology and south-directed shore drift in the area.

- The eastern shore of Budd Inlet is less heavily armored than the western shore. In this area, it is critical to preserve the connection between erosive bluffs and the littoral zone: reconnection of the bluffs to the shore through bulkhead removal would also be extremely valuable here. The northern part of this shore is characterized by tall bluffs subject to toe erosion. This means that even relatively benign shore protection, if it is successful in reducing toe erosion, is likely to reduce the sediment supply to this inlet. This is an area where conservation easements may be particularly valuable in preserving the sediment supply.

- Dana Passage is similar to, although less erosional than, Squaxin Passage. Localized restorations in pocket beaches and at estuaries could be effective, and measures to slow sediment transport could be tested. Improvements to the sediment supply would be difficult because of the high rate of littoral transport. Sediments sourced here would rapidly be lost offshore without restoration measures to retain them.

- Henderson Inlet is lightly developed and lightly armored at present. However, it is the most erosive of the four inlets. This means that pressure for further armoring is likely to grow. This area, along with the eastern shore of Budd Inlet, should be a particular focus of soft protection measures.

- Finally, the fact that there is no one predominant drift direction along the Thurston County portion of the Nisqually Reach suggests that much of the

beach sediment in this area is locally sourced, despite the presence of the Nisqually River to the east. The tall bluffs towards the north part of this reach provide a source of sediment through bluff toe erosion. The reach is actively eroding and local restorations at pocket beaches and at estuaries could be effective. Limitations and criteria for new bulkhead construction are recommended to help sustain current conditions.

Pilot projects incorporating complex, stable driftwood revetments in areas where bulkheads are threatened should be constructed and evaluated. Beaches in front of bulkheads often erode, lack shade, have less area covered by sediment on which forage fish spawn, and experience increased periods of tidal inundation. Such pilot projects should attempt to reverse these trends by creating complex structures that emulate natural wood debris accumulations at the top of the beach and trap sediment. Driftwood at the top of the beach may also slow littoral drift and erosion by reducing wave energy and wave reflection energy and by creating pockets where larger sediment will accumulate.

Monitoring

Monitoring beach changes along the Thurston County marine shorelines is a critical need to understand what is happening to shoreline habitat and the effects of existing erosion control measures. This is particularly important in the preservation, restoration, and control of sites identified in this report. Beach profiles obtained in this study represent a baseline from which future studies should build upon to further investigate and monitor beach sediment changes along the Thurston County marine shorelines. Additional beach profile sites (permanent georeferenced transects) should be established at locations within the preservation and restoration areas.

It is strongly recommended that a beach width monitoring program be set up to measure erosion rates directly. This would include measurements of both the erosion rate due to regional sediment starvation and any increased (active) erosion caused directly by shoreline armoring.

Beach response, as measured by sediment types, beach profiles, and forage fish habitat utilization, should be monitored to measure the efficacy of any pilot project. While the structures constructed in a pilot project should resemble complex accumulations of wood debris, they would need to be stable assemblages of real logs or concrete logs. Applying several treatments in similar settings is also recommended.

CHAPTER 1

Introduction

1.0 Introduction

The Thurston Regional Planning Council retained Herrera Environmental Consultants in collaboration with Moffatt & Nichol and Aspect Consulting to conduct a beach sediment study to assess the conditions of forage fish spawning habitat along the marine shoreline of Thurston County, Washington (Figure 1-1).

This study is an assessment of beach and sediment characteristics, sediment sources, and sediment transport influencing surf smelt (*Hypomesus pretiosus*) and Pacific sand lance (*Ammodytes hexapterus*) spawning habitat along marine shorelines of Thurston County.

Surf smelt and Pacific sand lance have specific spawning habitat requirements, including substrate type and size and a specific tidal elevation for successful spawning (Penttila 1995; 1978). The specific physical nature of surf smelt and Pacific sand lance spawning grounds (i.e., these fish only spawn in the upper beach area) and the limited extent of available spawning habitat in Puget Sound have made these species quite vulnerable to shoreline development and construction activities (WDFW 2004).

The principal focus of this study was to evaluate how shoreline armoring, particularly vertical bulkheads, influence forage fish habitat by altering the beach morphology and the characteristics, supply, and transport of sediment along the Thurston County marine shoreline.

This report describes the study objectives, study approach, a description of theoretical and empirical background information, study methodology, results, and conclusions. In addition, opportunities for habitat preservation and rehabilitation along the Thurston County marine shoreline are also addressed.

1.1 Study Objectives

The objectives of the beach sediment study were to: assess historical shoreline changes; quantify the principal areas supplying beach sediment to the shorelines; identify the physical processes most influencing sediment transport and beach morphology and characteristics; assess the relative effects of human development on beaches, and in turn on forage fish spawning habitat; and to identify opportunities for habitat preservation and rehabilitation along the Thurston County marine shoreline.

1.2 Study Approach

In order to assess sediment sources, processes, and the conditions influencing sediment transport and deposition, as well as beach characteristics related to forage fish spawning habitat, three working hypotheses were developed. The first of these hypotheses relates to local impacts:

1. *Shoreline bulkheads invoke physical changes to beaches that would otherwise not occur.*

The second and third hypotheses relate to the inlet-wide impacts of bulkheads:

2. *Bulkheads may affect sediment recruitment by decreasing or obstructing sediment input from actively eroding bluffs and landslides, thus adversely affecting forage fish habitat throughout the drift cell and possibly throughout the inlet.*

3. *Changes to upland tributaries entering Puget Sound in Thurston County have altered sediment budgets.*

1.3 Report Organization

This report begins with a discussion of general background information on coastal geomorphology and physical processes that govern sediment recruitment and sediment transport within the context of forage fish spawning habitat in Thurston County. This includes: a discussion of the nearshore ecosystem within the context of forage fish spawning habitat; the biology, life history, and spawning habitat of surf smelt and Pacific sand lance; and theoretical and empirical coastal geomorphology and physical beach processes. Subsequent chapters focus on background information, methodology, data analysis and results, discussion and conclusions, and identification of preservation and restoration sites. Finally, this report includes a series of map, figures, and tables which are included in the appendix section.

1.4 Caveats

A few caveats are essential to understanding what this report is, what it is not, and how it should or should not be used.

1. Identification of landslides was conducted only for the purpose of estimating the sediment budget and not as a delineation of geologic hazards.

2. The field sampling was performed to evaluate conditions representative of all Thurston County marine shoreline and not to differentiate specific areas within the county.

3. Quantitative analyses conducted using the beach profile data obtained in this study examined only the upper beach area, generally above MLLW.

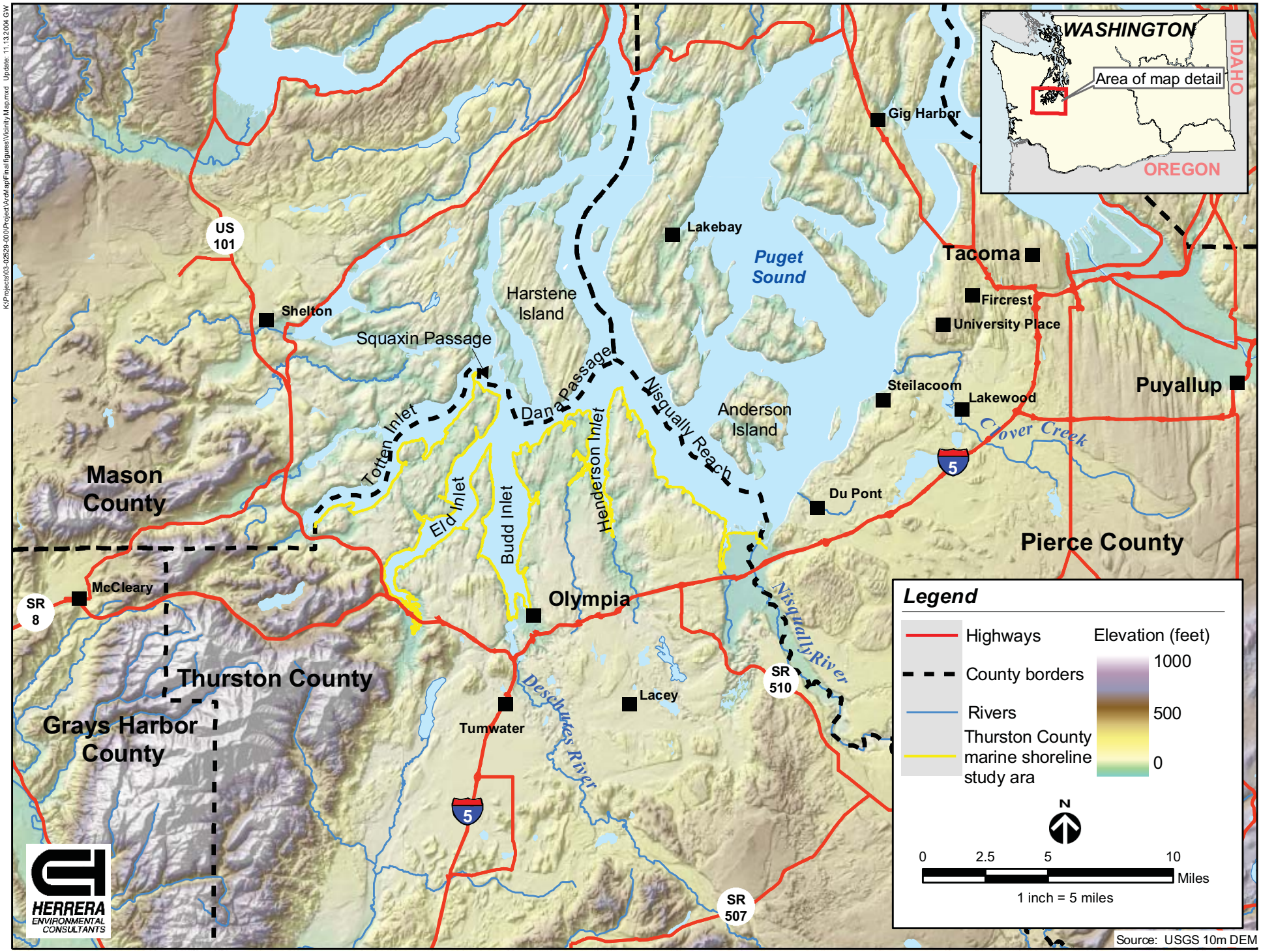


Figure 1-1. Vicinity map of the Thurston County marine shoreline study area.

Despite these caveats, the authors believe that this report is an extremely valuable and useful piece of science that will enhance the discussion of forage fish spawning habitat protection within the context of salmon recovery and marine shoreline planning. The study findings have resulted in an improved understanding of the processes influencing sediment transport and beach characteristics, and the management and protection of the marine shoreline of Thurston County.

CHAPTER 2

Background

2.0 Background

2.1 Introduction

In order to properly characterize the beach sediment characteristics, sediment transport, and sediment budgets influencing surf smelt and Pacific sand lance spawning habitat along the marine shoreline of Thurston County, it is important to describe what is known about these species' biology and habitat and to describe the general coastal geomorphology and physical processes that influence sediment transport and beach characteristics. The ecological functions associated with the spawning habitat for these species depend on complex interactions that occur within nearshore habitat areas. A glossary with definitions and illustrations of specialized terminology used in this report is presented in Appendix A.

2.2 Nearshore Ecosystem

Several general conceptual models provide the foundation for an understanding of the physical, chemical, and biological processes that shape and control nearshore habitats, biological communities, and species assemblages (Proctor et al. 1980; NOAA 1983; Williams et al. 2001; Brennan and Culverwell 2004; see Figure 2-1). Within the context of the Puget Sound nearshore geoclimatic setting, Williams et al. (2001) provides an ecological conceptual model applicable to the Thurston County marine shoreline:

> *…the geologic history of Puget Sound left massive deposits of sediments. The bathymetry and topography of Puget Sound create the basis for shallow, deep, and steep habitats. Seasonal weather patterns, precipitation, and ocean influences also contribute to these building blocks. A wide variety of physical, chemical, and biological processes interact with these building blocks to create habitat structure. Erosion and sediment transport processes carry sediments to beaches, spits, and other coastal landforms. Tides and rivers contribute minerals and nutrients, shape the land, and cyclically inundate and expose floodplain and shoreline areas. Freshwater flowing into Puget Sound via rivers, streams, and seeps creates complex patterns of salinity.*
>
> *These ecological processes create a diversity of habitat types that provide ecological functions such as spawning substrate for forage fishes, primary and secondary production, refugia, and other functions that are essential to ecosystem health and species viability. Where and when these processes operate without interruption, they create connected habitats. The quantity and quality of habitat also are linked to these processes; where they operate naturally, they are capable of generating high quality habitat functions. These processes and functions contribute to the food web through nutrient cycling, tidal flux, introduction of*

> *organic litter and insects, and maintenance of highly productive habitats such as eelgrass, macroalgae, and mudflats. The cumulative result of these processes working in concert is a complex landscape composed of a variety of functions that support diverse habitat types and community structure.*

Human intervention has resulted in significant modifications of many of the natural processes that form and maintain nearshore habitat and the communities of species assemblages that they support (Williams and Thom 2001; Nightingale and Simenstad 2001). For example, surf smelt and Pacific sand lance have specific substrate requirements for spawning (Penttila 1995, 1978). Nearshore development may affect the natural processes that form and maintain the specific substrate requirements that these species need for spawning, including sediment input and distribution, (i.e., beach erosion and littoral transport). Without the appropriate sediment input and distribution, the preferred sediment type could become depleted, which would lead to reduced or eliminated spawning habitat and a reduced population size. Reductions in these forage fish populations translate into reduced ecological interactions, including prey availability for salmon and numerous other fishes and wildlife species (Thom and Shreffler 1994; Williams and Thom 2001; Nightingale and Simenstad 2001).

2.3 Biology and Life History of Surf Smelt and Pacific Sand Lance

There are six main species of forage fish in Puget Sound: herring (*Clupea harengus pallasi*), northern anchovy (*Engraulis mordax*), Pacific sardine (*Sardinops sagax*), surf smelt (*Hypomesus pretiosus*), longfin smelt (*Spirinchus thaleichthys*), and Pacific sand lance (*Ammodytes hexapterus*) (Bargmann 1998). In Puget Sound, forage fish are a significant part of the prey base for marine mammals, sea birds, and fish populations, including salmonid species. Forage fish rely upon a variety of shallow nearshore and estuarine habitats and are a valuable indicator of the health and productivity of the marine environment (Williams et al. 2001). Of these six forage fish species, only surf smelt and Pacific sand lance spawn on the beach area (upper intertidal zone, approximately between MTL and MHHW). Consequently, only spawning habitat for these two species was analyzed and discussed in this report.

Within the context of the Pacific salmon recovery, all forage fish species play an important role. In the Puget Sound area, returning adult salmon, some resident stocks, and coastal bull trout use nearshore habitats as feeding areas where they consume forage fish such as Pacific herring, surf smelt, and Pacific sand lance (Penttila 1995; Brodeur 1990; Fresh et al. 1981; Kraemer 2003 personal communication).

The scope of this study included beach area characterization and the evaluation of how shoreline armoring influences forage fish habitat by altering various physical beach characteristics.

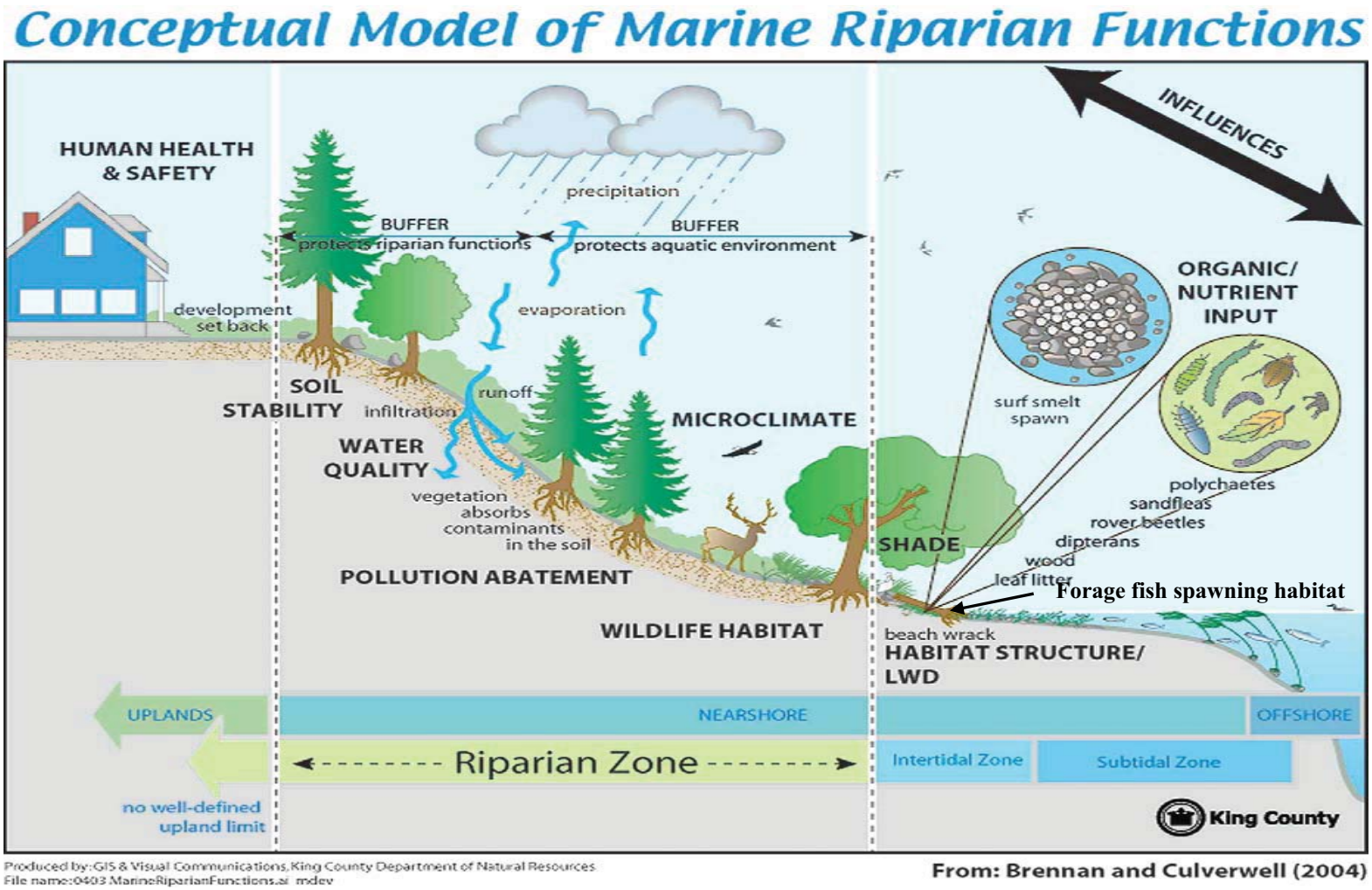


Figure 2-1. Puget Sound nearshore ecosystem, from Brennan and Culverwell 2004. Approximate location of the forage fish spawning habitat within the intertidal zone is shown (also see Figure 2-4).

2.3.1 Surf Smelt

Juvenile surf smelt reside in nearshore waters and may use estuaries for feeding and rearing (Emmett et al. 1991; Lemberg et al. 1997). Adult surf smelt are pelagic (Figure 2-2), but remain in nearshore habitats over a variety of substrates throughout the year (Emmett et al. 1991). They feed on a variety of zooplankton and epibenthic organisms, including planktonic crustaceans and fish larvae (Emmett et al. 1991; Fresh et al. 1981).

Surf smelt have specific spawning habitat requirements. Surf smelt spawn on gravel ranging in size from 1-7 mm in diameter, a size range commonly referred to as "coarse sand" or "pea gravel" (Figure 2-3). In addition to substrate characteristics, surf smelt require a specific tidal elevation for successful spawning. Surf smelt typically spawn at high tide, most frequently in the afternoon or early evening. Inside Puget Sound spawning is concentrated at a tidal elevation approximately between the mean tide level (MTL) and the mean higher high water (MHHW) (see Figure 2-4). Adult surf smelt are zooplanktivorous and prey upon copepods which, in the nearshore area, occur in the shallow exposed gravel-cobble and sand-eelgrass habitats (Simenstad et al. 1979).

Surf smelt eggs brooded in winter months require between 27 and 56 days to hatch, while those brooded in summer months require between 11 and 16 days (WDFW 2004). The location of smelt spawning grounds in the upper tidal zone at the upland-coastal margin, where human development is common, has made the species quite vulnerable to shoreline development and construction activities.

2.3.2 Pacific Sand Lance

The Pacific sand lance (Figure 2-5) is a common but poorly known nearshore schooling forage fish in Washington waters (Penttila 1995).

Pacific sand lance juveniles are pelagic and schooling, but may burrow into unconsolidated sediments at night to rest and escape predators (Emmett et al. 1991). Juvenile Pacific sand lance are primarily zooplanktivorous (Emmett et al. 1991). Juveniles rear in bays and nearshore waters (Lemberg et al. 1997). Adult Pacific sand lance likely move into coastal and estuarine waters during spring and summer for feeding and refuge from predators (Emmett et al. 1991). Adult Pacific sand lance are zooplanktivorous and prey heavily upon copepods (Fresh et al. 1981, Tribble 2000).

Pacific sand lance spawning occurs in the upper intertidal zone at tidal elevations ranging from approximately MTL to MHHW on sand to gravel beaches (Penttila 1995; Lemberg et al. 1997). The spawning season may last several months. The spawning frequency is likely to be highly variable, depending on the stock condition, habitat quality, and other factors (Penttila 2004 personal communication). Pacific sand lance deposit eggs on a broad range of beach surface substrates, from soft, pure fine sand beaches to beaches armored with gravel up to 30 mm in diameter, although most spawning appears to occur on the finer grained substrates in this range

(see Figure 2-6). Pacific sand lance eggs acquire a partial coat of sand grains which adhere to the eggs during deposition. The sand coating may serve to assist in capillary moisture retention when the eggs are exposed during the low tide. After deposition in the upper beach area (approximately MTL to MHHW), the coated Pacific sand lance eggs may be scattered over a wider range of the intertidal zone with each tidal exchange and by wave action. The incubation period is about four weeks (WDFW 2004).

Because Pacific sand lance spawn in the upper intertidal zone on sand gravel beaches, increasing development makes this species vulnerable to the cumulative effects of various types of shoreline development.

2.4 Surf Smelt and Pacific Sand Lance Spawning Habitat

Surf smelt and Pacific sand lance spawning habitat is created and maintained by natural processes such as erosion and littoral transport. In addition, the ecological functions associated with this spawning habitat depend on complex interactions between the marine and upland areas (nearshore zone).

The physical characteristics and functions of the nearshore zone, which encompasses the zone of direct functional interaction (e.g., sediment supply) between marine and upland habitats, are described below. The nearshore zone can be divided into: habitats that occur in the marine nearshore area (where surf smelt and Pacific sand lance spawn); banks, bluff, and backshore; and the marine riparian area (which support surf smelt and Pacific sand lance spawning habitat).

2.4.1 Marine/Estuarine Habitat

The marine nearshore area includes those habitats between extreme high water (EHW) and the lower limit of the benthic photic zone (the depth where light can no longer sustain plants). The lower depth range of the photic zone varies with the site, water clarity, and season. Healthy benthic vegetation can be found down to depths of about -33 to -98 feet relative to mean lower low water (MLLW = 0 feet) in Puget Sound (Williams and Thom 2001). In Thurston County, marine/estuarine habitat within the nearshore zone includes sand and mudflats; tidal marshes; river and stream mouths and deltas; sand spits; cobble, gravel, and sand intertidal areas; intertidal and subtidal eelgrass/macroalgae; subtidal kelp forest; and subtidal benthic areas.

Nearshore marine habitats have been extensively studied (Simenstad et al. 1979; Simenstad 1983; Simenstad et al. 1991; Duggins 1980; Harrold et al. 1988; Jackson and Winant 1983; Simenstad and Cordell 2000; Williams and Thom 2001) and are known to provide the following functions:

- Nutrient cycling
- Primary production

Figure 2-2. Three-year-old non-spawning female surf smelt (approximately one half the actual size).
Photograph by Dan Penttila, WDFW.

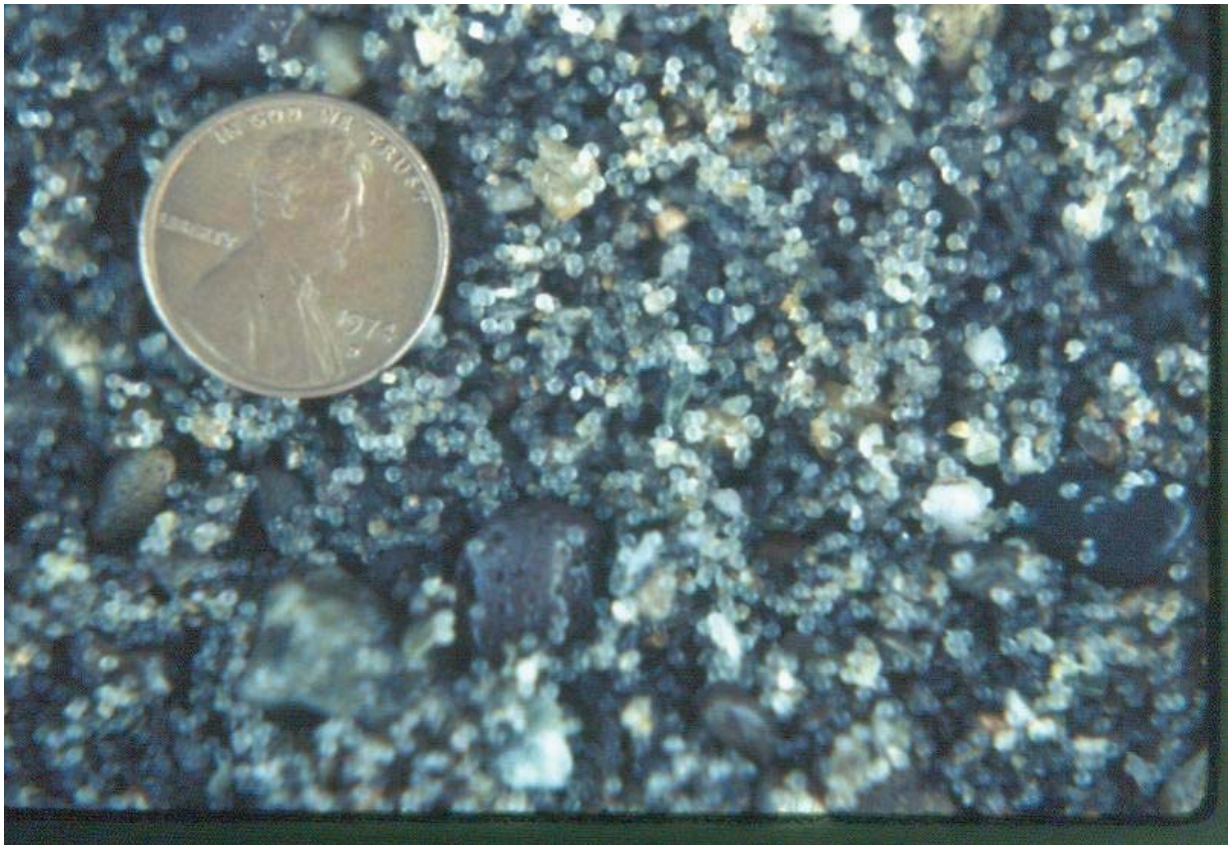


Figure 2-3. Surf smelt eggs on an unarmored beach.
Photograph by Dan Penttila, WDFW.

Figure 2-4. Surf smelt and Pacific sand lance spawning habitat on a sandy/pea gravel beach area of the Nisqually Reach (Transect 57), August 26, 2003. Habitat extent is shown and is located approximately between MTL and MHHW. Spawning habitat extent at any given location depends on the geomorphic configuration of the beach and the availability of suitable substrate.

Figure 2-5. Adult Pacific sand lance specimens (approximately one-half actual size). Photograph by Dan Penttila, WDFW.

Figure 2-6. Pacific sand lance eggs on an unarmored beach.
Photograph by Dan Penttila, WDFW.

- Organic matter input (riparian vegetation and large woody debris [LWD])
- Contribution to pelagic food webs through particulate and dissolved carbon
- Fish and wildlife support
- Herring spawning substrate
- Surf smelt and Pacific sand lance spawning habitat
- Salmonid habitat
- Habitat for rockfish species
- Substrate for macro algae, macroinvertebrates, and fish
- Food for bird species
- Wave and current energy buffering (eelgrass bed, kelp forest, and LWD on the upper beach area)
- Sediment trapping (eelgrass bed and LWD on the upper beach area)
- Ground water recharge
- Flood attenuation
- Water quality improvement.

2.4.2 Banks, Bluffs, and Backshore Habitat

Banks and bluffs are steeply sloping upland areas located adjacent to the intertidal zone. Banks and bluffs can be composed of sediments of varying grain sizes, including sand and small gravel that contribute to surf smelt and Pacific sand lance spawning habitat.

The backshore area is the upper beach area above MHHW. The backshore area can provide sand storage, and in areas where the coastal geomorphology includes the presence of a bluff, the backshore area is a point of entry for sediment into the system. According to the Washington State Department of Ecology, almost 621 miles of coastal bluff in Puget Sound experience shallow land sliding (Shipman 2001).

In addition to sand, LWD generally accumulates along the backshore areas at extreme high tides, and can help stabilize the shoreline (Zelo et al. 2000; MacDonald et al. 1994). Although not well documented in marine systems, LWD provides structurally complex roosting, nesting, refuge, and foraging opportunities for wildlife; foraging, refuge, and spawning substrate for fishes (through the accretion of sediments); and foraging, refuge, spawning, and attachment substrate for aquatic invertebrates (Brennan and Culverwell 2004). Logs embedded in beaches also

provide a source of organic matter, moisture, and nutrients that assist in the establishment and maintenance of dune and marsh plants (Williams and Thom 2001).

Banks, bluffs, and backshore areas provide the following ecological functions:

- Sand and LWD storage and associated functions
- Source of sediment to beaches
- Habitat for bluff-dwelling animals
- Substrate for riparian vegetation and associated functions
- Canopy cover and shade for the upper intertidal and supratidal zones
- Source of ground water seepage into the estuarine and marine waters.

2.4.3 Marine Riparian Habitat

Marine riparian habitats occur at the interface between terrestrial and aquatic ecosystems. In undisturbed areas, these habitats are often characterized by dense vegetation that may include Sitka spruce (*Picea sitchensis*), willow (*Salix* spp.), red alder (*Alnus rubra*), black cottonwood (*Populus trichocarpa*), roses (*Rosa* spp.), and Douglas spirea (*Spirea douglasii*) (Williams and Thom 2001; Williams et al. 2001). Marine riparian habitats in the upland areas along the shoreline likely provide some of the same functions that freshwater riparian areas provide (Desbonnet et al. 1995) as well as additional functions unique to nearshore systems (Brennan and Culverwell 2004; Williams and Thom 2001; Williams et al. 2001). Riparian vegetation moderates the quality of aquatic habitats by increasing slope stability, providing erosion protection (Myers 1993; Manashe 1993; Broadhurst 1998), and buffering against pollution and sediment runoff (Federal Interagency Stream Restoration Working Group 1998). Overhanging riparian vegetation provides shading that regulates microclimates important to surf smelt spawning (Penttila 2001) and solar radiation/desiccation limits the intertidal invertebrate distribution in the upper beach area (Foster et al. 1986). Therefore, loss of overhanging riparian vegetation along shorelines may reduce shading and result in reduced survival of forage fish eggs and larvae (Penttila 2001).

LWD can serve to stabilize beaches and help build berms and backshore areas (Brennan and Culverwell 2004).

In summary, the marine riparian zone provides the following ecological functions:

- Protection of water quality
- Bank and bluff stability
- Soil and slope stability
- Sediment control
- Microclimate and shade
- Wildlife habitat
- Nutrient input
- Fish prey production,
- Habitat structure (e.g., LWD)
- Substrate for riparian vegetation and associated functions.

2.5 Geomorphology and Physical Processes: Theoretical and Empirical Information

This section describes the physical processes that have shaped the 120.5 miles of marine shoreline in Thurston County. First, a description of the geological history and of the present-day processes that shape this part of southern Puget Sound is given. This is followed by a general description of coastal landforms (erosional, accretional, and estuarine). Finally, a discussion of littoral sediment transport is presented, together with a general discussion of the types of impacts that bulkheads can have upon beaches and nearshore areas.

There are four north trending inlets in Thurston County: Totten, Eld, Budd, and Henderson going from west to east. In addition, there are two passages between inlets: Squaxin and Dana Passages. Squaxin Passage is located to the northernmost portion of Totten and Eld Inlets. Dana Passage is located to the northernmost portion of Budd and Henderson Inlets. The eastern side of the county lies along the Nisqually Straits, northwest of the Nisqually River delta (see Figure 1-1).

2.5.1 Geology of the Southern Puget Basin

During the Pleistocene period (1.8 million to 8,000 years before present [ybp] (USGS 2004)), continental ice-sheet glaciers advanced southward from the Canadian Coast range and the Fraser Lowland and extended into the Puget Lowland. Regional stratigraphic records reveal deposits from at least 7 glacial advances into the lowland (Borden and Troost 2001; Troost 2003 personal communication). However, climatic records indicate that there may have been as many as 20 periods of global cooling (Shackelton et al. 1990) that could have resulted in glaciation of the lowland. The coastal bluff geology of Thurston County is dominated by deposits of the Late Pleistocene, the portion of the epoch of geologic time that extends from the end of the Vashon Stade of the Fraser glaciation, about 15,000 ybp to about 250,000 ybp.

Within the shoreline region of Thurston County, bedrock outcrops are rare and in most places the basement rocks are deeply buried below the unconsolidated sedimentary units (Dion et al. 1994). Bedrock crops out only at the southern end of Eld Inlet, near Mud Bay, where basalt and flow breccia are present. These bedrock units do not contribute significant amounts of sediment to the shoreline and nearshore system. The majority of the sediment supplied to beaches and nearshore environments is derived from the Quaternary glacial and non-glacial sedimentary units that lie above the regional basement bedrock.

Recent work (Logan et al. 2003a, 2003b; Walsh et al. 2003a, 2003b; Borden and Troost 2001) suggests that some of the sediments exposed on Thurston County shoreline bluffs date from the early and middle Pleistocene (2 million to about 300,000 ybp). However, the majority of the sediments date from the most recent glaciation (the Vashon Stade of the Fraser glaciation), the third most recent glaciation (the Double Bluff glaciation), and the non-glacial sedimentary periods between these glaciations. The second most recent glaciation (the Possession glaciation)

is poorly expressed in the stratigraphic record and left little glacial sediment in the South Sound region.

Each period of continental glaciation typically began with a tongue of ice blocking the northern end of the Puget Lowland. With normal northward drainage blocked, a large freshwater lake formed in the lowland, allowing accumulation of fine-grained sediments (silt, clay, and fine sand) called glaciolacustrine deposits. These fine-grained beds later formed regional aquitards that contribute significantly to bluff instability.

As the ice sheet advanced farther southward, the sediment supply to the lowland lake increased significantly and coarsened as a glacial outwash plain filled the lowland lake with deposits of sand and gravel. These pro-glacial outwash deposits are also called advance glacial outwash. Where exposed to flowing water in drainages, or to wave action on bluff faces, these deposits are easily eroded. Glacial outwash provides a significant source of sand and gravel to the marine shoreline.

If the ice sheet advanced far enough to the south, as it did during the Vashon Stade of the Fraser glaciation and Double Bluff glaciation, much reworking of sediments occurred below the ice. The majority of the meltwater from these large ice sheets flowed below the ice and eroded and carved out the large channels that are present today as the many deep valleys and sounds and inlets that compose the lowlands and waterways of Thurston County. The modern location and geometry of the coastal bluffs reflects 328 feet of sea-level rise and shoreline erosion during the 12,000 years since deglaciation.

In many areas of the uplands, a veneer of glacial till (a poorly sorted mixture of clay, silt, sand, gravel, and boulders) was deposited at the interface of the older sediment and the base of the glacial ice. The grain size distribution of the till and its high degree of over-consolidation (compaction by glacial ice) produced a very dense, nearly impermeable deposit that caps much of the upland areas and moderate slopes above the waterways. This glacial till is typically up to 30 feet thick, forms a regional aquitard, and may perch shallow ground water. A seepage face forms where ground water levels intersect a coastal bluff (Figure 2-7). Landsliding is common above a seepage face. The glacial till is resistant to erosion by flowing water and wave action and generally limits erosion of upland areas and bluffs. Where breached by ravines and coastal bluff faces, the till often forms very steep to vertical faces. Because of their high percentage of fine sediment, high cohesion, and resistance to erosion, glacial tills contribute much less coarse sediment to Puget Sound shorelines than similar exposures of glacial outwash consisting of un-cohesive sand and gravel.

After retreat of the glaciers, meltwater streams and melting ice left deposits of recessional glacial outwash on the emergent landscape and lake deposits where water was impounded. These outwash deposits are often present as several feet of sand and gravel at the tops of the bluffs, or considerable thicknesses of sand and gravel where it in-filled former glacial melt-water channels. Thick deltas of recessional outwash are present at the mouths of major drainages and provide a source of sand and gravel to marine shorelines through mass wasting and fluvial processes.

Figure 2-7. Photo of seepage face, site 22, East Eld Inlet, August 26, 2003. Substrate is mapped as unsorted and highly compacted mixture of clay, silt, sand and gravel deposited directly by glacier ice.
From Walsh et al. (2003b).

Between periods of glaciation, Lowland geologic processes operated much the same as they do today with rivers and streams transporting sediment to the lowland area. Most of the sediment in the non-glacial deposits of Thurston County consists of silt, clay, and fine to medium-grained sand. These deposits are often present as one thick sequence in Thurston County, where they were long recognized as the "Kitsap Formation". These deposits are now known to consist of deposits from two inter-glacial climatic periods: the Olympia beds which were deposited prior to the Fraser glaciation (60,000 to 16,000 ybp), and the Whidbey Formation which was deposited after the Double Bluff glaciation (about 125,000 to 80,000 ybp). Non-glacial deposits are much more thinly interbedded than the more massive glacial deposits, and contain layers of organic matter and peat beds. The fine-grained beds in the non-glacial deposits may act as aquitards and perch ground water. Where the water table intersects a bluff face, landslides are common above the seepage face. Non-glacial deposits are modest contributors of sand, silt, and clay to marine waters.

The geologic units exposed along Thurston County shoreline bluffs vary considerably (WDNR 2003a, 2003b, 2003c, 2003d, 2003e, and 2004). If all the geologic units were present, the idealized stratigraphy exposed in coastal bluffs would consist of a thin veneer of sandy recessional outwash over several to tens of feet of hard resistant till. This would be underlain by sandy and gravelly advance glacial outwash, over hard glaciolacustrine silt and clay, over a variety of non-glacial sands, silts and clays, and peats. These would be underlain by older glacial deposits, and so forth. In reality, exposed bluffs rarely if ever contain all of the lowland stratigraphic units. The Fraser glacial deposits are generally the best preserved due to their recent age and position above older sediments.

Mapped bluff sediments along the Nisqually Reach generally consist of Vashon advance glacial outwash (Qga) over undifferentiated pre-Fraser glacial and non-glacial sediments. Along Henderson Inlet, bluff sediments are dominated by Vashon recessional lacustrine deposits consisting of silt and clay and fine sand. Pre-Fraser sandy units and sandy Vashon glacial outwash are the most common source sediments on the Budd Inlet bluffs. Vashon till (Qgt) is also common on the uplands and slopes rising from Budd Inlet. Eld and Totten Inlet slopes are comprised primarily of Vashon till with minor exposures of Vashon advance outwash and pre-Fraser sandy and gravelly deposits.

2.5.2 Geology of Thurton County Coastal Bluffs

Coastal bluffs in Thurston County are predominantly quaternary glacial outwash of varying ages and composition (WDNR 2003a, 2003b, 2003c, 2003d, 2003e, and 2004). The most prevalent shoreline material identified by the Washington DNR geology maps is unstratified Vashon till, which is composed of highly compacted clay, silt, sand, and gravel. Unstratified Vashon till is not highly erodable. Vashon till dominates the coastal bluffs of Eld Inlet, East Henderson Inlet, and Totten Inlet and covers large areas along West Budd Inlet, Dana Passage, and West Henderson Inlet. The coastal bluffs of East Budd Inlet, West Eld Inlet, and Squaxin Passage contain some areas of sand and of Pre-Vashon gravel (Qpg) which is made up of gravel that is relatively resistant to erosion.

According the Washington DNR geology maps (2003a, 2003b, 2003c, 2003d, 2003e, and 2004), most Thurston County coastal bluffs that are not Vashon till or Pre-Vashon gravel are erodable. Squaxin Passage and Totten Inlet contain large areas of coastal shoreline mapped as landslide deposits (Qls), which are typically made up of rock, soil and organic matter. These deposits are only mapped where landslides are large or landslides obscure the underlying geology. Landslide deposits are indicative of frequent landsliding and are highly erodable. Coastal bluffs along West Budd inlet and East Eld inlet are comprised of Vashon advance outwash, which consists of sand, gravel, silt, and clay deposited during glacial advance. The Vashon advance outwash is erodable. Coastal bluffs along Henderson inlet and the Nisqually Reach have long reaches of Latest Vashon fine-grained sediments (Qgof) which is made up of lacustrine clays to fine sandy silts with sparse dropstones. This geologic unit is mapped where it is over 5 feet thick. This unit often fails along bluffs. Pre-Vashon sand-size or finer deposits (Qps) dominate the coastal bluffs of West Budd Inlet, Dana Passage, and Nisqually Reach. These non-glacial deposits of massive to cross-bedded sand are interbedded with silt and gravel. This gravel supports forage fish spawning habitat. This unit is erodable and often fails along bluffs.

2.5.3 Southern Puget Basin

The Thurston County shoreline is located in the Southern Basin of Puget Sound. The Southern Basin consists of 16 percent of the total area of Puget Sound basin and nine percent of the total volume; but consists of 29 percent of the total shoreline and approximately 21 percent of the total tideland (Figure 2-8). The Southern Basin has significantly more shoreline than any other region in the Puget Sound. This feature is mainly due to the presence of several islands (Fox, McNeil, Anderson, and Hartstene) and the group of shallow inlets that make up the Mason and Thurston County shorelines (Hammersley, Totten, Eld, Budd, and Henderson).

The average depth of the Southern Basin (120 feet) is significantly less than any of the other basins of Puget Sound (Figure 2-9). The deepest portion of the basin is in a channel running from Carr Inlet down between McNeil and Anderson islands and up toward Case Inlet. The channel is deepest east of Balch Pass (615 feet). The deepest part of the channel between the Nisqually Reach and Case Inlet occurs between Devils Head and Johnson Point at a depth of 360 feet. The shallowest region of the entire Puget Sound system occurs southwest of Hartstene Island, in the Hammersley, Totten, Eld, Budd, and Henderson Inlets. The inlets are characterized by large intertidal areas caused by a large tidal range and gentle slopes associated with the inlets.

Puget Sound shorelines lie within the littoral zone where erosion and sediment transport are primarily driven by wave energy. The principal geomorphic elements of the littoral zone include (i) the shoreface that extends from the lower limit of littoral sediment transport (i.e., “closure depth”) to mean low tide, (ii) the foreshore extending from mean low to mean high tide, and (iii) the backshore that extends from mean high tide to adjacent uplands (Figure 2-10). This study focuses on the foreshore and backshore of the littoral zone.

Coastal Geomorphology is integrally linked to the physical processes that erode uplands, deliver sediment to the shoreline, and move sediment along the shoreline. These processes include tidal

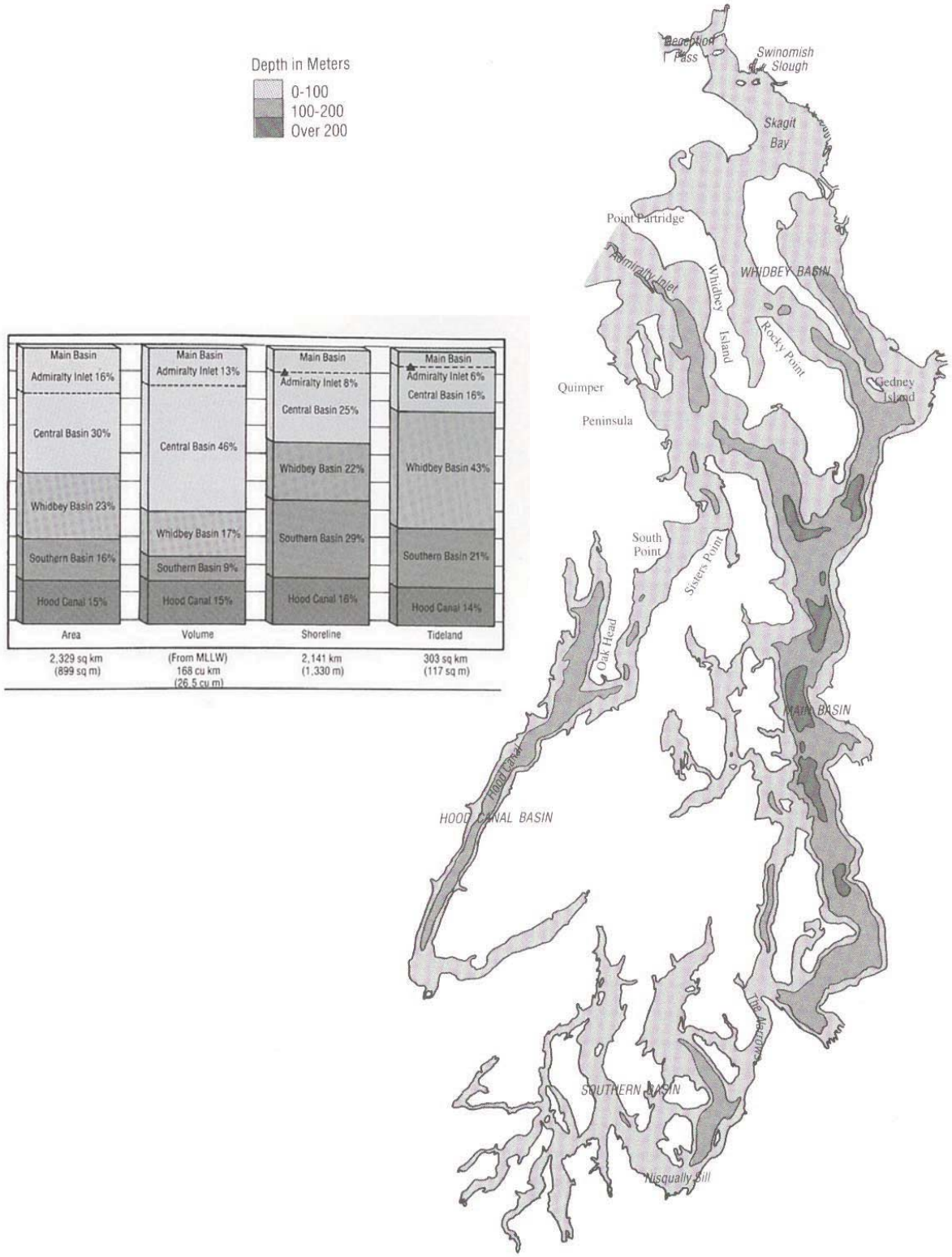


Figure 2-8. Map and bar chart representing the composition of Puget Sound area, volume, shoreline, and tideland.
From Burns (1990).

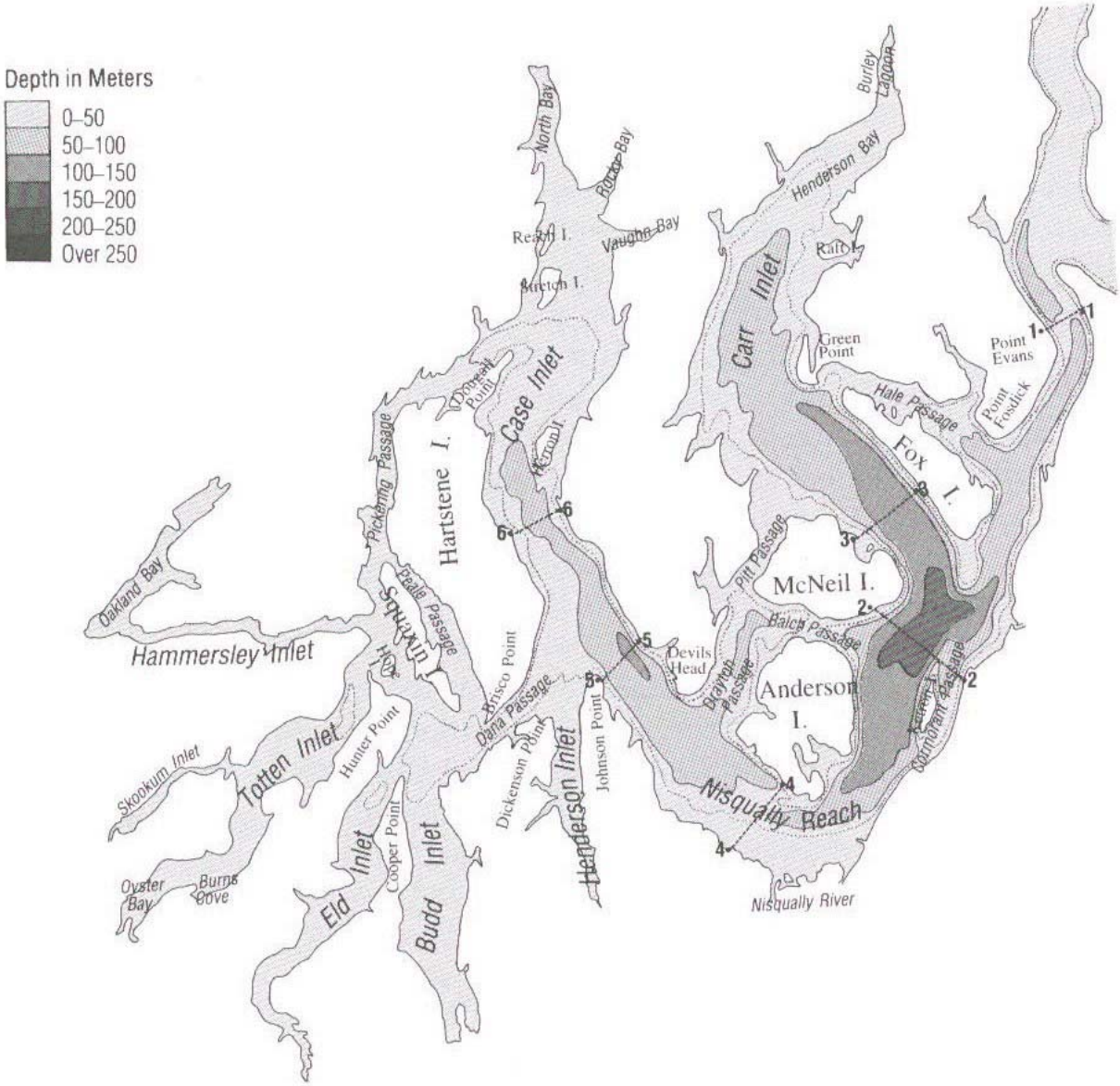


Figure 2-9. Bathymetry of Southern Basin, Puget Sound.
From Burns (1990).

fluctuations, wave energy, and upland runoff (Figure 2-11). Coastal landforms are a function of the relative contribution of each process and the supply and characteristics of sediment to the littoral zone (Figure 2-11). Natural or artificial changes that affect these processes, and the supply of sediment, will likewise influence coastal landforms and associated ecosystems and habitat.

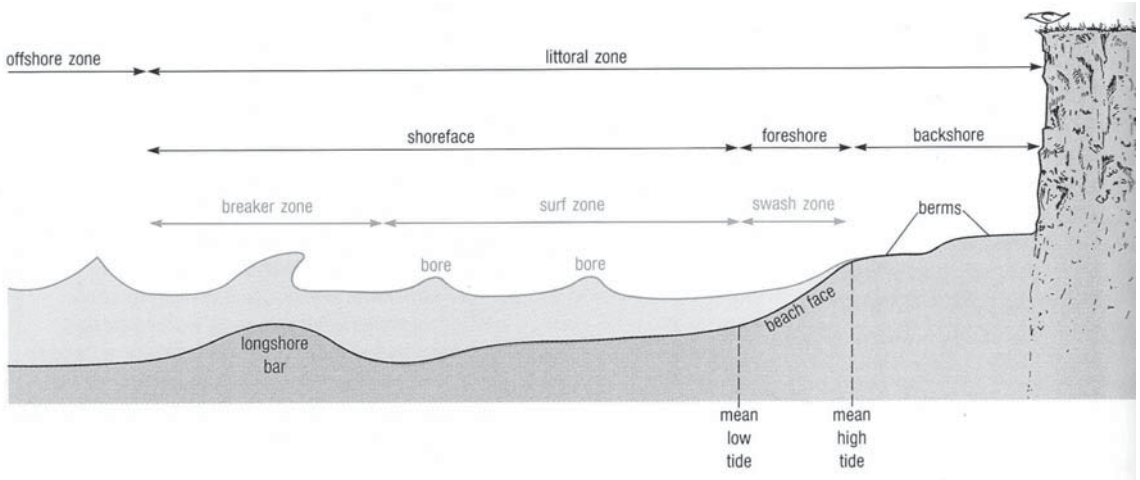


Figure 2-10. Definition of nearshore features of a beach profile.
From Brown et al. (1989).

The evolution of costal landforms is closely linked to changes in relative sea level. Changes in relative sea level can result from changes in ocean level or changes in land elevation (e.g., isostatic rebound, tectonic uplift, or subsidence).

Past sea-level rise is due to two main causes: global mean sea-level rise; and vertical land movements which produce a localized, relative sea level change (Canning 2001). Sea level at Seattle has risen approximately 7.9 inches (20 cm) over the twentieth century (Figure 2-12). The global average rise in sea level over the past century has been in the range of 1 to 2.5 mm/year (0.3 to 0.8 feet per century). Subsidence in Thurston County, in the range of 1 to 2 mm/year (0.3 to 0.6 feet per century) increases the rate of local sea level rise relative to the land.

The global average rate of sea level rise is expected to increase in future as a result of climate change. The Intergovernmental Panel on Climate Change (IPCC) projected a best estimate of 1.6 feet increase between 1990 and 2100 (Warrick et al. 1996). Canning (2001) reports that the Canadian Centre for Climate Modelling and Analysis estimates an additional 0.7 feet increase by 2100 in the East Pacific as a whole (for a total of 2.9 feet; Table 2-1). The rate of local subsidence is unlikely to change.

Accelerated sea-level rise will increase coastal erosion and eliminate backshore environments where shorelines have been armored.

Table 2-1. Estimated projections of sea-level rise for Thurston County.

Factors Affecting Sea Level	1990	2000	2025	2050	2075	2100
Global average sea-level rise (ft.)	0.0	0.1	0.3	0.7	1.2	1.6
East Pacific surcharge (ft.)	0.0	0.1	0.3	0.3	0.8	0.7
Local subsidence (ft.)	0.0	0.1	0.2	0.6	0.4	0.6
Total Sea-level Rise (ft.)	0.0	0.2	0.8	1.2	2.3	2.9

Source: Canning (2001).

2.5.4 Upland Topography and Watersheds

Most of the 120.5 miles of marine shoreline in Thurston County consist of coastal bluffs with east and west exposure along Totten Inlet, Eld Inlet, Budd Inlet, Henderson Inlet, and the Nisqually Reach. Relatively small sections of the shoreline have northern exposures between the Inlets along Squaxin and Dana Passages. The shoreline is interrupted occasionally by small pocket estuaries or embayments. The major watershed outlets to Puget Sound along the Thurston County shoreline are situated at the southern ends of the Inlets and the Nisqually Reach. The largest drainage basin by far is the Nisqually River, which flows into Puget Sound at the south end of the Nisqually Reach between Thurston and Pierce Counties (Table 2-2). The Deschutes River, the second largest fluvial input in Thurston County, drains the only other large watershed and discharges into Budd Inlet after first passing through Capitol Lake, an artificial freshwater impoundment created at the southern end of the Inlet.

Table 2-2. Principal watersheds discharging to Puget Sound within the study area.

Inlet	Principal Tributaries	Total Area (sq. mi.)	Data Sources
Totten Inlet	Skookum Creek [a] Kennedy Creek Schneider Creek	65	Lombardo et al. 2003 TRPC 2002
Eld Inlet	Perry Creek McLane Creek	40	Lombardo et al. 2003 TRPC 2002
Budd Inlet	Deschutes River	162	WDOE 2004
	Other rivers including; Ellis Creek Moxlie/Indian Creek Schneider Creek	44	TRPC 2002 Tabbutt 2001 WDOE 2004
Henderson Inlet	Woodland Creek	50	TRPC 2002
Nisqually Reach	McAllister Creek Nisqually River	751	WPN *et al.* 2001 WDOE 2004

[a] Mason County.

While there are several dams within the area, with the exception of the Deschutes River the area controlled is a relatively small fraction (less than 10 percent) of the drainage total area.

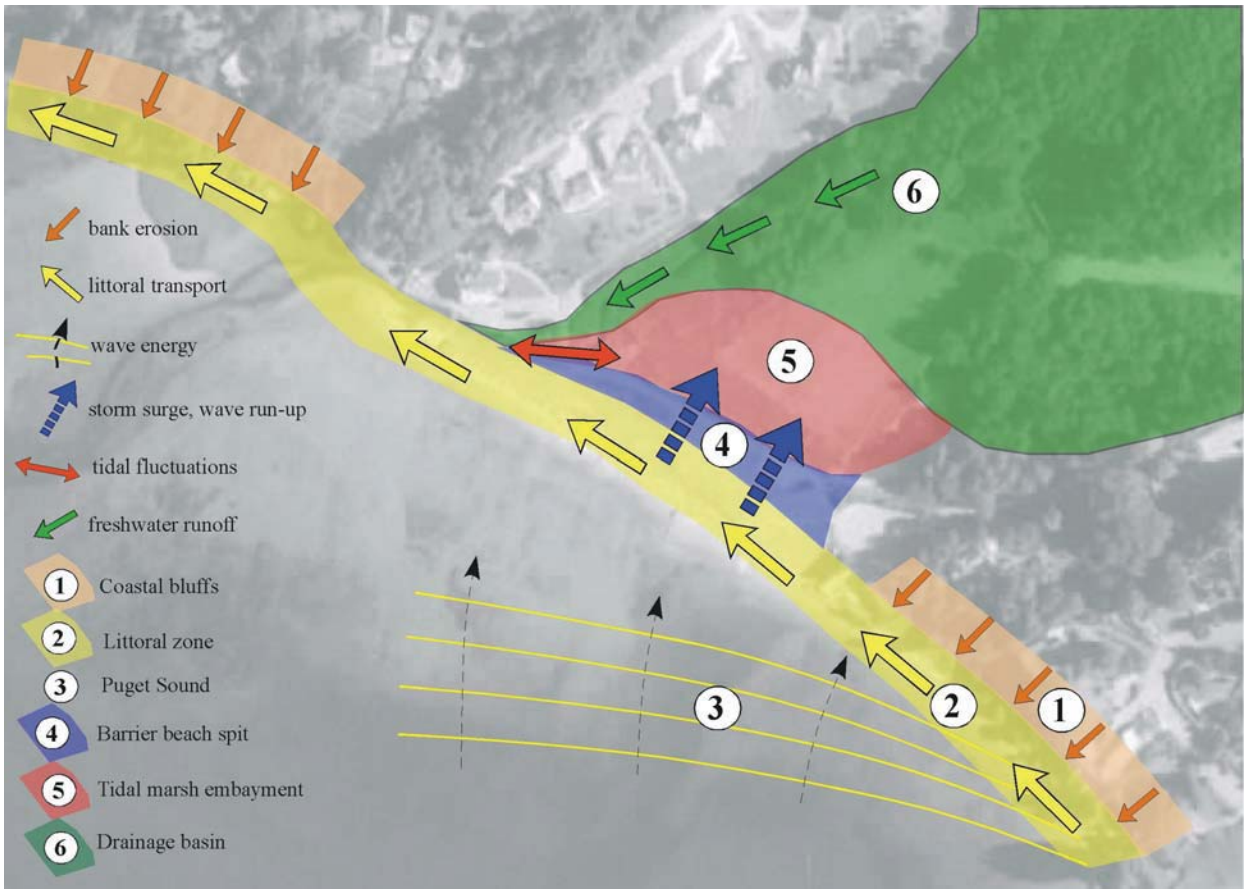


Figure 2-11. Hypothesized geomorphic process domains along the Puget Sound shoreline (Fetherston et al. 2001).

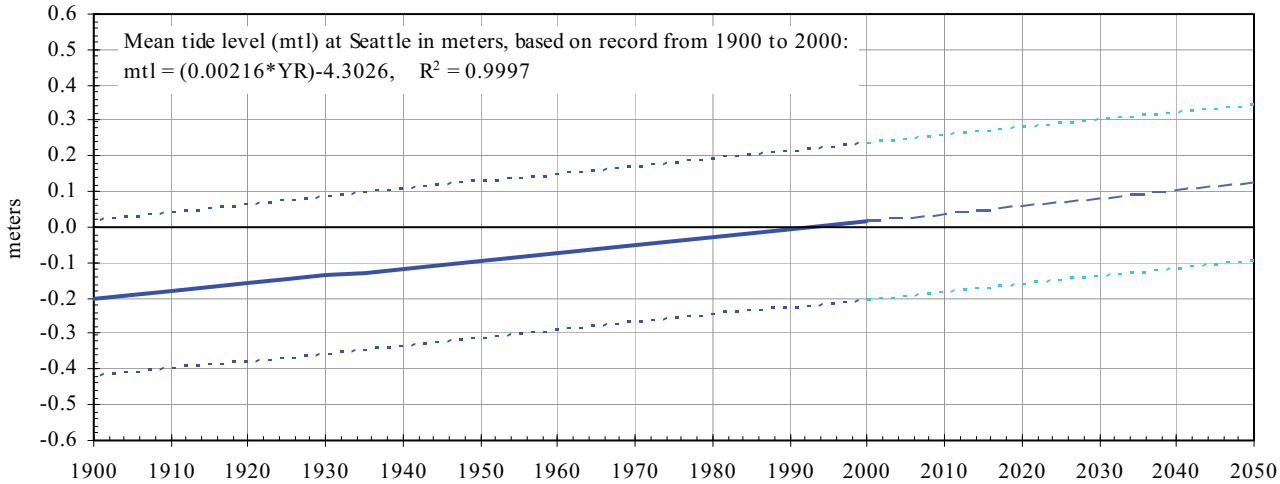


Figure 2-12. Historic sea level rise at Seattle projected to 2050 (NOAA 2004). Dashed lines represent the range in water level fluctuations about the long-term running average.

The Nisqually basin originates at an elevation of 14,410 feet in Mount Rainier National Park and flows through areas that are predominantly sparsely developed, including the Nisqually Indian Reservation, Fort Lewis Military Reservation, and the Nisqually National Wildlife Refuge. The Deschutes River, which flows into Budd Inlet, is the second largest fluvial input in Thurston County. The Deschutes River begins in the Long Term Forestry lands in Lewis County at an elevation of approximately 4,390 feet and flows into Capitol Lake, which was created when the Deschutes River was dammed in 1951. The lower portion of the Deschutes drainage basin has more development than the other drainage basins in Thurston County.

The landmasses between the inlets of Thurston County are characterized by low, rolling hills that rarely reach elevations of 200 feet above sea level and, between inlets, do not rise above 300 feet in elevation. The only high elevation area near the Thurston County shoreline is approximately 5.5 miles to the southeast of Totten and Eld inlets, where elevation rises rapidly to 2,660 feet at the peak of Larch Mountain.

Topography near the shoreline is relatively constant across the inlets. In areas characterized by many small subbasins, which occur in every inlet, elevations generally do not rise above 75 feet within 300 feet of the shoreline. However, in areas with larger subbasins, elevations are typically 100 to 150 feet above sea level within 300 feet of the shoreline and often rise to 50 to 100 feet above sea level directly adjacent to the shoreline.

2.5.5 Shoreline Protection

Approximately 36 percent of Thurston County's shoreline has been armored with bulkheads, rock revetment, and occasionally, wood structures (Table 2-3). This table excludes a portion of the Nisqually River shoreline that is more fluvial than marine in nature. The shoreline typically is armored with concrete bulkheads, which range in height from 3 feet to over 10 feet tall and are located within the upper part of the tidal zone (between MTL and MHHW). Armoring is not distributed uniformly along the shoreline; parts of Thurston County, such as northwest Budd Inlet, have areas of bulkheads that stretch uninterrupted for miles while other areas remain largely unarmored.

2.5.6 Erosional Landforms

Erosional coastlines are characterized by steep, narrow, and coarse beaches. Hardpan (geologic material underlying beach alluvium) may be exposed or close to the surface, and beach surface coarsening (a thin layer of coarse material such as cobbles overlaying the beach) may be present. Around the majority of Puget Sound, the boundary between beaches and upland areas is associated with steep bluffs. Eroding bluffs are one of the principal sources of sediment to the adjacent beaches.

Bluff recession in Puget Sound primarily depends on the wave environment (fetch, storm size and duration, and nearshore bathymetry), geology (resistance of materials to erosion), and beach characteristics (width and elevation) (Canning and Shipman 1994). Zelo et al. (2000) cited typical erosion rates in the range of 1 foot per decade (0.1 foot/year), often reflecting the loss of

several feet of bluff or bank in a landslide every twenty or thirty years. Keuler (1988) found that long-term rates in central Puget Sound were about 0.3 feet/year and maximum rates of 1.0 feet/year occur on the exposed west side of Whidbey Island (Canning and Shipman 1994). The mechanisms of mass wasting associated with bluff erosion are dependent on the intensity (i.e., wave energy) of shoreline erosion (intersection of upper beach and hillslope toe), bluff geology, bluff height, and vegetative cover.

Table 2-3. Percentage of the Thurston County shoreline that is armored.

Inlet	Side of Inlet	Length of Shoreline (miles)	Length of Armoring (miles)	Percent of Shoreline Armored
Totten	East	15.5	2.9	19%
Squaxin Passage		2.4	1.7	71%
Eld	East	17.2	5.7	33%
	West	20.7	8.0	39%
Budd	East	10.2	2.5	24%
	Olympia	4.6	4.4	94%
	West	8.2	5.8	71%
Dana Passage		8.4	3.1	37%
Henderson	East	9.6	2.5	26%
	West	11.8	1.5	13%
Nisqually Reach		11.9	4.8	40%
All inlets		120.5	42.9	36%

Data Source: TRPC (2003a). A portion of the Nisqually River shoreline is excluded from this and other tables because it is not strictly marine in nature.

Ruotsala (1979) describes three general classes of slope failure along coastal bluffs: slow flowage (creep); rapid flowage (earthflow and mudflow); and landslide (slump, debris-slide, debris-fall, rock slide, and rock fall). Causes of slope failure can be categorized as contributing conditions (lithological, stratigraphic, structural, topographic, climatic, and organic) and active causes (prying, repeated expansion/contraction, gullying, removal of support, overloading slope, vibration, etc.) (Figure 2-13).

Creep

Creep can be defined as "slow downslope movement of surficial soil or rock debris, usually imperceptible except to observations of long duration" (Sharpe 1938; Ruotsala 1979). The primary mechanism influencing creep is multiple expansion and contraction of the soil (Figure 2-14).

Earthflow and Mudflows

Earthflow can be defined as "slumping at the end of the flow and the formation of a bulging, badly crevassed dome at the toe" (Sharpe 1938; Ruotsala 1979). This process involves a substantial amount of water, which results in the domed structure at the toe of the movement (see Figure 2-15).

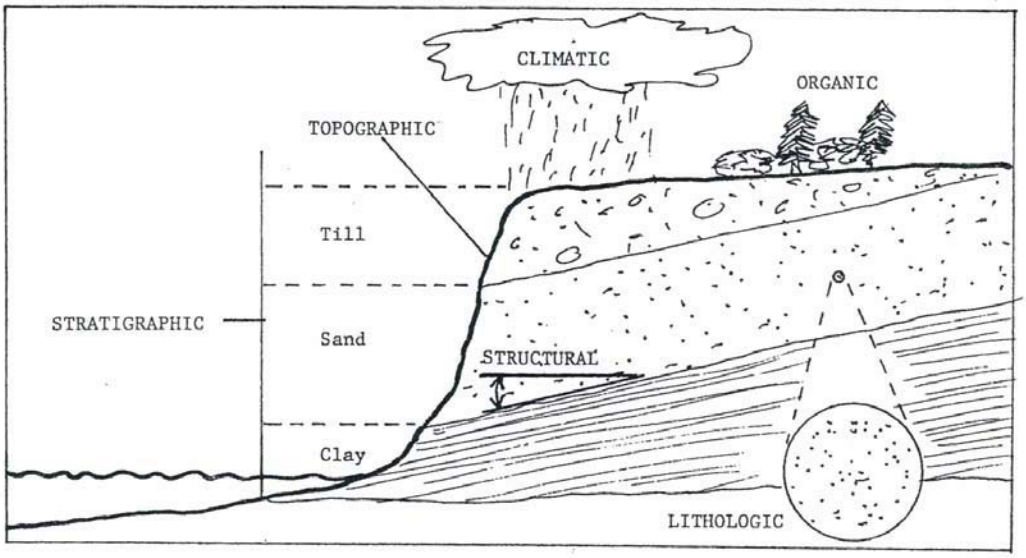


Figure 2-13. Schematic of contributing conditions of slope failure.
From Ruotsala (1979).

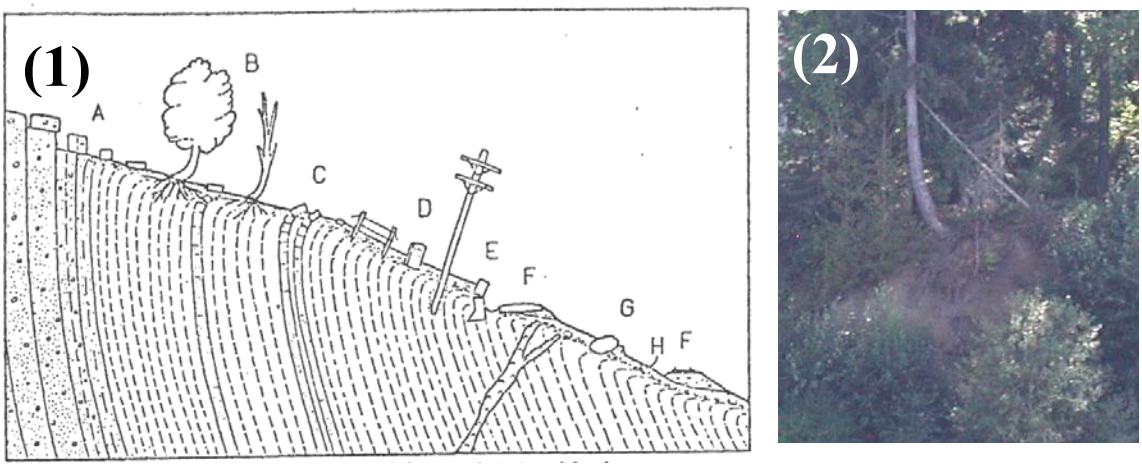


Figure 2-14. (1) Schematic cartoon of soil creep evidence illustrating: joint blocks displacement ("A"); trees with curved trunks ("B"), downslope bending/dragging of bedrock ("C"); displaced land structures such as poles, walls, foundations, or roads ("D", "E" & "F"), turf moves downhill from creeping boulders ("G"), line of stones at base of creeping soil ("H") (from Ruotsala 1979, Sharpe 1938). (2) Photograph of tree with curved trunk where soil creep is occurring at top of erosional scarp, Thurston County shoreline.

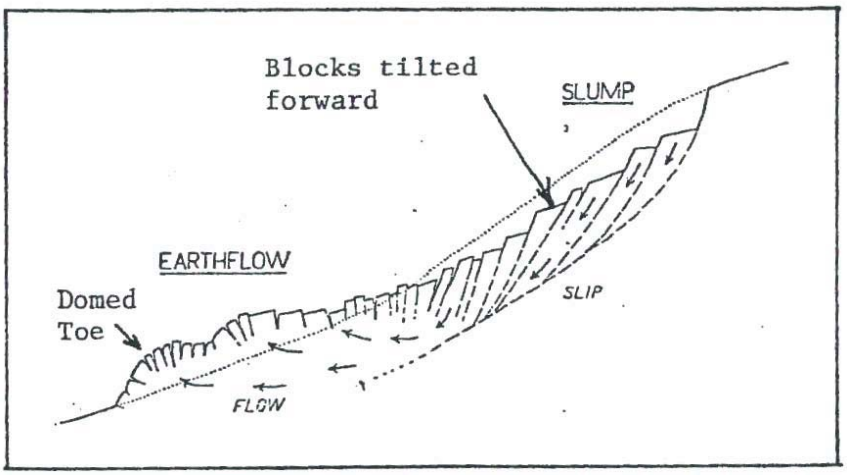


Figure 2-15. Schematic of a cross-section of an earthflow and slump.
From Ruotsala (1979); Sharpe (1938).

Mudflows contain a higher water content and occur on a steeper slope than earthflows (Sharpe 1938; Ruotsala 1979). Heavy precipitation in a short period of time and on erodible material may generate mudflows.

Slumps

A slump can be defined as "a downward slipping of a mass of rock or unconsolidated material of any size, moving as a unit or as several subsidiary units, usually with a backward rotation (along a surface concave upward)" (Sharpe 1938; Ruotsala 1979). This movement is different than earthflow because the process involves very little water, therefore no domed structure exists at the toe of the movement (Figure 2-15).

Debris Slide and Debris Fall

A debris slide (see Figure 2-16) can be defined as the "rapid downward movement of predominantly unconsolidated and incoherent earth and debris in which the mass does not roll backward but slides or rolls forward, forming an irregular hummocky feature" (Sharpe 1938; Ruotsala 1979). This process is a dry movement; if water was present the process would be termed a "debris-avalanche."

Rock Slide and Rock Fall

The definitions of rock slide (Figure 2-16b) and rock fall (Figure 2-16c) are similar to debris slide and debris fall, except that the material in movement is newly detached bedrock, not unconsolidated material (Sharpe 1938; Ruotsala 1979).

2.5.7 Accretionary Landforms

There are many different accretionary landforms present in Puget Sound. A few of the main types of landforms are listed below and depicted in Figure 2-17.

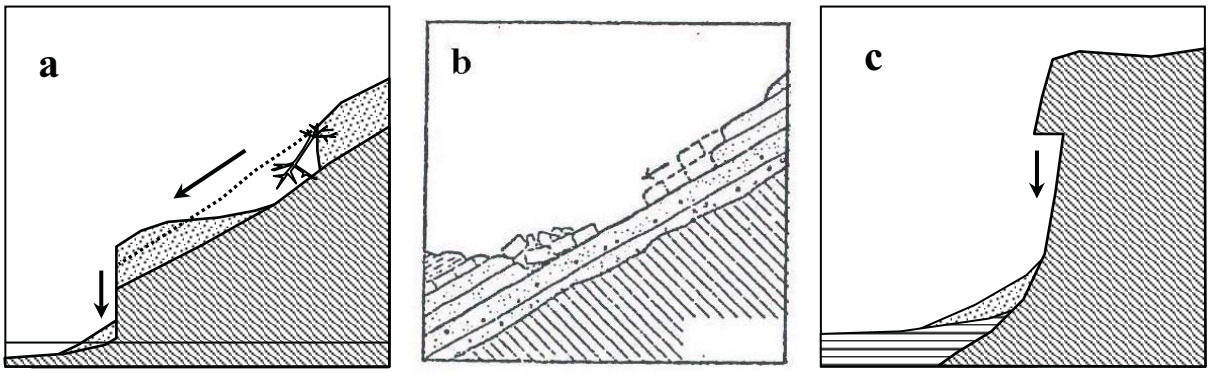


Figure 2-16. Schematic of (a) debris slide; (b) rock slide; (c) rock fall.
From Ruotsala (1979); Sharpe (1938).

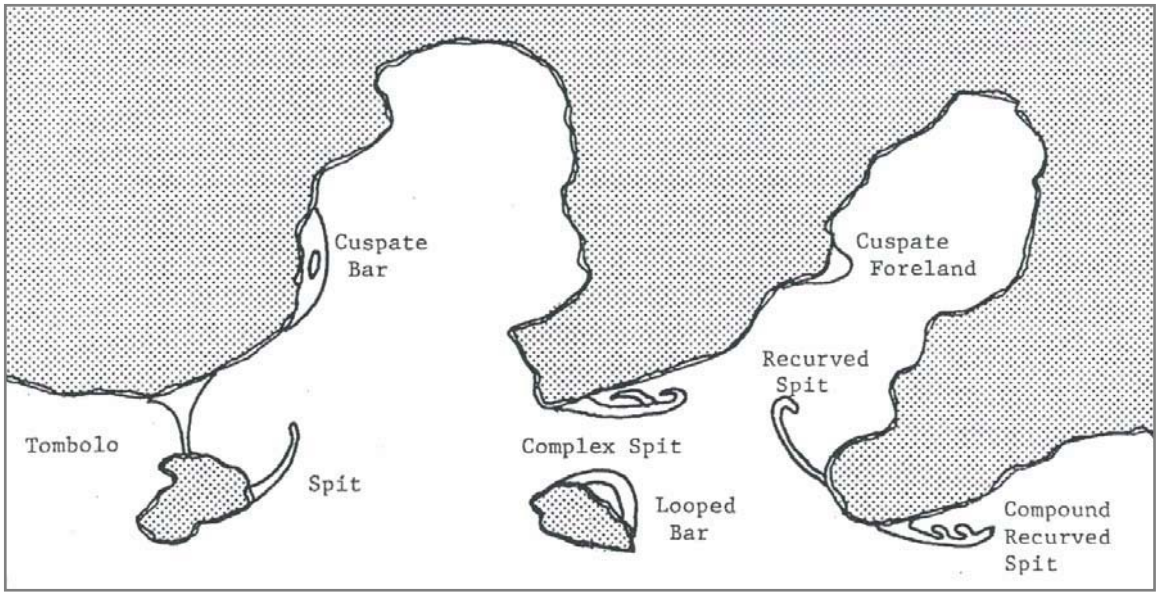


Figure 2-17. Shoreline accretion features.
From Ruotsala (1979).

- Beaches – a deposit of unconsolidated sediment (alluvium), created and shaped by wave action.
- Spit – a strip of beach connected to land on one end and in deep water at the other end. A spit is lengthened by wave action or prevailing currents which move and deposit sediment at the end of the spit (Ruotsala 1979).
- Simple Spit – created by a longshore current (one predominant direction) moving sediments (Ruotsala 1979).

- Recurved Spit – a spit with a single curved back at the end of the strip of land. The recurved spit may be caused by opposing wind driven or tidal currents which transport sediments along main direction of spit, then at the end of the spit the material is moved in the bay behind the spit (Ruotsala 1979).

- Compound Recurved Spit – caused by intermittent currents building a head when moving in one direction, and then shifting to extend the head in another direction (Ruotsala 1979).

- Complex Spit – composed of independent spits growing in the inside of an embayment, caused by secondary current systems occurring within the embayment (Ruotsala 1979).

- Winged Headland – consists of a growth of spits in the opposite direction from a headland (Ruotsala 1979).

- Bar – ridges of sand exposed when tides are low. They serve as breakers during storms, but can be unstable and shift during storms and between seasons (Ecology 2004a).

- Looped Bar – caused by sediments being deposited on the leeward side of landmasses located offshore from the mainland. This deposition creates a looped structure around a lagoon, bay, or marsh (Ruotsala 1979).

- Tombolo – created similar to the looped bar, except the depositional ridge connects the offshore landmass to the mainland. Tombolos can range in size from a couple of feet to thousands of feet long (Ruotsala 1979).

- Double Tombolo – two ridges connecting the offshore landmass to the mainland. These features usually form where there is a seasonal shift in shore drift (Ecology 2004a).

- Cuspate Bar – formed by two main sources: the first is the end of a recurved spit eventually extending back to the mainland forming a rounded point (Ruotsala 1979); the second is a tombolo left standing after the offshore structure is eroded away by wave action (Ruotsala 1979). Cuspate bars are characterized by a marshy area in the center of the bar.

- Cuspate Foreland – triangular shaped capes formed by the convergence of two shore drifts (Ecology 2004a).

- Delta – form where streams and rivers deposit sediment at a greater rate than can be eroded by wave action (Ecology 2004a).

- Tidal Flats – gently sloping sandy or muddy beaches, with substrata that may be composed of a mixture of mud (substrata <0.06 mm diameter, usually mixed with organics; Dethier 1990).

Cooper Point between Budd and Eld Inlets provides an example of a sand and gravel beach in Thurston County (see Figure 2-18). Cooper Point is a north trending spit with a relatively gentle east facing slope (approximately 7 percent) and steeper west facing slope (approximately 13 percent) (Figures 2-18a and 2-18c). Cooper Point also provides an example of typical shoreline armoring found along Thurston County shorelines, a vertical concrete bulkhead located at the upper beach and in contact with water surface during higher high tides (Figure 2-18b).

2.5.8 Estuaries

Estuaries are embayments that serve as transition zones between marine and freshwater environments. The largest estuary in Thurston County is the Nisqually River delta at the southern end of the Nisqually Straits. Smaller estuaries are located at the southern end of each of the major inlets in the county. Coastal bluffs are periodically interrupted by topographic embayments where small streams enter Puget Sound to create "pocket estuaries". Examples of pocket estuaries occur throughout Thurston County, such as Gull Harbor on the east side of Budd Inlet, Young Cove on the west side of Eld Inlet, and Big Fish Trap along Dana Passage.

2.5.9 Littoral Sediment Transport

The principal source of energy responsible for moving sediment in the intertidal zone of Puget Sound is waves. This is a small fraction of the energy of ocean waves. In the smaller bodies of water that make up Puget Sound, there is insufficient open water space (fetch) for the wind to build waves to their maximum height (Finlayson and Shipman 2003). Therefore, the largest waves likely to occur in Puget Sound have less than 2 percent of the energy of storm waves on the northeast Pacific Ocean (Downing 1983, Nordstrom 1992).

One of the most fundamental aspects of coastal geomorphology is how wave energy is dissipated along the shoreline. Table 2-4 lists the principal variables influencing beach morphology that are assumed to be influenced by armoring and those that are assumed to remain constant. It is assumed that coastal modifications do not affect the wave energy delivered to a shoreline. Any coastal modification that extends to or below the water surface will have some effect on how wave energy is dissipated along the shoreline. Water surface elevations are assumed to lie beneath extreme high water (EHW).

Southern Puget Sound is fetch limited, which means that there is insufficient open water distance for waves to attain their maximum energy for a given wind speed and duration. Maximum wave energy or fully developed sea requires that both the storm duration and fetch are long enough so that energy being dissipated internally and radiated outward (by waves) is equal to the rate of energy transferred from the wind to the water (Komar 1998). Maximum fetch distances are associated with the north-south alignment of the major inlets in Thurston County (Table 2-5).

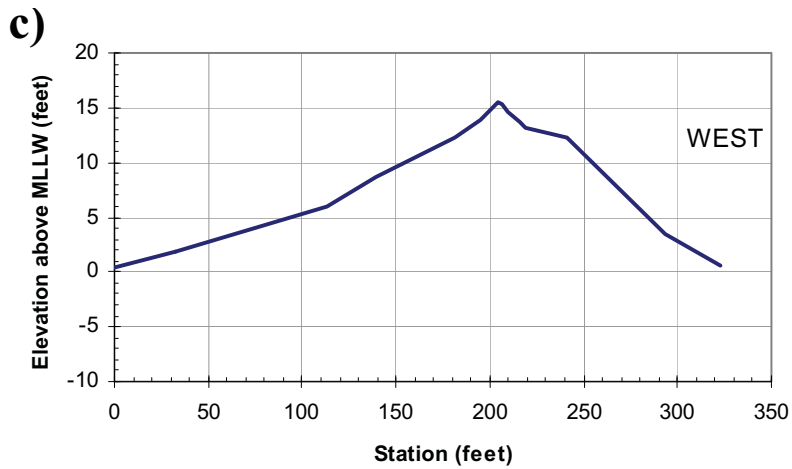


Figure 2-18. Illustration of tidal variation at Cooper Point showing how a typical bulkhead intercepts the water surface only at higher tides. Water elevations in photos are approximately 0.5 feet (a) and 16 feet (b) from MLLW. View is to the south with Budd Inlet to the left and Eld Inlet to the right. Cooper Point is a sand and gravel spit formed by littoral drift moving south out of Budd and Eld Inlets. Beach transect surveyed on June 16, 2003 is presented in (c).

Table 2-4. Principal variables influencing beach morphology that are assumed to remain constant and to be potentially affected by coastal development.

Unaffected Variables (Remain Constant)
Incident wave energy
Material characteristics of geologic units comprising coastal bluffs and hardpan beneath alluvial beach sediments (e.g., stratigraphy, strike and dip, cohesion, grain size distribution).
Potentially Affected Variables
Direct ("Active") Effect of Armoring
Wave energy dissipation factor
Wave reflection coefficient
Indirect ("Passive") Effect of Armoring
Local input rate of sediment to beach, littoral sediment budget

Table 2-5. Approximate fetch distances for Thurston County shorelines (km).

Water Body	N	NE	E	SE	S	SW	W	NW
Totten Inlet	2	n/a	n/a	n/a	n/a	4.5	3.0	1.5
Eld Inlet	3	7[a]	5[b]	2	3.5	4	1.5	1.5
Budd Inlet	15[a]	5.5[c]	2.5	3.5	9.5	3.0	2.5	3.5
Henderson Inlet	16[d]	4[d]	0.9	1.6	5	1.5	1	1
Nisqually Reach	6[d]	8[e]	7	9	5.5	n/a	n/a	16[d]

[a] from Squaxin Passage.
[b] from Dana Passage.
[c] from Peale Passage.
[d] from Case Inlet.
[e] from Drayton Passage.
n/a not applicable.

The inlets and passages of southern Puget Sound are well protected by the surrounding physiography and small fetch distances that rarely exceed 16 km (Table 2-5). The largest waves form during large storms. The most significant storms in Puget Sound occur in the winter and tend to blow from the Pacific around the southern side of the Olympic Peninsula and north-northwest over Puget Sound. The principal summer storms tend to blow from north to south.

Based on the fetch and maximum winds typical in southern Puget Sound of about 50 knots, significant wave heights and periods are unlikely to exceed 1.5 m and 3 seconds, respectively (CERC 1984). Given these wave characteristics, the maximum depth of the littoral zone or seaward limit of on-shore sediment transport is unlikely to exceed 9 m (30 ft) below mean low water; significant transport is unlikely to occur below -15 feet MLLW.

2.5.10 Shoreline Armoring, Wave Energy and Erosion

Numerous documents have suggested a link between armoring (particularly by bulkheads) accelerated beach erosion and the loss of nearshore habitat (e.g., Mulvihill et al. 1980, Thom and

Shreffler 1994, MacDonald et al. 1994, Sobocinski 2003, Williams and Thom 2001, Brennan and Culverwell 2004). Of these documents, Thom et al (1994) summarize biological impacts due to armoring; MacDonald et al. (1994) discuss impacts of shoreline armoring on geological processes and physical features, and Williams et al. (2001) compiles and describes direct impacts, indirect permanent effects, and cumulative effects resulting from shoreline armoring.

The possible effects of shoreline armoring can be summarized as direct or indirect, and include the following:

Direct Effects

1. **Encroachment.** Encroachment involves the placement of bulkheads or other structures on the upper or lower beach instead of at the toe of the bluff. If a bulkhead is originally constructed seaward of the upper limit of the beach below extreme high water (EHW), it immediately narrows the beach causing a habitat loss. Fill and encroachment can sometimes be identified from current or historical photographs.

2. **Active erosion.** Active erosion is a mechanism by which armoring, particularly bulkheading, accelerates beach erosion by reflecting wave energy and amplifying edge waves. This in turn increases sediment suspension and subsequently the rate of sediment removal from the beach. When active erosion is present, the beach loss in front of armoring is greater than background or the natural erosion rate.

Indirect Effects

1. **Passive erosion.** Passive erosion describes the fact that, if armoring is constructed and stabilizes a shoreline undergoing natural retreat (erosion), the armoring precludes the formation of new upper beach habitat. Initial construction of armoring structure leaves the upper beach intact, but over time natural erosion removes beach substrate in front of the structure and eventually the upper beach is lost.

2. **Sediment impoundment**. Sediment impoundment describes the possibility that armoring cuts off the upland supply of sediment to a beach, leading to beach loss. As a bluff erodes, it feeds sediment into the littoral cell. If armoring stops this erosion from occurring, a corresponding quantity of sediment would be missing from the littoral cell. This normally affects the down-drift beaches, by affecting the overall littoral supply, rather than the beach directly in front of the bulkhead.

3. **Shoreline Simplification.** Armoring, particularly a bulkhead, can reduce the physical complexity of the upper beach, such as the loss of wood debris accumulations in the upper beach. Armoring can also be associated

with a significant loss of overhanging shoreline vegetation and wood debris accumulations, thereby reducing shade and the physical complexity of the upper beach.

Figure 2-19 illustrates the first three of these mechanisms: encroachment, active erosion, and passive erosion. All three mechanisms tend to result in narrower and lower beaches in front of armoring compared to unarmored beaches. The relative contribution of the different processes to the total erosion depends on site conditions and the extent of shoreline modifications. Sediment impoundment tends to have a greater effect on beaches located downdrift of an armored beach.

The erosion rate induced by bulkheads can be estimated by comparing adjacent armored and unarmored beaches. The retreat distance is approximately that distance by which the armored beach has narrowed compared to the unarmored beach.

The concept that bulkheads and other armoring can steepen and coarsen beach due to their interactions with waves is long-established, although most studies have focused on high-energy, open-coast environments rather than protected areas with low wave energy such as the Puget Sound. For example, the Shore Protection Manual (CERC 1984) states the following:

> *The use of vertical- or nearly vertical-face wall can result in severe scouring when the toe or base of the wall is in shallow water. Waves breaking against a wall deflect energy both upward and downward. The downward breaking component causes scouring of the material at the base of the wall. To prevent scouring, protection should be provided at the base of the wall… Vertical walls also reflect energy back offshore where resonant effects may cause beach profile changes.*

The more recent Coastal Engineering Manual (USACE 2002) makes a similar statement:

> *However, erosion of the seabed immediately in front of the structure will in most cases be enhanced due to increased wave reflection caused by the seawall. This results in a steeper seabed profile, which subsequently allows larger waves to reach the structure.*

However, field evidence of the steepening of shoreline profiles due to wave interactions has been elusive. A recent literature review (Kraus and McDougal 1996) reaches the following conclusions:

1. *Reflection is probably not a significant contributor to beach profile change or to scour in front of seawalls, at least for the duration of a storm…*

2. *If the beach profile is close to its equilibrium shape, then the arrival of a storm may not change the profile greatly (or cause erosion)…*

3. *Scour does not necessarily occur at seawalls…*

4. *During storms, the beach profile in front of a wall retains about the same amount of sand (has about the same general shape) as a beach without a wall…*

5. *Sediment can move alongshore past a seawall…*

6. *Small-scale physical model results are likely to be misleading and should be considered as yielding qualitative information at best and completely erroneous information at worst…*

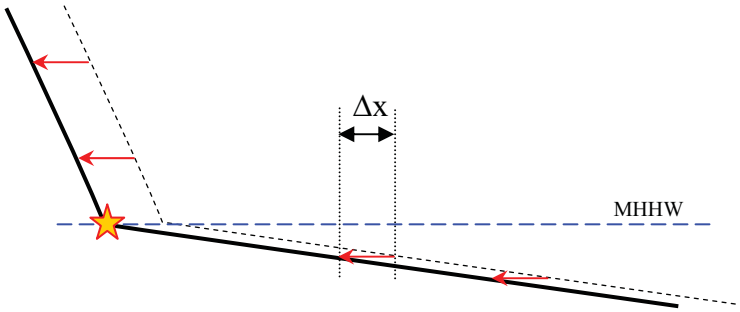
Similar statements are made by Wiegel (2002). An additional point is that, generally, a vertical seawall has a smaller footprint than a revetment. The California Coastal Commission, which enforces the California Coastal Act including limitations on the construction of seawalls and revetments, now generally prefers vertical seawalls to revetments for this reason (Ewing 2004 personal communication). However, these modifications apply to different environments involving much larger beaches and littoral systems than found in Puget Sound.

There is field evidence of end effects at seawalls that extend seaward of the surrounding bluff face (Griggs and Tait 1989). However, the only clear evidence of the effects of seawalls found by Griggs was that there was accelerated scour at the base of seawalls during storms, and that recovery from scour was, if anything, more rapid on the seawall-back beach. Recovery in the environments studied by Griggs and Tait (1989) may be possible because of a wide littoral zone, large sediment supply, and minimal sediment loss to deep offshore areas. In contrast, Puget Sound beaches have narrow littoral zones and are prone to sediment loss to deep offshore areas. Hence, the effect that active erosion may have in Puget Sound beaches is of greater concern.

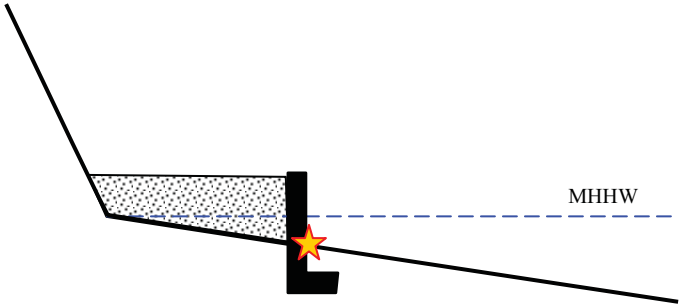
This controversy relating to the one process of active erosion does not call into doubt the main point that as a result of some combination of these different processes, over time a wide, fine sediment (sandy and small gravel) beach can be transformed into a narrow beach of large gravel or cobbles, and may even be reduced to a hard clay layer (hardpan). The upper limit of the beach can be lowered such that the entire beach is under water for a portion of the tidal cycle. These impacts can degrade or eliminate spawning areas for surf smelt, Pacific sand lance, and herring may be lost due to removal of fine sediments from the intertidal zone. In addition, bulkheads can degrade the nearshore habitats that provide protection and food for many benthic feeding fish, including salmon (Thom et al. 1994; Williams and Thom 2001; Brennan and Culverwell 2004).

An example of significant beach loss adjacent to bulkheads in Puget Sound is given by MacDonald et al. (1994). At Lincoln Park (Seattle, Washington), the beach lowered, narrowed, and hardened dramatically in the 10-20 years following construction of the bulkhead (Figure 2-20).

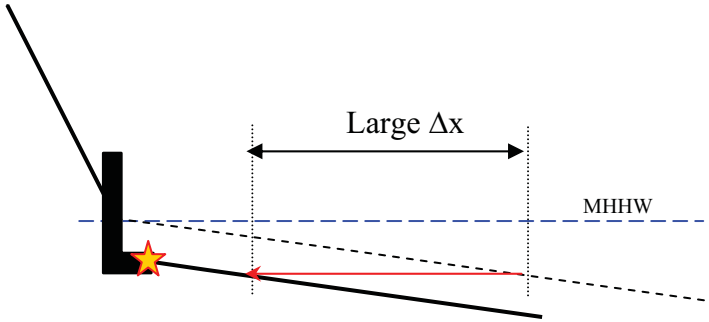
Natural erosion of beach profile. The beach retreats a distance Δx due to sediment deficit, but its overall shape is unchanged and no upper beach habitat is lost.



Encroachment. The upper beach habitat is immediately lost when a bulkhead or other armoring is constructed to retain fill.



Active Erosion. A bulkhead can accelerate erosion of beach by increasing wave energy. This leads to a greater rate of beach retreat, together with all the impacts of passive erosion on upper beach habitat



Passive Erosion: A naturally eroding beach retreats a distance Δx due to sediment deficit, as in the first case. However, the back of the beach is fixed, so upper beach habitat is lost and the beach becomes narrower.

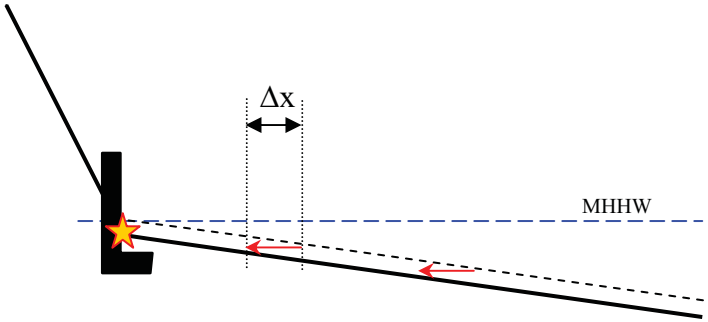


Figure 2-19. Comparison of the behavior of an eroding unarmored beach with the behavior of an armored beach subject to the effects of encroachment, active erosion, and passive erosion. Broken line: initial beach profile. Solid line: final beach profile. Star: illustrates the final elevation at the back of the beach.

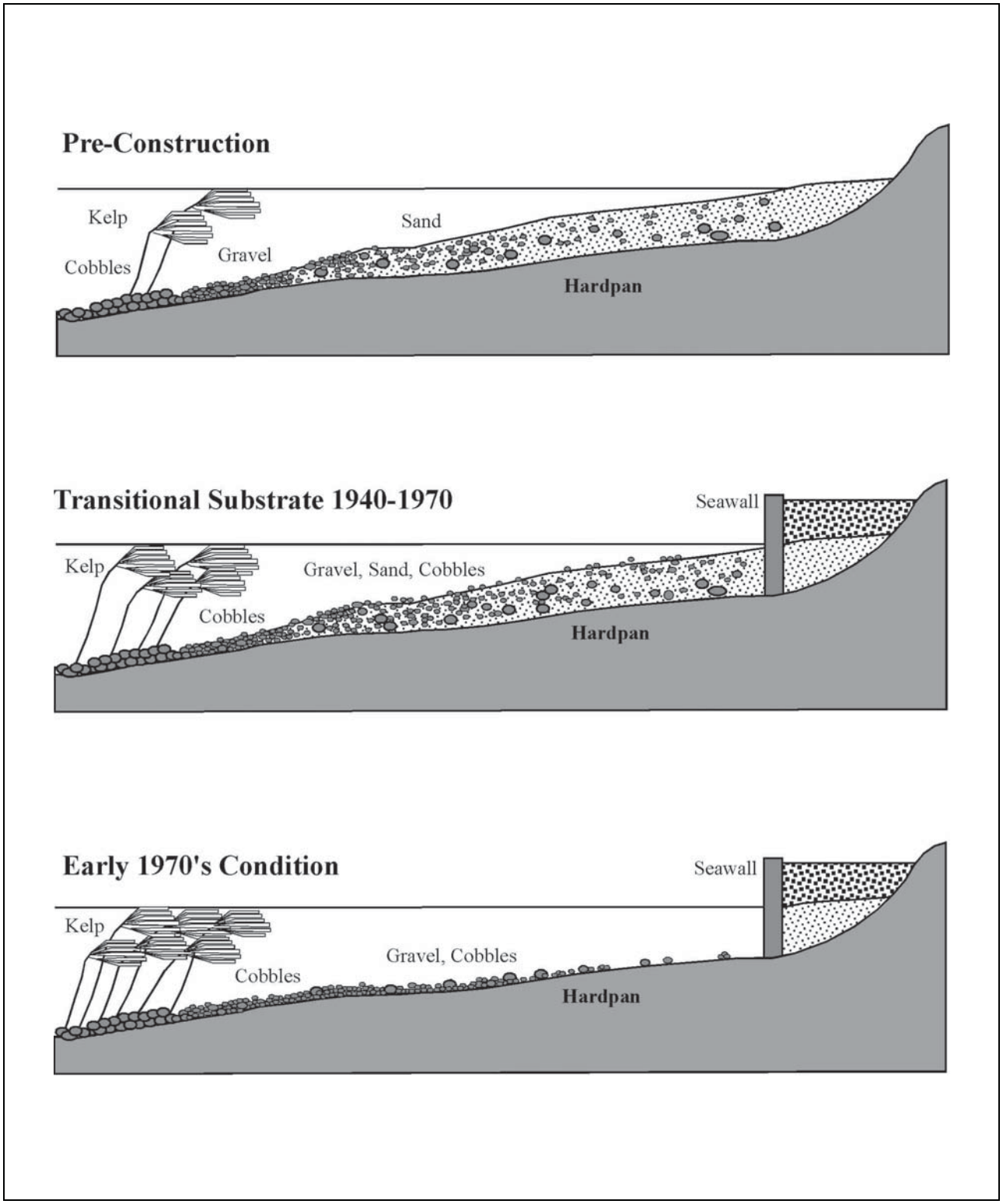


Figure 2-20. Observed changes at Lincoln Park (Seattle) attributed to construction of a bulkhead that encroached on the upper beach.
Thom et al. 1994.

CHAPTER 3

Methods

3.0 Methods

3.1 Introduction

An essential part of this study was the development of a sampling protocol for this marine shoreline sediment survey and assessment (Herrera 2003). The sampling protocol was developed in coordination with the Thurston Regional Planning Council, and was reviewed by the Thurston County Nearshore Technical Committee. The methodology used in this study, and presented in this chapter, is consistent with the sampling protocol (Herrera 2003).

This study consisted of two general approaches: 1) a GIS analysis of existing aerial photographs and digital elevation data to identify sediment sources and sinks, impacts of bulkheads on upper beach areas, and long-term erosion and aggradation trends on the Thurston County shoreline; and 2) field surveys of representative beach profiles to document and categorize the various geomorphic beach characteristics present, to identify the effect of bulkheads on sediment characteristics and erosion, and to aid in identification of sediment sources and sinks.

The major field phase of the study was performed between August 25 and August 28, 2003. In addition, field verification of beach profile data and interpretation of aerial photograph and digital elevation data was performed at representative beach sites in September, 2003.

3.2 GIS Study Elements

The GIS and background information analysis of this study included the following elements:

1. Identification and analysis of existing information and data gaps
2. Mapping of recent and historical mass wasting areas (including spatial extent and estimated date of occurrence)
3. Mapping of large-scale historical shoreline changes, bathymetry changes, and artificial shoreline alterations (i.e., beach erosion or accretion, bulkhead intrusion, and artificial fill)
4. Mapping of structures including boat launch ramps and outfalls that block alongshore sediment transport
5. Digitization of the shoreline geology and stratigraphy from the Washington Department of Ecology's *Coastal Zone Atlas of Washington* (Ecology 1980)

6. Delineation and description of areas to consider for preserving and rehabilitating ecological functions and habitat.

3.2.1 Analysis of Existing Information

The following sources were reviewed in compiling existing information:

- U.S. Army Corps of Engineers historical aerial photographs (USACE 1944)
- Recent orthorectified vertical aerial photographs from Thurston GeoData Center (2000)
- Oblique aerial photographs from Washington Department of Ecology (Ecology 1976–1997, 1992, 2000)
- Historical hydrographic surveys from the National Oceanic and Atmospheric Administration, National Ocean Service (U.S. Coast Survey 1855, 1873–4, 1878–9; U.S. Coast & Geodetic Survey 1913, 1936)
- Drift cells mapped by Schwartz and Hatfield (1982) for Washington Department of Ecology
- Bathymetry data from National Oceanic and Atmospheric Administration for various dates
- Thurston Regional Planning Council GIS map layers associated with Thurston County's marine shoreline
- Washington State ShoreZone Inventory GIS map layers from Washington Department of Natural Resources, Nearshore Habitat Program (WDNR 2001)
- Washington Department of Ecology's *Coastal Zone Atlas of Washington* (Ecology 1980)
- Oakland Bay Hammersley Inlet Nearshore Assessment (Anchor Environmental 2002)
- Channel Erosion Along the Deschutes River (Collins 1994)
- Capitol Lake Adaptive Management Plan (TRPC 2002)
- Geologic maps of the Thurston County shoreline from Washington Department of Natural Resources, Division of Geology and Earth Resources (WDNR 2003a, 2003b, 2003c, 2003d, 2003e, and 2004).

3.2.2 Identification, GIS Mapping, and Assessment of Historical and Recent Sediment Sources

In order to assess historical shoreline changes (i.e., beach erosion and accretion), historical sites delivering sediment to the marine shoreline of Thurston County were identified and mapped, including sites of mass wasting (i.e., bluffs with shallow surficial erosion and deep seated landslides), and stream and river outlets. All GIS mapping was correlated with Washington State ShoreZone Inventory (WDNR 2001) units to facilitate cross-referencing of existing information with the results of this study. Coastal mapping was based on a digital elevation model (DEM) with six foot pixels created with lidar (light detection and ranging), historical and recent rectified aerial photographs, and aerial oblique shoreline photographs available from Washington Department of Ecology for 1976–1977, 1992, and 2000. Sediment delivery sites were mapped as GIS shapefiles.

3.2.3 Rivers and Streams

Watershed areas were estimated from a number of sources, including Lombardo et al. (2003) (total watershed area for Totten and Eld Inlets), Golder Associates (2003) (sub-watershed areas for WRIA 14, including Totten Inlet and the western side of Eld Inlet), Tabbutt (2001) (watershed areas for creeks throughout Thurston County), Thurston County (2002) (watershed areas for the different inlets, limited to the areas actually within Thurston County), Ecology (2004b) (watershed areas for the Nisqually and Deschutes Rivers), and Watershed Professionals Network et al. (2002) (watershed area for McAllister Creek). River and stream outfalls in Puget Sound are typically coincident with deltas of fluvial sediments. Stream deltas and delta-like areas were mapped as points. These were identified as areas of fan shaped beaches (in plan form). These areas could be true stream deltas or delta-like areas at the confluence of two drift cells. Three stream deltas were surveyed in the field to help assess the relative importance of fluvial sediment supply in the littoral sediment budget. The following elements also were noted:

- Presence/absence of culverts
- Locations of culvert outfalls
- Locations and widths of stream mouths.

3.2.4 Mass Wasting

Puget Sound beaches are commonly set against steep, forested hillslopes composed of relatively unstable glacial sediments. Feeder bluffs are hillslopes that contribute sediment to the shoreline either through chronic surficial erosion or through periodic landsliding. Vegetation and topographic relief provide a means of identifying feeder bluffs and can be integrated into a basic protocol for classifying coastal hillslopes.

Landslide areas were mapped as polygons in a GIS shapefile in order to quantify the extent of landslides on the shoreline of each inlet. The following information was collected for each polygon:

- Landslide occurrence and approximate age (i.e., less than 2, 3–5, 5–10, and more than 10 years old) based on visual estimation of vegetation age and, where applicable, woody debris age
- Whether a slide contributed wood debris
- Whether the area was actively eroding.

These polygons were used to estimate the relative contribution of feeder bluffs in the littoral sediment budget for Thurston County marine shorelines. The areas of all landslide polygons were recorded and were summarized by inlet.

Initially, landslide sites in Budd Inlet were identified on oblique photos and verified from a boat while in the field in June 2003. Landslides identified in the field were compared to aerial and oblique photography from the year 2000 and four lidar-derived hillshade from 2002 to identify characteristics that could aid in identification and delineation of landslide sites. The DEM (digital elevation model) was examined using different hillshade layers of the DEM with incident light coming from the NW, NE, SE, and SW to refine the accuracy of landslide mapping. Exposed soil, trees on the beach that are perpendicular to the shoreline, accumulations of sediment at the base of hillsides on aerial photographs, and hummocky areas on shaded relief images were identified as typical characteristics of areas that were eroding or had experienced landsliding. Using this information, landslides and eroding areas along the Thurston County coastline were digitized at a resolution of approximately 1:1000 to 1:1500.

Landslides were initially mapped from the DEM and aerial photos, were then checked for consistency and were then spot checked in the field.

Landslides that were not easily identified on photographic coverage, but could be identified by scallop shapes in the hillshade layers were estimated to be over 10 years old and were digitized in a separate file. These are difficult to identify because no soil is typically visible in the aerial photos.

Landslides digitized in this study were compared to those shown on available Washington Department of Natural Resources geologic maps as landslide deposits (WDNR 2003a, 2003b, 2003c, 2003d, 2003e, 2004a). A subset of landslides were not compared to these maps because the Summit Lake geologic map was not published in time to be included in this analysis. WDNR only recorded landslides in areas where the landslide obscures the underlying geology and consequently did not map many smaller landslides which were observed and mapped in this study.

3.2.5 Historic Shoreline Change

Historical vertical aerial photographs (USACE 1944) were georeferenced for comparison with recent aerial photography (Thurston GeoData Center 2000) to identify long term trends in

erosion and accretion. Given the relatively low rates of shoreline change in this area, it was unlikely that this would provide detailed information regarding the overall erosion or accretion rates. However, it provided the opportunity to identify any major historic changes which would be extremely important, if present.

3.2.6 Historic Bathymetric and Shoreline Surveys

Historic bathymetric and shoreline surveys (U.S. Coast & Geodetic Survey 1936) were georeferenced for comparison with four bathymetry transects measured in the field to identify whether or not inlets are a sediment sink, and for a comparison with shorelines visible in recent aerial photography to search for large-scale accretion or erosion of shorelines (Thurston GeoData Center 2000). Earlier surveys (U.S. Coast Survey 1878-9) were also examined. As with the analysis of historical aerial photographs, this was an investigation that had a low probability of providing new information, but if it did provide new information, this would be extremely significant.

Inlet bathymetric cross-sections were developed using a 30 meter digital elevation model (DEM) of Puget Sound (Finlayson et al. 2000) (Appendix C). Bathymetry cross section measurements were overlaid onto 1936 hydrographic surveys (Coast and Geodetic Survey 1936).

3.2.7 Artificial Shoreline Alterations

Estimated natural shoreline data were used to assess forage fish spawning habitat area that has been lost due to the construction of bulkheads. The natural shoreline, or the approximate shoreline that would have existed without bulkhead intrusion on beaches, was mapped by modifying a Thurston County GIS shapefile in areas where bulkheads have been built on beaches. TRPC created the shoreline boundary of the county border GIS shapefile using Thurston GeoData Center (2000)'s aerial photo set. This GIS shapefile was copied and the shoreline was modified to correspond to the estimated natural shoreline in all areas where bulkheads encroached. Bulkhead-free areas and slope break were used as a guide. Modifying the shoreline was not possible in the Olympia area, where the high level of development and filling makes the natural shoreline difficult to discern. A copy of the original Thurston County GIS shapefile was used with the modified, natural shoreline polygon to identify areas where bulkheads are built on natural shoreline. Areas of the resulting polygons were calculated and summarized by inlet to assess inlet-wide effects on forage fish spawning habitat.

3.2.8 Blocking Structures

Structures that block sediment transport along drift cells were digitized using vertical and oblique aerial photographs (Thurston GeoData Center 2000; Ecology 2000). Drift blocking structures were only digitized for non-permeable structures such as rock groins or causeways and not for pile-elevated docks. These structures typically jut out onto the upper beach at a 90 degree

angle to the shoreline. Structures were delineated along the centerline of the structure following a line from the upper beach area to the end of the structure.

3.2.9 Identification of Preservation and Restoration Sites

Using key geomorphologic features that were found in this study to affect sediment and upper beach habitat, preservation and restoration areas were delineated in GIS. General preservation and restoration areas were delineated using field observations, aerial photos, lidar, and ground photos to identify factors that can affect the quality and quantity of forage fish spawning habitat. In addition to general preservation areas, specific preservation and restoration locations were selected for features that are uniquely important to maintaining and improving habitat.

3.3 Characterization of Drift Cells

A drift cell is a reach of the marine shoreline within which sediment erosion, deposition, and transport occur. The different drift cells on a marine shoreline are normally considered independent of each other, i.e., all the sediment sourced within a particular drift cell remains within that drift cell, unless it is lost offshore. Thus, drift cells define nearshore areas of influence based on the sources and sinks of material transported alongshore. Drift cells develop due to local wind-generated waves combined with local bathymetry and geomorphology.

The division of a marine shoreline into drift cells can be an oversimplification because, in some cases, there is a small amount of interchange of sediment between drift cells. However, the division of the shoreline into drift cells is a critical tool for shoreline analysis and management in Puget Sound. For the present study, the following sources were used to characterize drift cells:

- Washington Department of Ecology's *Coastal Zone Atlas of Washington* (Ecology 1980)
- Net shore-drift mapping by Schwartz and Hatfield (1982)
- Thurston Regional Planning Council GIS map layers associated with Thurston County's marine shoreline (TRPC 2003a).

For the purpose of estimating the sediment budget, potential transport rates within drift cells reported in the *Coastal Zone Atlas of Washington* (Ecology 1980) were used as a basis for estimating the upper limits of the transport rates out of the major inlets of Thurston County. For all other purposes, including selecting sites for field measurements, the mapping in Schwartz and Hatfield (1982) was used. (This mapping was also used as a basis for the TRPC GIS layers). This later mapping could not be used to estimate transport rates because it provides no quantitative estimates of transport rates.

For the purpose of planning the beach survey, beach sampling sites were selected in larger drift cells representative of a shoreline. During the field effort, the drift direction at each sampling site was confirmed based on geomorphic features of the shoreline and other field indicators. Field observations of net shore-drift indicators included sediment accumulations up-drift of woody debris, groins, pipes, or other barriers to littoral sediment transport.

Figure 3-1 illustrates the major drift cells in Thurston County.

3.4 Sediment Budget Development Methodology

Within the littoral environment, if more sand is transported away from a beach than toward that beach, erosion results. A sediment budget is a way of quantifying this observation by identifying each process by which sediment enters or leaves an area, quantifying the volume of sediment corresponding to each process, and checking that the results are in balance. A sediment budget is generally expressed in an equation:

$$S_i = S_o + S_s$$

where S_i = quantity of sediment input to the littoral zone, S_o = quantity of sediment output from the littoral zone, and S_s = quantity of sediment stored in the littoral zone. Figure 3-2 is a conceptual illustration of the sources and sinks that are typically identified in a sediment budget. In this figure, beach accretion represents an increase in the quantity of sediment stored in the site; other processes are considered as inputs or outputs.

The first step in preparing a sediment budget is to divide the shoreline of interest into essentially independent cells, or areas whose inputs, outputs, and transport can be investigated independently. Ideally, a sediment budget would be developed for each drift cell of interest. However, the data needed to do this was not available at a sufficient level of geographic detail. Based on the availability of information, the present study developed a sediment budget for each individual inlet and reach: Totten Inlet, Squaxin Passage, Eld Inlet, Budd Inlet, Dana Passage, Henderson Inlet, and the Nisqually Reach. Each sediment budget presented in this report is effectively a sum over the sediment budgets for all of the drift cells within the inlet or reach considered. No exchange of sediment between inlets was considered.

The second step is to identify the different inputs, outputs, and storage areas or reservoirs. The sediment inputs considered were fluvial sources and landslides (this includes identifiable bluff erosion events). The sediment outputs considered were alongshore flow out of the inlets and into the deep channels to the north of the Thurston County shoreline and offshore transport into deep water within the inlets. Only one reservoir was considered, the beaches and nearshore. However, the change in storage was divided into two categories: decreases in storage identified through beach erosion, and increases in storage in response to sea level rise. Sea level rise effectively increases the storage in an otherwise stable beach because that beach would actually have to accrete, i.e., become higher, to keep up with the rising sea level and so maintain the same width and elevations relative to the sea.

These inputs, outputs, and reservoirs are described further in Section 4. As described there, each item was estimated based on some combination of the existing literature, the GIS study, and fieldwork.

The study did not attempt to calculate the rate of beach erosion by evaluating all inputs and outputs to the system and taking the difference. Because both the sediment inputs and outputs are large and only approximately known, such an approach would lead to huge errors. Rather, the sediment budget was used as a framework in which the different sediment sources and transport processes could be evaluated as either "large" (and, therefore, important for management of the system) or "small" (and not important for sediment supply).

3.4.1 Selection of Areas for Sediment Budget Analysis

A major decision in regard to the sediment budget for Thurston County was whether the sediment budget should be developed by drift cell, by inlets, or for the whole of Thurston County. Ideally, the sediment budget should be constructed by drift cell because these are largely independent of one another. However, the necessary information for this could not be obtained with a sufficient level of geographic detail.

The drift cells compiled by Schwartz and Hatfield (1982) suggest that the inlets can generally be defined in isolation. With one exception, the drift direction in the northern one-quarter (or more) of each inlet, on both sides, is to the north and out of the inlet. The only exception is the western side of Henderson Inlet, where the only significant identified drift is into the inlet, near the mouth (see Figure 3-1).

3.5 Field Study Elements

The field phase of the study included the following elements which are listed below and discussed in detail:

1. Beach Sampling Site Selection Criteria
2. Beach Sampling Protocol
3. Beach Transect Sampling
4. Additional Parameter Sampling
5. Identification and Prioritization of Potential Preservation and Restoration Sites
6. Data Compilation and Management.

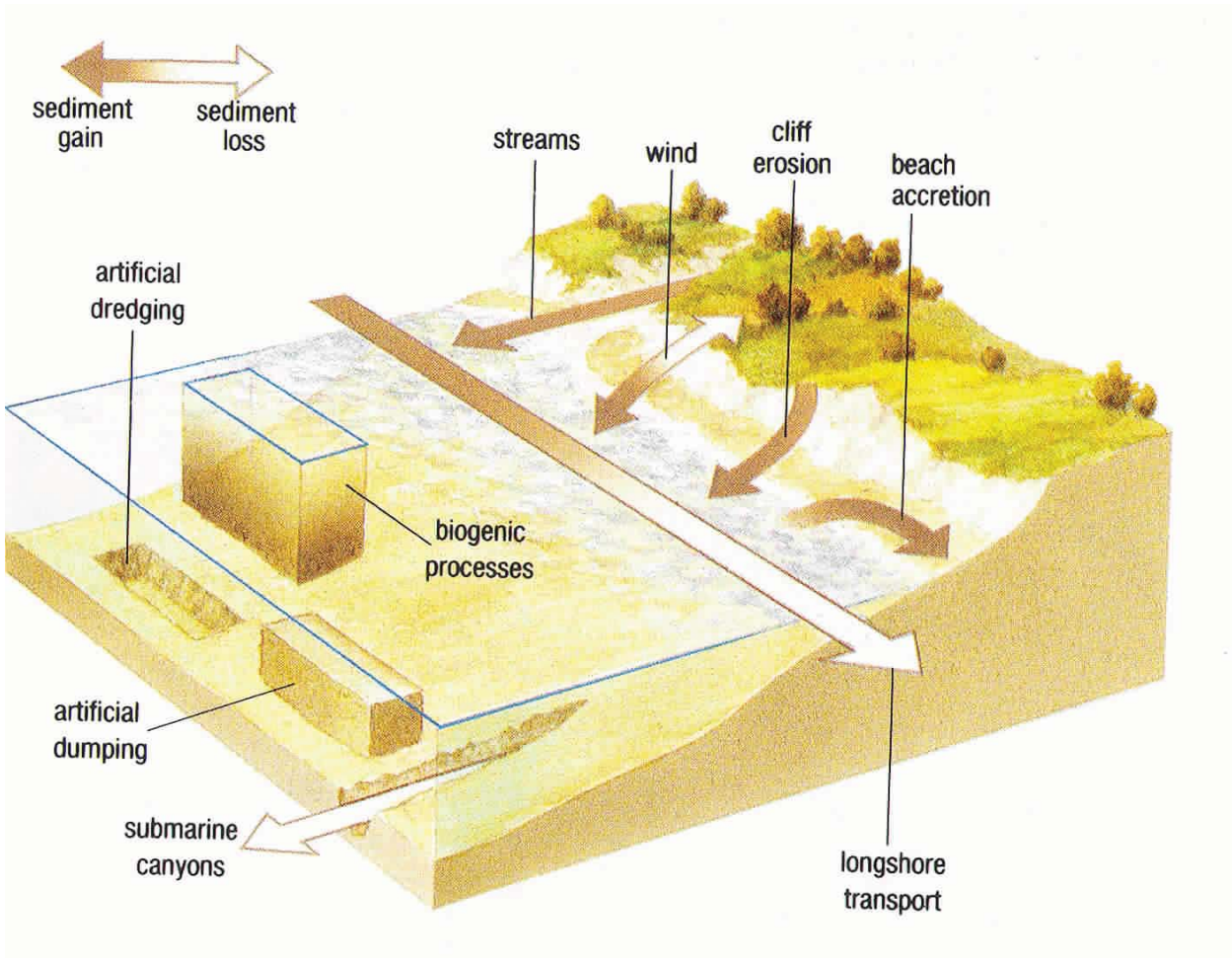


Figure 3-2. Conceptual illustration of littoral zone sediment budget.
From Brown et al. (1989).

3.5.1 Beach Sampling Site Selection Criteria

Site selection for the project field survey was based on: results of the evaluation of existing information; an analysis of historical change; principal sources of sediment delivery to marine shorelines; nearshore processes; data gaps; and results of the field reconnaissance conducted on June 16, 2003.

In order to sample a representative range of marine shoreline conditions within Thurston County, 29 paired beach sampling sites (a total of 58 beach transects) were selected. The selected beaches were distributed along Totten Inlet, Eld Inlet, Budd Inlet, and Henderson Inlet, as well as on Squaxin Passage, Dana Passage, and the Nisqually reach (Figure 3-3). Note that areas shown as armored shoreline include concrete bulkheads, rock revetments, placed logs, and, in the Nisqually delta, dikes. The majority of shoreline armoring is concrete bulkheads.

To the extent possible, each pair of beach sampling locations had one transect located in front of a bulkhead or other shoreline armoring and the other transect located on an unarmored shoreline without any manmade structures. This sampling approach allowed for comparative analysis such as parametric or nonparametric statistical analysis of paired samples, facilitating direct measurement of localized impacts of bulkheads.

The criteria for beach sampling site selection, based on comparability between pairs, included the following:

- Location in the same drift cell
- Location on a beach with a similar aspect
- Similar geology
- Location at the base of a hill with similar hillslope and bluff relief
- No recent landslide activity nearby
- At least 250 feet of separation between unarmored and armored beach
- Minimum beach length of 500 feet, where possible
- Absence of significant natural or manmade features protruding into the water between the beach site pair.

In addition to the 29 paired beach sampling sites, three beach sites were surveyed at stream delta or drift cell confluences to determine accretion characteristics at these discrete sites and to assess the relative importance of fluvial inputs from small streams. At each delta or drift cell confluence site, a transect parallel to the shoreline was surveyed. The delta profile from a transect of the beach was recorded, and the median surface grain size was measured.

3.5.2 Beach Transect Sampling

All beach transects were laid out perpendicular to the shoreline and extended from the slope toe or bulkhead to the water. To the extent possible, paired transect data were collected during low tide conditions; the beach delta and landslide samples could be collected during mid-tide conditions. The parameters recorded at each transect are detailed in the following subsections.

Field sampling was consistent with general guidelines for marine nearshore investigations (Simenstad et al. 1991; Ruotsala 1979).

Site: Location (GPS) and Time

The location of each transect was recorded using a Trimble® global positioning system (GPS) unit (resolution +/- 6 – 16 feet). The time of sample collection was recorded to determine the tidal elevation. Accuracy of readings was typically within 6 to 15 feet after differential correction. Transect measurements were recorded and stored in the handheld Trimble GPS unit. The transect data were downloaded into a spreadsheet after field work was completed.

Beach Profile

Beach profiles were measured for assessment of beach erosion and accretion. A minimum of four geographical locations were measured for each transect using an Impulse 200® rangefinder. Survey locations were recorded at slope breaks and at changes in sediment characteristics. (The instrument measures distances of 500+ meters with an accuracy of 3 centimeters at 50 meters, and measures angles with an accuracy of 0.1 degrees.)

Beach Sediment Characteristics

Beach sediment grain size was characterized visually along each transect using the sediment classifications in Table 3-1. Additionally, occurrence of hardpan and beach surface coarsening (i.e., a thin layer of coarse sediment over finer sediment) was noted to identify evidence of beach erosion. Beach sediment characteristics were noted at each point along the transects where the sediment characteristics change significantly (e.g., grain size changes by 50 percent or more). These data were used during the assessment of beach coarsening in relation to the presence of bulkheads. Photos of various representative beach sediment classes are provided in Appendix F.

Table 3-1. Grain size classes used to classify sediment types.

Class	Size Range (diameter)
Boulder	> 256 mm
Cobble	64 - 256 mm
Gravel	2 - 64 mm
Sand	0.0625 - 2 mm
Silt	0.002 - 0.0625 mm
Clay	< 0.002 mm

Characteristics of the Upper Beach Area

The nature of the upper beach area was classified as unarmored, bulkhead, riprap, artificially placed logs, or other. The location of the upper beach was defined as the furthest inland point of the transect.

Beach Shade Cover

To better characterize the existing forage fish spawning habitat conditions in relation to the actual habitat utilization and to shoreline modification, canopy cover at each beach site was recorded (as shade available or shade unavailable).

Locations and Quantities of Driftwood

The locations and quantity of driftwood at each beach transect were noted and recorded at the following level of detail:

- The width of beach over which logs extend
- Basal diameter of the 10 logs closest to the transect
- General orientation of logs (0, 30, 60, or 90 degrees to the beach)
- Length of beach over which the 10 measured logs extend
- Presence and size of barnacles on the logs
- Total length of beach with similar conditions extending in either direction from the transect line.

This information was also used for the general characterization of forage fish spawning habitat conditions in relation to the degree of shoreline modification.

Barnacle, Mussel, and Shell Fragment Sizes and Locations

Barnacle and mussel distribution and size were characterized visually along each transect to establish the zone in which they occur in relation to beach width and substrate type. These organisms were used as biological (indirect) indicators of the sediment beach disturbance regime. In addition, when present, the shell fragment zone was noted and recorded in relation to the beach cross-section along each transect. These data were used as supporting evidence regarding predictions about beach erosion or accretion.

Exposure of Beach Platform Below Beach Sediment

Areas with beach platform exposure (bedrock/glacial deposits underlying beach sediment) were visually characterized along each transect. This information was used as supporting evidence regarding predictions about beach erosion or accretion.

Beach Erosion or Accretion

In addition to the indirect field indicators of erosion and accretion described above, direct evidence of beach sediment erosion and accretion were noted and recorded at each beach sampling site. The degree of erosion and/or accretion was measured at bulkheads to determine erosion and accretion rates based on available installation date records for specific structures. All of these indicators of erosion and accretion were used to help confirm the historical

photographic analysis. In addition, other indirect visual indicators such as scarps and spits were characterized and recorded (using free-text description and photographs).

Shore-Drift Direction

Field indicators of shore-drift direction included spits and sediment accumulation on groins, deposited wood, jetties, and other features located perpendicular to the shoreline. This was used as confirmation of the previous drift cell mapping by Schwartz and Hatfield (1982).

Upland Condition

The upland was characterized as having one of the following conditions: forested, mature or immature; natural pasture; landscaped (ground cover only); or impervious (low- or high-density development). This information was used in an assessment of the degree to which general upland modifications may influence sediment recruitment within the context of the reduction or elimination of landslide potential.

3.5.3 Statistical Data Analysis

Statistical analyses were performed to compare habitat and geomorphic attributes for unarmored and armored beaches that were paired together. For attributes that are measured on a continuous scale, the data for paired beaches were compared using a Wilcoxon paired-sample test (Zar 1984). The Wilcoxon paired-sample test is a nonparametric analogue to the paired t-test. Through the use of a paired test, variability or noise in the data between the unpaired beaches was blocked out of the analysis. In this way, differences between the paired unarmored and armored beaches were more readily detected. A nonparametric test was used in this analysis because the data did not always meet the required assumptions for using a parametric test (e.g., normality of paired differences). The specific beach attributes that were tested using this approach were total beach width, total width of habitat, beach slope, percent of beach showing beach surface coarsening, and height of top of beach. In all cases, statistical significance in these tests was assessed at an alpha (α) level of 0.05.

The width of beach between MTL and MHHW was calculated from MTL to the lower of: MHHW and the top of the beach at the base of the hillslope (unarmored sites) or; the base of the bulkhead or other structure (armored sites). The width of spawning habitat was estimated by evaluating the beach width between MHHW and MTL, and subdividing that portion of the beach according to the dominant substrate type (cobble, gravel, sand, fines [silt and clay], or other such as shells). See Appendix F for photos of these representative sediment types. It was assumed that spawning habitat exists where sand and gravel substrate was present in this elevation range. Beach slope was evaluated from the beach width between MHHW and MTL and the elevation change between these datums. The width of the beach that shows beach surface coarsening between MTL and MHHW was estimated in a similar way.

For data that were collected on a nominal scale (i.e., presence or absence), the data from paired beaches were compared using the McNemar's test (Zar 1984). Like the Wilcoxon paired-sample

test described above, the McNemar's test also blocks out variability or noise in the data from unpaired beaches so that differences between the paired unarmored and armored beaches can be more readily detected. The McNemar's test evaluates whether a particular attribute is present in the same proportion at both the unarmored and armored beaches. The specific beach attributes that were tested using this approach were presence/absence of beach surface coarsening, presence/absence of beach platform exposure, presence/absence of barnacles, and presence/absence of shade. In all cases, statistical significance in these tests was assessed at an alpha (α) level of 0.05.

Effects of Armoring on Beach Characteristics

To identify the impact of surrounding bulkheads, armored transects were sorted into four groups based on the percentage of beach that is armored (0-25 percent, 26-50 percent, 51-75 percent, and 76-100 percent) within 300 feet in either direction of the transect location. For each grouping, the number of transects where the top of the beach was near (within 1 foot) or below MHW was recorded. Also, the percentage of armored transects that were more than 1 foot lower than their paired unarmored transect across the uppermost 50 feet of beach (example: Appendix D-7) was recorded for each grouping. Unarmored transects were also sorted into four groups. For each grouping, the number of transects with the top of the beach near (within 1 foot) or below MHW was recorded. The number of transects that were more than 1 foot above their paired transect was also recorded.

3.5.4 Additional Parameter Sampling

Bathymetric Measurements

Bathymetric measurements were performed at four locations in Budd Inlet and Eld Inlet. One transect (including six to ten measurements) was established across each inlet near the mouth. These measurements were collected using the GPS and depth sounder instruments. The horizontal accuracy of the measurements was approximately 20 feet, as determined from the standard deviation of the GPS measurements and dominated by the drift of the vessel; the vertical accuracy was approximately 1 foot, as determined from previous comparisons between this and more accurate bottom-mounted depth sounders.

The results were compared with measurements from the 1936 hydrographic surveys (U.S. Coast & Geodetic Survey 1936). Given the limited accuracy of the depth sounder instrument used in that sediment study, it was not anticipated that any significant differences between the 1936 measurements and the new measurements would be identified. However, a limited investigation of potential changes in the bathymetry was considered important because if there were any major changes, they would have a very large impact on the overall sediment budget for the inlets.

The data density from earlier datasets (U.S. Coast Survey 1873-1874 and 1878-1879) was too low for a meaningful comparison of the bathymetry, and therefore these surveys were not georeferenced.

Inlet Cross-Sections

Inlet cross-sections were prepared using ESRI Spatial Analyst from a 30 meter digital elevation model (DEM) of the topography and bathymetry of Puget Sound (Finlayson et al. 2000). The vertical datum of the cross-sections is NGVD29 (which is equivalent to mean sea level). The dataset contains some inherent inaccuracies due to the difficulties of combining terrestrial and marine topography datasets and due to low topographic resolution within Puget Sound.

Stream Delta Measurements

Additional measurements were collected at three sites corresponding to apparent stream delta locations. At each delta site, a separate transect parallel to the shoreline was surveyed across the stream at approximately the mean tide elevation. The surface grain size at each measurement location was also recorded. This set of measurements was used to assess the relative importance of the fluvial sediment supply from small streams that drain to the Thurston County marine shoreline.

Mass Wasting Characteristics (landslide dimensions)

Based on the information gathered during the GIS analysis, the data related to mass wasting sediment inputs were field-verified. Field surveys were used to estimate the depths of typical landslides, for calculations of landslide volumes from GIS-delineated landslide areas. Mass wasting measurements were made at predetermined sets randomly selected from the GIS-delineated landslide areas.

3.5.5 Identification and Prioritization of Potential Preservation and Restoration Sites

The project team conducted field beach identification, confirmation, and documentation of potential preservation and restoration sites identified during the preliminary survey of available information.

3.5.6 Data Compilation and Management

Field survey data were compiled for inclusion in an electronic data dictionary and (when applicable) in a GIS database. All GIS mapping was correlated with Washington State ShoreZone Inventory (WDNR 2001) units to facilitate cross-referencing and management of existing information with the results of this study. Selected products of the GIS analyses and field work were delivered electronically to Thurston County.

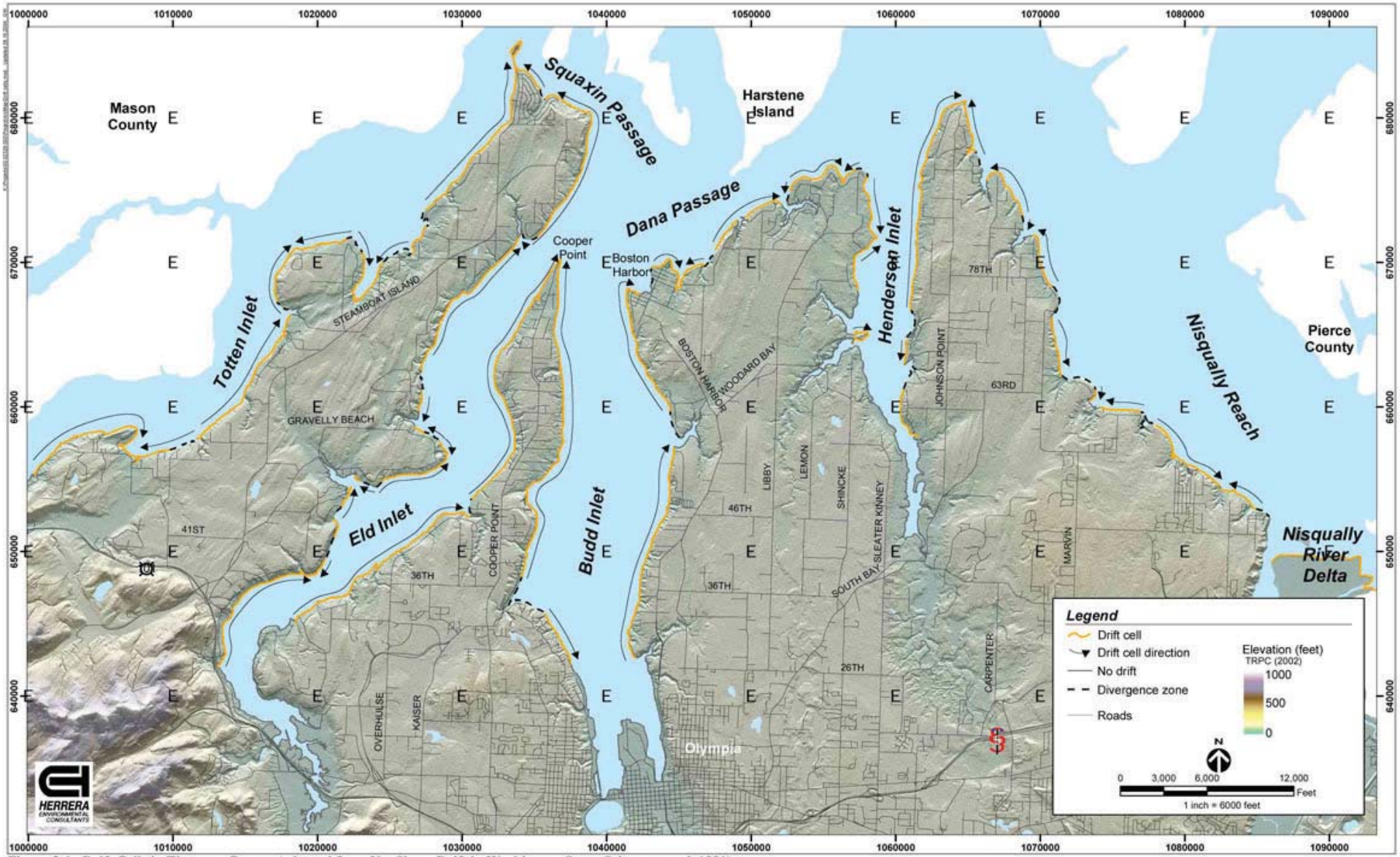


Figure 3-1. Drift Cells in Thurston County (adapted from Net Shore-Drift in Washington State, Schwartz et al. 1991).

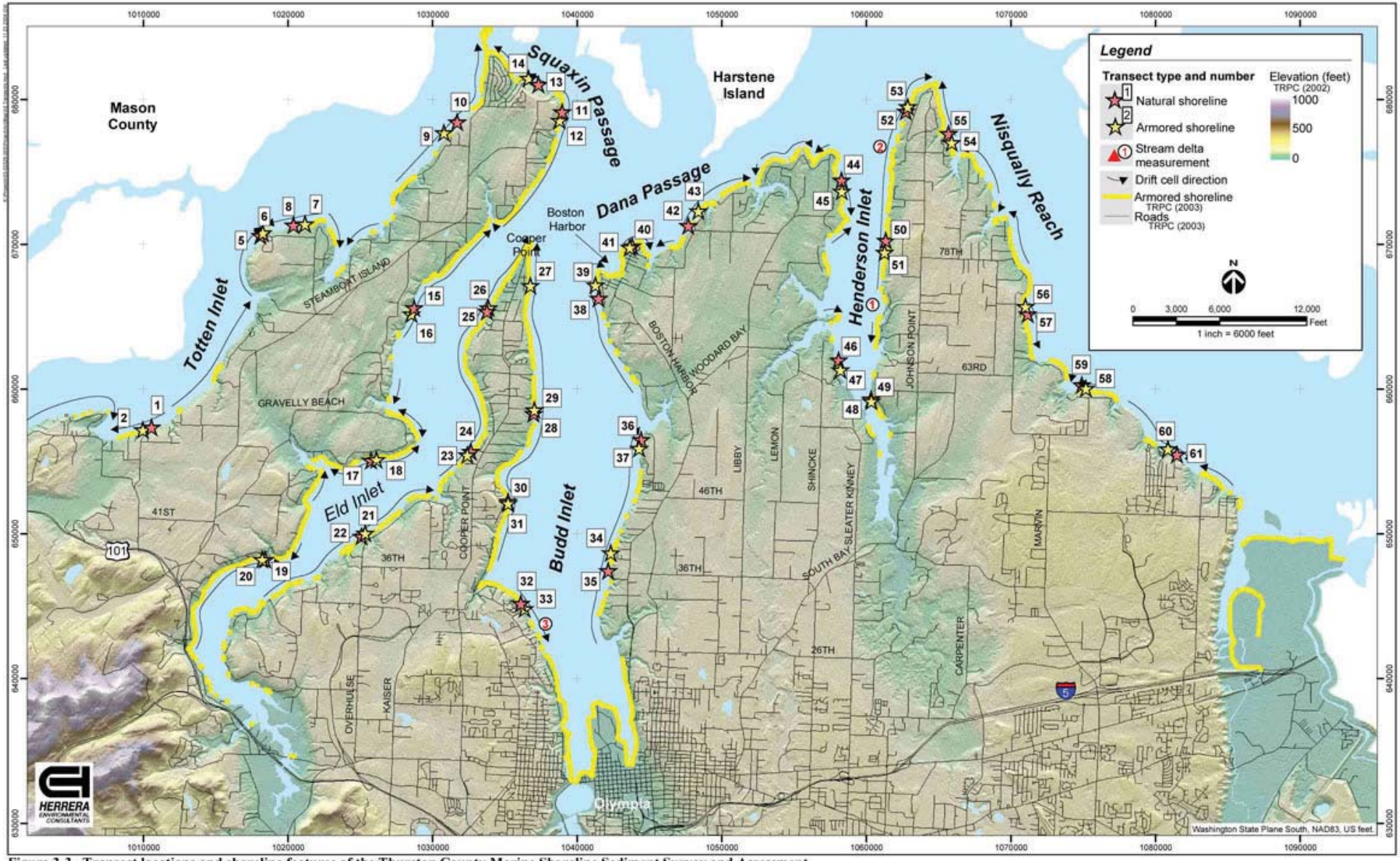


Figure 3-3. Transect locations and shoreline features of the Thurston County Marine Shoreline Sediment Survey and Assessment.

CHAPTER 4

Results

4.0 Results

4.1 GIS Data Analysis

Selected products of the GIS analyses and field work have been delivered electronically to the Thurston Regional Planning Council in ESRI shapefile format. These shapefiles include Federal Geographic Data Committee (FGDC) ESRI standard metadata in XML format, which is viewable by both ESRI products and most web browsers. Washington State Plane South (feet) is the projection for all delivered shapefile data and the datum is NAD83.

The following is a list of delivered shapefiles with brief descriptions of the data stored within them:

- *Bathymetry.shp* – Depths from four transects conducted in Thurston County corrected to MLLW and to NAVD88. Includes approximate 1930s depths from georeferenced U.S. Coast and Geodetic Survey maps. (The bathymetric profiles created are presented in Appendix H).

- *Bulkhead_areas.shp* – Interpolated area of upper beach lost to bulkhead construction. Modern shoreline mapping data provided by Thurston County (GIS shapefile) were copied and modified to estimate natural or preconstruction shoreline where bulkheads or other armoring structures have been built on beaches. Shorelines in unarmored areas were used to estimate the footprint area of the armoring and fill. This information was used to estimate the total area of habitat lost. An example of the upper beach lost to bulkhead construction in the northwestern part of Budd Inlet is shown on Figures 4-1 and 4-2.

- *Landslide_erode.shp* – Areas with landslides and erosion were identified using aerial and oblique photos and lidar-derived shaded relief maps and were digitized over aerial photos and lidar shaded relief maps. GIS technicians compared landslides identified in the field to aerial and oblique photography from the year 2000, and a lidar-derived hillshade from 2002 to aid in identification of landslide sites. Exposed soil, trees on the beach that are perpendicular to the shoreline, accumulations of sediment at the base of hillsides, and hummocky areas on shaded relief images were used to identify areas that were eroding or had experienced landsliding. The approximate area of the landslide was digitized at a resolution of 1:1000 to 1:1500. The approximate age of landslides was estimated from the age of vegetation growing on the landslide and from the state of the woody debris delivered to the beach (where applicable). Additionally, eroding areas, as determined by exposed sediment were digitized in the same manner. The presence or absence of locally-derived woody debris was recorded for each landslide. All landslide areas mapped as part of this GIS analysis are shown on

Figures 4-3 through 4-6. Examples of landslides identifiable on lidar but not on aerial photos are shown on Figures 4-7 and 4-8. An example illustration of a small number of landslide areas is shown on Figures 4-9 through 4-11 over vertical aerial photos, oblique aerial photos, and lidar, respectively.

- *Manmade_structures.shp* – Structures that block sediment transport along drift cells were digitized using vertical and oblique aerial photographs (TGDC 2000; Ecology 2000, respectively). Drift blocking structures were only digitized when a structure was not permeable (such as pile-elevated docks) and where structures jut onto the upper beach at a 90 degree angle to the shoreline. Structures were delineated along the center of the structure with a line from the upper beach area to the end of the structure. An example of a sediment-blocking manmade structure is shown on Figure 4-12.

- *Shore_additions.shp* – Areas where the wetted shoreline was artificially increased between 1944 and 2001.

- *Shore_reductions.shp* – Areas where the wetted shoreline was artificially reduced between 1944 and 2001. This shapefile also includes filled inlets.

- *Transect.shp* – Locations of 29 paired transects established on the Thurston County shoreline. Appendix D contains illustrations of the transects and Appendix E and the shapefile contain a summary of the data collected at each transect (for all transect locations see Figure 3-3 in Chapter 3).

- *Thurston_Shoreline_Geology.shp* – Polygon shapefile of surficial geology along the Thurston County shoreline digitized from the Coastal Zone Atlas of Washington published by the Washington State Department of Ecology in 1980.

- *Prioritization.shp* – Reaches along the Thurston County shoreline that meet specific preservation or restoration criteria derived in this study. Reaches were designated high priority when the majority of the criteria were met. All prioritization reaches that were mapped are shown in Figure 6-2, Chapter 6.

- *Preservation sites.shp* – Specific sites with unique habitat-related characteristics that should be preserved or restored. All preservation sites that were mapped are shown in Figure 6-2, Chapter 6.

4.2 Beach Characterization

Beach characteristics such as sediment type and upland condition vary by site and are primarily determined by the local coastal geomorphology. Unarmored beach sites were characterized by the presence of a back beach area typically covered by overhanging vegetation and by a

Figure 4-1. Illustration of upper beach area covered by bulkheads (displayed over a vertical aerial photograph).

Location	Encroachment distance (feet)
ΔX_1	15
ΔX_2	9
ΔX_3	17

Figure 4-2. Illustration of upper beach area covered by bulkheads (displayed over an oblique photograph). Three example encroachment locations and distance of encroachment are shown.

Figure 4-9. Illustration of landslide delineation over vertical aerial photograph. Landslides were identified and delineated at a scale of approximately 1:1,500.

Figure 4-10. Illustration of landslide delineation over an oblique photograph.

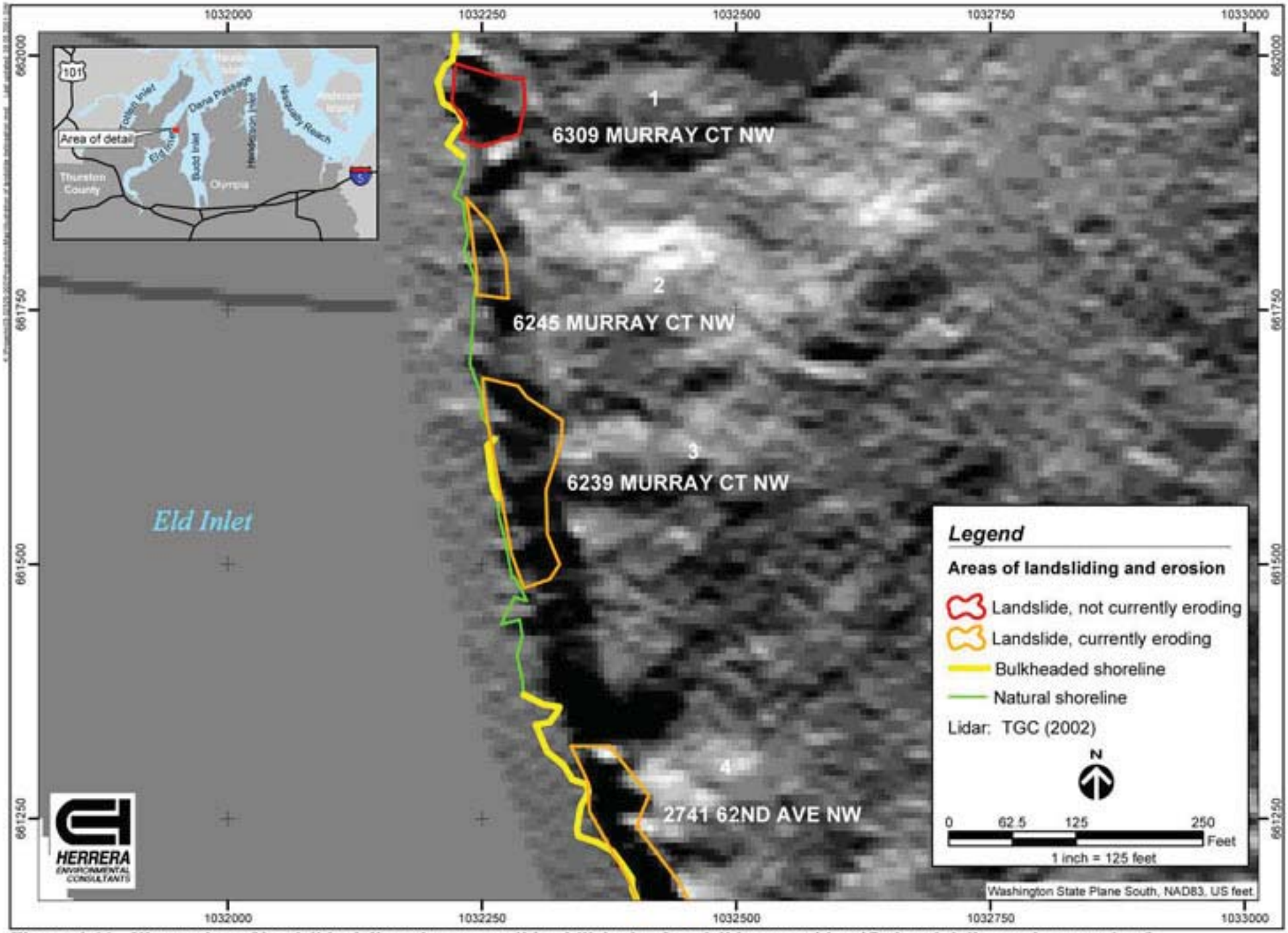


Figure 4-11. Illustration of landslide delineation over a lidar hillshade. Landslides were identified and delineated at a scale of approximately 1:1,500.

Figure 4-12. Illustration of a manmade structure blocking drift. Structures were delineated from aerial and oblique photographs.

moderate to abundant supply of large woody debris. Armored beach sites were characterized by the lack of back beach area, overhanging vegetation, and large woody debris, both autochthonous (from adjacent hillslope) and allochthonous (drift that originated elsewhere). The observations and analyses of beaches examined in this study are presented below. These results, from beaches representative of the larger Thurston County shoreline, demonstrate differences observed in various habitats associated with unarmored and armored beaches.

4.2.1 Beach Transects

The field survey data parameters collected at each beach transect are presented in Table 4-1. The beach transect data collected during the field investigation are presented in Appendix E.

4.2.2 Beach Characteristics at Paired Sites

Statistical analyses were performed to compare habitat and geomorphic attributes for paired unarmored and armored beaches (Table 4-2). Specifically, a Wilcoxon rank sum test (Zar 1984) was used to evaluate whether there were significant ($\alpha = 0.05$) differences in the following attributes across paired linear transects for all major Thurston County inlets combined ($n = 29$) and individual inlets having sufficient data ($n > 4$):

- Width of beach between MTL and MHHW
- Width of habitat, or beach that is predominantly sand or gravel, between MTL and MHHW
- Beach slope between MTL and MHHW
- Percentage of the beach that exhibits beach surface coarsening between MTL and MHHW
- Top of beach height relative to MLLW.

Results from the statistical tests showed that both beach width and the width of habitat were significantly shorter between MTL and MHHW in front of bulkheads when the data from all inlets were analyzed (see Table 4-2). Additionally, top of beach height was shown to be significantly lower in front of bulkheads when data from all of the inlets were analyzed. Between MTL and MHHW, the percentage of beach that is armored and the slope of the beach were not shown to be significantly different between unarmored beaches. For individual inlets, the top of beach height was shown to be significantly lower for armored beaches within Henderson Inlet. Other inlet-specific trends are likely difficult to detect due to the low sample size (i.e., between five and six sites for each inlet). Selected paired transect data collected in the field is presented in Appendix E.

Table 4-1. Field survey data parameters collected at each beach transect during the field investigation performed for the Thurston County Marine Shoreline Sediment Survey and Assessment.

	Survey Data Parameters	Data Recorded	Field Entry into GPS
1	Beach site location	Site coordinates	Yes
2	Beach slope	Slope from minimum 4-point transect of beach	Yes
3	Beach sediment characteristics	Visual estimate of median surface grain size	Yes
4	Beach surface coarsening	Yes or no	Yes
5	Characteristics of upper beach limit	Unarmored, bulkheaded, revetment, artificially placed logs, or other armoring	Yes
6	Upland conditions	Mature forest (MF) Second-growth forest (SF) Natural pasture (NP) Ground cover only (GC) Low-density development (LD) High-density development (HD)	Yes
7	Beach shade availability	Width of beach beneath canopy	Yes
8	Barnacle, mussel, and shell fragment size and location within transect	Extent along transect	Yes
9	Presence of beach platform and approximate depth of beach	Yes or no (If yes, record elevation as function of water level and time)	Yes
10	Beach erosion or accretion and shore-drift direction	Eroding or accreting site	Yes
11	Bathymetric measurements	Location (GPS) coordinates and depth	Yes
12	Stream delta measurements	Location (GPS) coordinates Slope from transect of beach Visual estimate of median surface grain size	Yes
13	Locations and quantities of driftwood	Measure representative log size and number of logs associated with location (GPS) coordinates and length of beach with similar characteristics	No

Habitat and geomorphic attributes that were measured on a nominal scale (presence or absence) were also compared between paired unarmored and armored beaches using the McNemar's test (Zar 1984). The attributes tested included the presence/absence of beach surface coarsening, presence/absence of beach platform exposure, presence/absence of barnacles, and presence/absence of shade (see Table 4-3). These tests showed that there was a significantly ($\alpha = 0.05$) higher number of unarmored beaches with shade relative to armored beaches.

Initial analyses showed no statistically significant difference in substrate type between the unarmored and the armored shorelines. However, there does appear to be a slight, statistically nonsignificant shift from sand to gravel and (to a smaller degree) to cobble at armored shoreline areas (Figure 4-13). The total width of beach between MHHW and MTL was summed over all unarmored and over all armored transects, and the fraction of that total width that was identified for each substrate type was calculated.

Table 4-2. Statistical analysis of habitat and geomorphic attributes for paired unarmored and armored beaches in Thurston County based on a Wilcoxon paired-sample test.

Attribute	Inlet(s)	Sample Size	Null Hypothesis (H_O)	Alternate Hypothesis (H_A)	Test Result [a]	p-Value	Median Difference [b]
Total Beach Width	All Inlets	29	Armored ≥ Unarmored	Armored < Unarmored	**Reject H_O**	0.025 > p > 0.01	-8.46 feet
Total Beach Width	Eld Inlet	6	Armored ≥ Unarmored	Armored < Unarmored	Do not reject H_O	0. 25 > p > 0.10	-9.48 feet
Total Beach Width	Budd Inlet	6	Armored ≥ Unarmored	Armored < Unarmored	Do not reject H_O	p > 0.25	-0.46 feet
Total Beach Width	Henderson Inlet	5	Armored ≥ Unarmored	Armored < Unarmored	Do not reject H_O	p = 0.10	-15.75 feet
Total Width of Habitat	All Inlets	29	Armored ≥ Unarmored	Armored < Unarmored	**Reject H_O**	0.025 > p > 0.01	-9.39 feet
Total Width of Habitat	Eld Inlet	6	Armored ≥ Unarmored	Armored < Unarmored	Do not reject H_O	p > 0.25	-2.75 feet
Total Width of Habitat	Budd Inlet	6	Armored ≥ Unarmored	Armored < Unarmored	Do not reject H_O	0. 25 > p > 0.10	-8.25 feet
Total Width of Habitat	Henderson Inlet	5	Armored ≥ Unarmored	Armored < Unarmored	Do not reject H_O	0. 25 > p > 0.10	-5.99 feet
Slope	All Inlets	29	Armored ≤ Unarmored	Armored > Unarmored	Do not reject H_O	p > 0.25	0.002
Slope	Eld Inlet	6	Armored ≤ Unarmored	Armored > Unarmored	Do not reject H_O	p > 0.25	0.004
Slope	Budd Inlet	6	Armored ≤ Unarmored	Armored > Unarmored	Do not reject H_O	p > 0.25	0.003
Slope	Henderson Inlet	5	Armored ≤ Unarmored	Armored > Unarmored	Do not reject H_O	p > 0.25	0.002
Percent of Beach Surface Coarsening (BSC)	All Inlets	29	Armored ≤ Unarmored	Armored > Unarmored	Do not reject H_O	p > 0.25	0.03
Percent of BSC	Eld Inlet	6	Armored ≤ Unarmored	Armored > Unarmored	Do not reject H_O	p > 0.25	-0.05
Percent of BSC	Budd Inlet	6	Armored ≤ Unarmored	Armored > Unarmored	Do not reject H_O	p = 0.25	0.06
Percent of BSC	Henderson Inlet	5	Armored ≤ Unarmored	Armored > Unarmored	Do not reject H_O	p > 0.25	0.03
Height of Top of Beach	All Inlets	29	Armored ≥ Unarmored	Armored < Unarmored	**Reject H_O**	0.0025 > p > 0.0005	-1.83
Height of Top of Beach	Eld Inlet	6	Armored ≥ Unarmored	Armored < Unarmored	Do not reject H_O	0. 25 > p > 0.10	-1.55
Height of Top of Beach	Budd Inlet	6	Armored ≥ Unarmored	Armored < Unarmored	Do not reject H_O	p > 0.25	-0.61
Height of Top of Beach	Henderson Inlet	5	Armored ≥ Unarmored	Armored < Unarmored	**Reject H_O**	p = 0.05	-2.18

[a] Statistical significance was evaluated at an alpha (α) level of 0.05.
[b] Median difference (unarmored – armored) across all paired beaches.
General note: the weak findings for individual inlets is related to the small number of independent samples in each inlet. Further sampling might allow statistically significant results to be determined for individual inlets.
Source: Zar 1984.

Table 4-3. Statistical analysis of habitat and geomorphic attributes for paired unarmored and armored beaches based on a NcNemar's test (Zar 1984).

Attribute	χ^2 Value	p-Value [a]
Presence/Absence of Beach Surface Coarsening	3.13	0.0771
Presence/Absence of Beach Platform Exposure	0.57	0.4497
Presence/Absence of Shade	6.75	**0.0094**
Presence/Absence of Barnacles	0.50	0.4795

[a] Values in **bold** indicate there was significant difference between unarmored and armored areas for the indicated attribute ($\alpha = 0.05$).

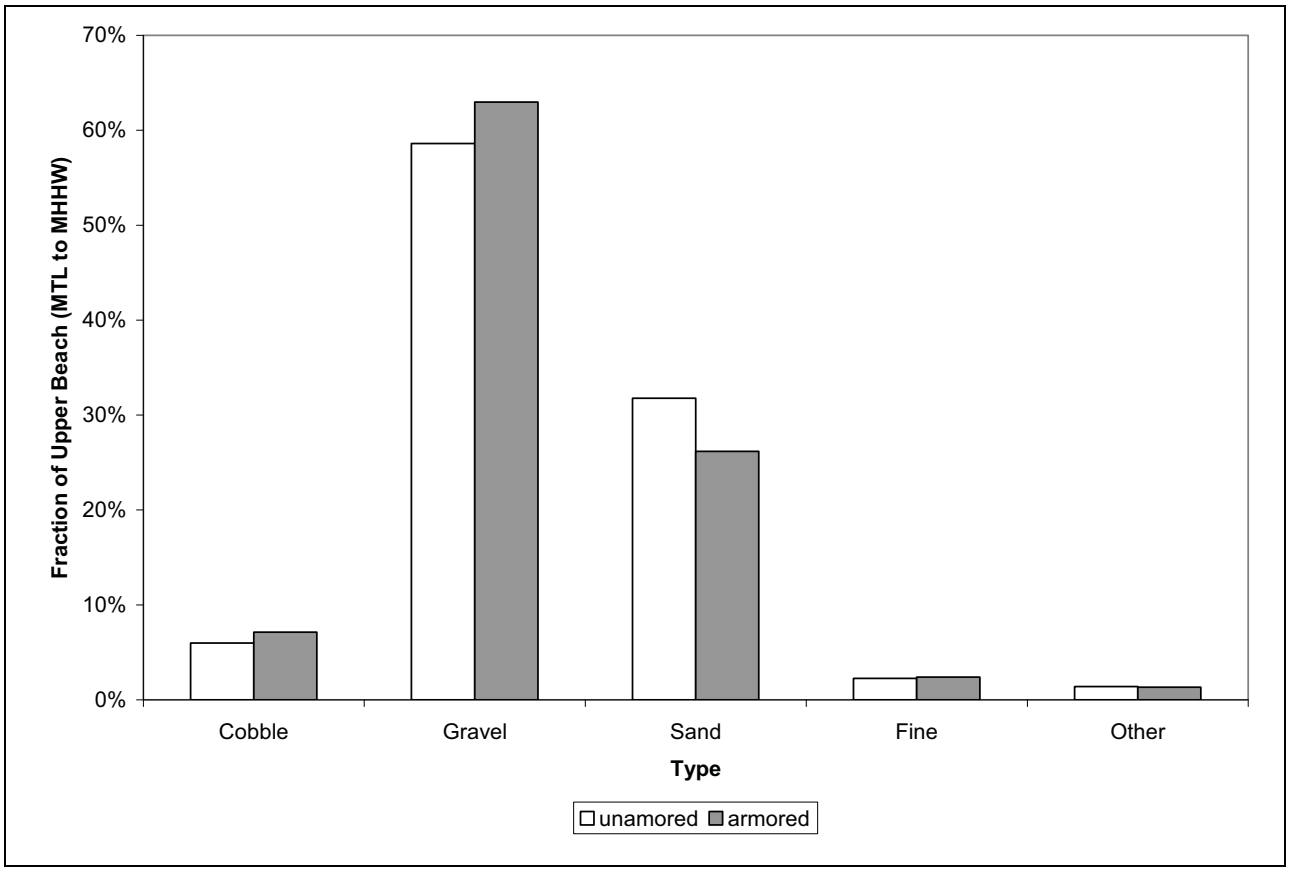


Figure 4-13. Substrate type distribution as a fraction of the upper beach area based on the total width of beach between MTL and MHHW.

4.2.3 Wood Debris

The presence or absence of wood debris provided the strongest characteristic that distinguished unarmored from armored beaches (see Table 4-4). Armored shorelines had either smooth, vertical concrete bulkheads (83 percent) or rock revetments (17 percent) abutting the upper beach. Wood debris was present at 76 percent of unarmored shorelines, but only 3 percent of the

armored shorelines. This difference is most likely due to a loss of local recruitment along armored shorelines, although it is known that woody debris is removed from some armored areas as a "housecleaning" operation; this was observed along the Nisqually Reach during the field work.

Table 4-4. Presence/absence of large wood debris observed at the 29 paired study transects of unarmored and armored shorelines along Puget Sound, Thurston County.

	Unarmored Shorelines	Armored Shorelines [a]
One or more large pieces of wood debris [b]	22	1
No wood debris present	7	28
Total number of transects	29	29

[a] Presence of bulkheads or revetments along beach.
[b] Wood consisted of autochthonous (from adjacent hillslope) or allochthonous (wood that originated elsewhere) tree trunks, with or without rootwads, at least 5 m in length and 0.10m in diameter.

Wood debris along the marine shoreline of Thurston County consists primarily of autochthonous deposits derived from adjacent uplands (Figures 4-14 and 4-15). Evidence used to distinguish between allochthonous and autochthonous wood debris includes:

Observation	Autochthonous (in-situ wood)	Allochthonous (driftwood)
Stem or trunk orientation relative to shoreline	Perpendicular	Parallel
Piece density	Low-moderate	High
Barnacles on wood	Yes	No
Partial stem embeddment in beach substrate	Yes	No
Evidence of mass wasting in adjacent uplands	Yes	No

Much of the wood debris is oriented perpendicular to the shoreline after falling from the adjacent hillslope. Partial burial in the beach and the presence of barnacles indicate that the wood is relatively stable and has not been subjected to mechanical wear or abrasion as in the case of driftwood. Driftwood also tends to be deposited with stems parallel, not perpendicular to the beach (Figure 4-16). In these types of environments, wood debris deposition on the beach is dependent on adjacent riparian forests and recruitment processes such as mass wasting, shoreline erosion, and windthrow. Where wood accumulation is dominated by local recruitment, wood deposits will only be sustained by maintaining adjacent marine riparian forests.

The Thurston County marine shorelines may be subject to a general reduction in driftwood supply resulting from the cumulative effects of historic clearing of wood from rivers and inland marine waters for navigation, riparian deforestation along rivers and marine shorelines, urbanization, armoring of marine shorelines, and a historic reduction in the quantity of timber rafts moved through Puget Sound.

Based on the field assessment and the findings of this study, the specific factors that may contribute to a lack of wood debris at armored shorelines may include the following:

- Reduction in local wood supply due to forest clearing above armoring
- Reduction in erosion along toe of bluff (intent of armoring)
- Landowner removal of wood debris along armored beaches
- Deeper water depths for longer distances along an unarmored than an armored beach
- Higher wave energy, edge waves, and currents along a bulkhead.

4.2.4 Effects of Bulkheads on Beach Characteristics

The results of this study indicate that a bulkhead is more likely to be associated with a lower beach if the majority of the adjacent shoreline is armored (see Table 4-5). Only when armoring covers more than 50 percent of the shoreline do maximum beach elevations in front of bulkheads fall near or below MHW. Of the 10 transects at bulkheads with 50 percent or less adjacent shoreline armored, none have maximum beach elevations near or below MHW. However, of the 19 transects at bulkheads with 50 percent or more of adjacent shoreline armored, eight have maximum beach elevations near or below MHW. Differences between armored and unarmored shoreline (beach) elevations also appear to correspond to the percentage of shoreline armored adjacent to the armored transect. Of the 10 transects with less than 50 percent of adjacent shoreline armored, 40 percent displayed elevation differences greater than 1 foot between armored and unarmored transects. Of the 19 paired transects with more than 50 percent of adjacent shoreline armored, 14 (or 74 percent) displayed elevation differences greater than 1 foot.

Table 4-5. Summary characteristics of transects with varying percent of armored shoreline within 600 feet of transect location.

Percentage of Shoreline Armored Within 600 Feet of Transect Location (%)	Total Number of Transects In Category	Transects With No Beach Above MHW + 1 Foot	Number of Paired Transects With >1 Foot Elevation Difference Across the Top 50 Feet of Beach
Armored Transects			
0-25	5	0	1
26-50	5	0	3
51-75	6	3	4
76-100	13	5	10
Unarmored Transects			
0-25	16	2	5
26-50	7	1	5
51-75	5	1	4
76-100	1	0	1

Figure 4-14. Example of autochthonous wood recruitment along a section of unarmored shoreline (northeast Totten Inlet, August 23, 2003).

Figure 4-15. Example of autochthonous wood accumulation along a section of unarmored shoreline (southeast Eld Inlet, August 26, 2003).

Figure 4-16. Example of allochthonous wood along a section of unarmored shoreline (southwest Eld Inlet, August 26, 2003).

The maximum elevation of unarmored beaches was not shown to be affected by the percentage of surrounding shoreline that is armored.

The GIS dataset of bulkhead locations along the Thurston County marine shoreline used in this analysis was obtained from TRPC (2003). Some errors were observed in this dataset when checked in the field, but the dataset correctly identifies most bulkhead locations.

The effect of bulkhead age on beach characteristics could not be determined using the current datasets due to lack of age information for much of the armoring.

4.3 Sediment Budget

The sediment budget analysis performed for this study identified and attempted to quantify the major inputs, outputs, and storage areas (reservoirs) of sediment within the littoral system of Thurston County. The intent of the sediment budget was to identify the major factors influencing the littoral system and is only intended as a rudimentary approximation and not a thorough, detailed analysis. In particular, the questions addressed through the sediment budget are as follows:

- Which of the potential sources (large rivers, small creeks, and mass wasting including landslides and bluff erosion) are significant in Thurston County?
- How significant is direct offshore loss of sediment compared to alongshore transport of sediment (littoral drift), in particular, to the deep channels to the north of Thurston County?

A sediment budget was constructed for each individual inlet and reach within Thurston County: Totten Inlet, Squaxin Passage, Eld Inlet, Budd Inlet, Dana Passage, Henderson Inlet, and the Nisqually Reach. Ideally, an individual sediment budget should be constructed for each drift cell of interest. However, this was not possible due to the limited geographic density of the available data. The sediment budget by inlet effectively averages the sediment processes within an inlet, and addresses the questions above at a relatively large spatial scale.

4.3.1 Assumptions

Only the sand size and larger sediment fraction was included in the estimates of sediment budget. Forage fish spawning habitat requires sand and small gravel beaches.

The first assumption made in constructing the sediment budget was that it is meaningful to develop a separate sediment budget for each inlet and reach. The drift cells in Thurston County (e.g., see Figure 3-1) support the assumption that the different inlets can be treated as essentially independent. In almost all cases (except Henderson Inlet), longshore transport is out of the

inlets. Thus, it is not necessary (or desirable) to construct a "combined" budget for the entire shoreline. As previously described, it was not possible to construct a sediment budget for the individual drift cells because that would entail much more detailed sampling than was possible in this study.

The second set of assumptions relates to the set of sediment inputs (S_i), sediment outputs (S_o), and processes that change sediment storage (S_s) considered in the sediment budget equation:

$$S_i = S_o + S_s$$

Figure 4-17 illustrates the elements considered in the present study. Potential sediment inputs considered are from large rivers; from smaller, typically unnamed creeks; and from mass wasting (bluff erosion and landslides). Potential sediment outputs considered are alongshore drift out of the inlet, from which the sediment is typically lost into the deep channels north of Thurston County; and offshore losses directly into the deep channels adjacent to the beaches. Beach erosion decreases the quantity of sediment stored in the littoral zone. The quantity of sediment in the littoral zone must increase if a beach is to be sustained under a rising sea level as in the case of Thurston County.

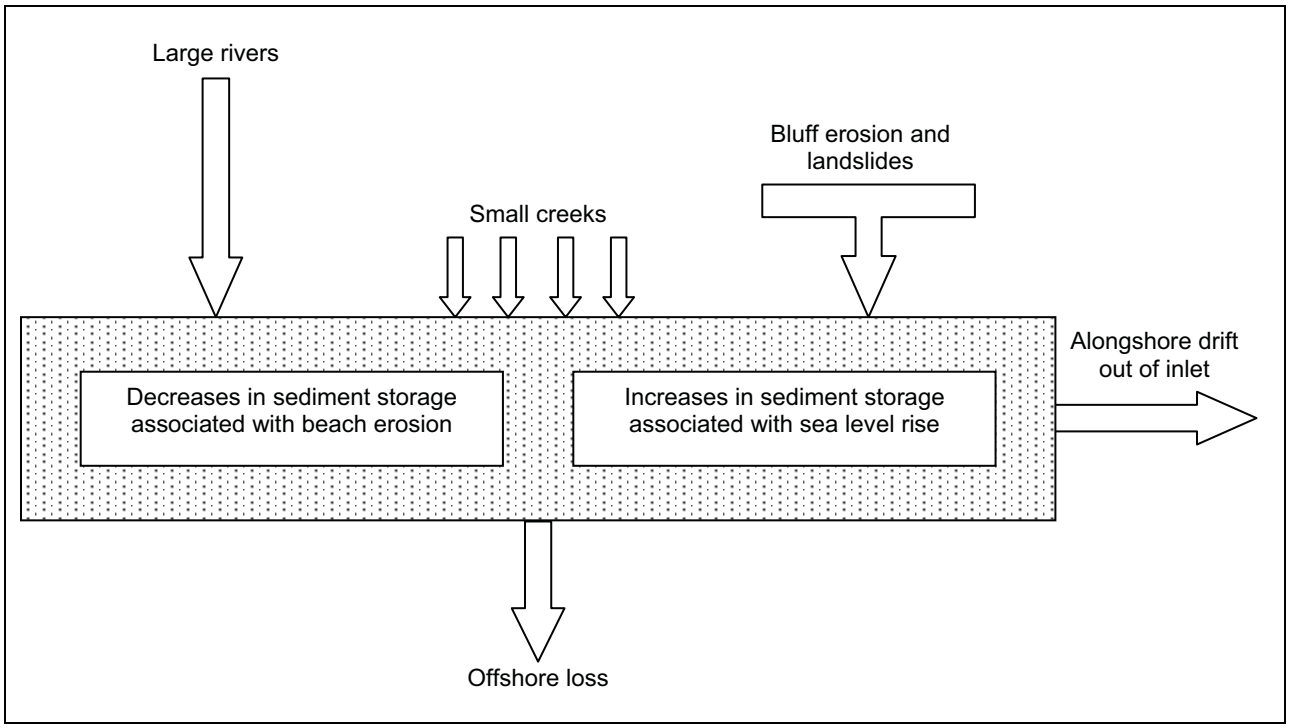


Figure 4-17. Inputs, outputs, and changes in storage considered within the present sediment budget.

Finally, it is assumed that the different potential sources of sediment do, in fact, deliver that sediment to the littoral system. This is obviously true with bluff failures where sediments from the bluffs are delivered directly to the beach. With fluvial sources, depending on the general

morphology, sediment can be delivered directly from the river to a deep offshore location. Given the steep slopes and deep channels in Puget Sound, if the sediment is delivered from a large river to a location that is deep enough, it will never make its way back onto the beach. This may, for example, be the case with sediment that was historically supplied by the Deschutes River. The present sediment budget assumes that initially, all of the potential sediment supply from each source does, in fact, enter the littoral system.

As described below, the conclusion of the sediment budget analysis is that both large rivers and mass wasting have the potential to supply similar quantities of sediment to the littoral system; small creeks have a much smaller potential sediment supply. It is possible that the potential supply from the larger rivers is not delivered to the littoral system, in which case only mass wasting would be significant.

4.3.2 Fluvial Sources: Large Rivers

The potential sediment supply from larger rivers was evaluated based on dredging records from Capitol Lake (which is a direct measure of the sediment transported by the Deschutes River), and from the relative watershed areas of the different rivers. As previously described, this approach provides an estimate of the amount of sediment transported by the rivers. It is also possible that a large fraction of the coarse sediment is immediately transported offshore and is not delivered to the littoral system.

Coarse sediment carried by the Deschutes River is trapped in Capitol Lake prior to reaching Budd Inlet. Approximately 35,000 cubic yards of sediment have been trapped annually in Capitol Lake between 1952 and 1998 (TRPC 2002). This is a long-term average, and the rate of sediment delivery may be decreasing over time; between 1991 and 1998 the sediment deposition was only 28,600 cubic yards per year. This report uses the long-term average figure, since sediment budgets typically are suitable for addressing the long-term (at least decadal) behavior of a littoral system.

Sediment sampling in the top 3 feet of the Middle Basin of Capitol Lake indicated a variable grain size consisting of sands (27 percent), silts (60 percent), and clays (13 percent). Silts and clays that reach the marine littoral zone are typically swept offshore almost immediately, meaning that only sands and, (when present), gravel contribute to the littoral sediment budget. Consequently, the potential input from the Deschutes River to the Budd Inlet sediment budget is 27% × 35,000 cubic yards per year, or 9,450 cubic yards per year.

Fluvial inputs from other sources were estimated on the basis of the watershed area, and the fluvial sediment supply was assumed to be proportional to the watershed area listed in Table 2-2. The majority of the overall watershed contributing to each inlet corresponds to the larger rivers and creeks: Skookum, Kennedy, and Schneider creeks in Totten Inlet; Perry and McLane creeks in Eld Inlet; Ellis, Moxlie/Indian, and Schneider creeks and the Deschutes River in Budd Inlet; Woodard and Woodland creeks in Henderson Inlet; and the Nisqually River and McAllister Creek in the Nisqually Reach. This approach gave an estimate of the fluvial sediment supply

from the Nisqually River consistent with previous estimates (ENSR 1999). Table 4-6 gives the resulting estimates.

Table 4-6. Estimated potential sediment (sand and larger) supply from large rivers for each inlet and reach in Thurston County.

Inlet / Reach	Potential Supply (cy/year)	Notes
Totten Inlet	1,900	Half the total input to Totten Inlet; the western shore is in Mason County.
Squaxin Passage		No significant rivers.
Eld Inlet	2,300	
Budd Inlet	2,600	Supply from rivers excluding the Deschutes (the potential supply from the Deschutes River is 9,500 cy/year).
Dana Passage		No significant rivers.
Henderson Inlet	2,900	
Nisqually Reach	22,000	One-half of the total supply from the Nisqually River. This is likely an overestimate of the fraction of the Nisqually River's sediment available to the littoral system of Thurston County.

4.3.3 Fluvial Input: Small, Unnamed Creeks

Small, typically unnamed creeks individually transport small quantities of sediment. However, there are many such creeks. Additionally, a small creek that flows over the top, rather than cutting through the beach, could deposit all of its sediment on the beach. This is in contrast to some larger rivers which can deposit much of their sediment too far offshore to return to the littoral system. For these reasons, it is important to assess whether the small creeks, in aggregate, provide a significant sediment supply to the littoral system.

The watershed analysis summarized in Table 2-1 showed that minor creeks have a much smaller watershed area than do the larger rivers, even in aggregate. Furthermore, recent work by Haugerud (2003) indicates that forest vegetation effectively "froze" the topographic expression of many small watersheds in the Puget Sound Lowlands shortly after the continental ice sheet receded 10,000 years ago. This suggests that historically, all but the larger rivers were relatively minor sediment sources.

As will be shown in Table 4-9, the potential sediment input from mass wasting is similar to that from the larger rivers. Therefore, the watershed analysis suggests that the sediment input from small creeks is small in aggregate compared to that from mass wasting. Individual small creeks could be important for small drift cells but, in the aggregate, their effect on the littoral sediment budget appears small.

In order to investigate further the sediment inputs from small creeks, the field study included shore-parallel measurements across the mouths of three small, unnamed streams. These streams were selected from the WDOE (2000) oblique photographs as apparently having significant deltas, suggesting that they may be a significant source of sediment.

Not all features that resemble deltas are formed from fluvial sediments. A "true" fluvial delta is formed where a stream or river deposits sediment at a greater rate than can be eroded by wave action or other marine processes (Ecology 2004a). Two common characteristics of delta sediments, in addition to the obvious protruding shoreline, are as follows (Wright 1978):

- The most rapid deposition and the deposition of the coarsest material take place near the river mouth, on the upper parts of the delta. Seaward, the percentage of coarse material diminishes rapidly.
- A significant fraction of the materials deposited near the river mouth is from river bed load.

In identifying whether the three sites are indeed stream deltas in the sense of being formed from locally-sourced fluvial sediments, both of these characteristics should be investigated. However, the first characteristic is difficult to apply to deltas along the marine shoreline of Thurston County for two reasons. First, in areas dominated by high tidal ranges (including Thurston County), strong offshore currents can transport the coarser sediments a considerable distance, meaning that the progressive fining of sediments offshore is interrupted by tidal mixing. Second, a progressive fining of sediments offshore was observed at many of the transects investigated in the present study, meaning that this is not an unambiguous indicator of delta formation. For both of these reasons, the current analysis focuses on the second characteristic: the congruence of sediment size between the river bedload and the delta sediments.

In contrast to a river delta, the accretion features that form at the confluence of two drift cells can have a very similar shape to a delta and it may coincide with a stream mouth. However, it is formed from entirely different processes and there need be no relationship between the sediment sizes on the beach and in the stream bed.

There is a third explanation for delta-like shoreline features coincident with creek outfalls that form without the creek exporting any sediment. The flow of water through the littoral zone at a creek outfall can create a "bulge" in the littoral area. If sediment moving parallel to the shoreline through littoral processes encounters a creek outfall it will be deflected seaward by the bulge. The flux of sediment parallel to the shoreline slows and sediment accumulates forming a fan-shaped bulge in the beach. Hence, by interrupting the littoral "conveyor belt", creek outfalls can create a delta-like land form without necessarily supplying sediment.

The locations of the three stream mouths investigated are identified as stream deltas in Figure 3-3 (Chapter 3). For convenience, they are referred to as stream deltas, even though they may not be "true" deltas formed by the deposition of fluvial sediments.

Stream delta 1, illustrated in Figure 4-18, is located on the east side of Henderson Inlet, approximately halfway down the inlet. The small spit to the left of the stream mouth is gravel, and covered with grass on the inland (protected) side. Figure 4-19 illustrates the location of the transect sampled in stream delta 1, together with the dominant sediment types along the transect. The center of the main stream channel is at around +6 feet MLLW, or slightly below mean tide level. The main spits on either side of the delta are composed of gravel, as are the adjacent

beaches; silt and sand are trapped behind the spit to the left, in a small lagoon. Shells dominate the bed of the main stream channel.

It is apparent that this stream is a trap for sediment rather than a source. The evidence includes the pattern of sediment deposition: the accretional features, particularly the two spits on either side of the delta, are of much coarser sediment compared to the stream bed. In addition, the stability of the sand spit that has formed upstream on the left side of the estuary suggests that the stream flow is not able to transport the gravel that makes up the accretional features. The drift cell information provided in Schwartz and Hatfield (1982) also suggests that this site is near a confluence of two drift cells. (This local detail of the drift cell information is not shown in Figure 3-1.)

Stream deltas 2 and 3, illustrated in Figures 4-20 and 4-21, respectively, are at the mouths of much smaller streams compared to stream delta 1. These streams are very shallow across the beach. While they can be clearly discerned in the field, the transect measurements indicate that they are extremely shallow, i.e., less than 1 foot in depth.

Stream delta 2 is at an armored site near the northeastern tip of Henderson Inlet. While there was no streamflow during the site visit, a remnant channel was present along the right-hand side of the bulkhead where it meets a riprap wall.

The dominant substrate coarsens from sand and gravel along the stream channel to cobble away from the stream channel. The thalweg of the stream channel on the beach is of armored gravel (i.e., gravel with a thin layer of coarser material on top) suggesting that the finer material has been washed away. In other words, the stream appears to be eroding the beach as it flows across it: the stream is not a net source of sediment to the beach. The stream does appear to be transporting some sand and gravel; however, cobbles are the dominant substrate outside the channel, so the relative quantity of sediment supplied by this stream does not appear to be large compared to the overall littoral drift.

It is possible that the observed shoreline is a relict delta consisting of cobbles that were transported by the stream before the bulkhead and modifications were constructed. This seems unlikely however, because a stream with enough flow to transport cobbles would probably undercut or otherwise damage a bulkhead that was built across its path.

Stream delta 3 is located in the southeastern portion of Budd Inlet, just south of Butler Cove. The stream associated with delta 3 is a small, natural channel flowing over and between cobbles before it reaches the beach, then flowing in a small depression over the beach (Figure 4-22). The channel at stream delta 3 appears to be erosional above the beach. There is a headcut approximately 50 feet upstream of the beach, and the stream is undercutting a clay bluff (Figure 4-22). Cobble is the dominant bed substrate above the beach. The dominant substrate throughout the beach is gravel, which was not observed in the stream bed above the beach. Thus, it does not appear that the creek is contributing a significant amount of sand or gravel to the beach. The stream may be a source of clay and other fines, but these would be rapidly transported offshore.

Figure 4-18. Aerial photograph illustrating stream delta 1, on the east side of Henderson Inlet (Ecology 2000).

Figure 4-19. Location of the transect and sediment characteristics of stream delta 1 (Ecology 2000).

Figure 4-20. Aerial photograph showing stream delta 2, on the east side of Henderson Inlet, north of stream delta 1 (Ecology 2000).

Figure 4-21. Aerial photograph illustrating stream delta 3, on the west side of Budd Inlet (Ecology 2000).

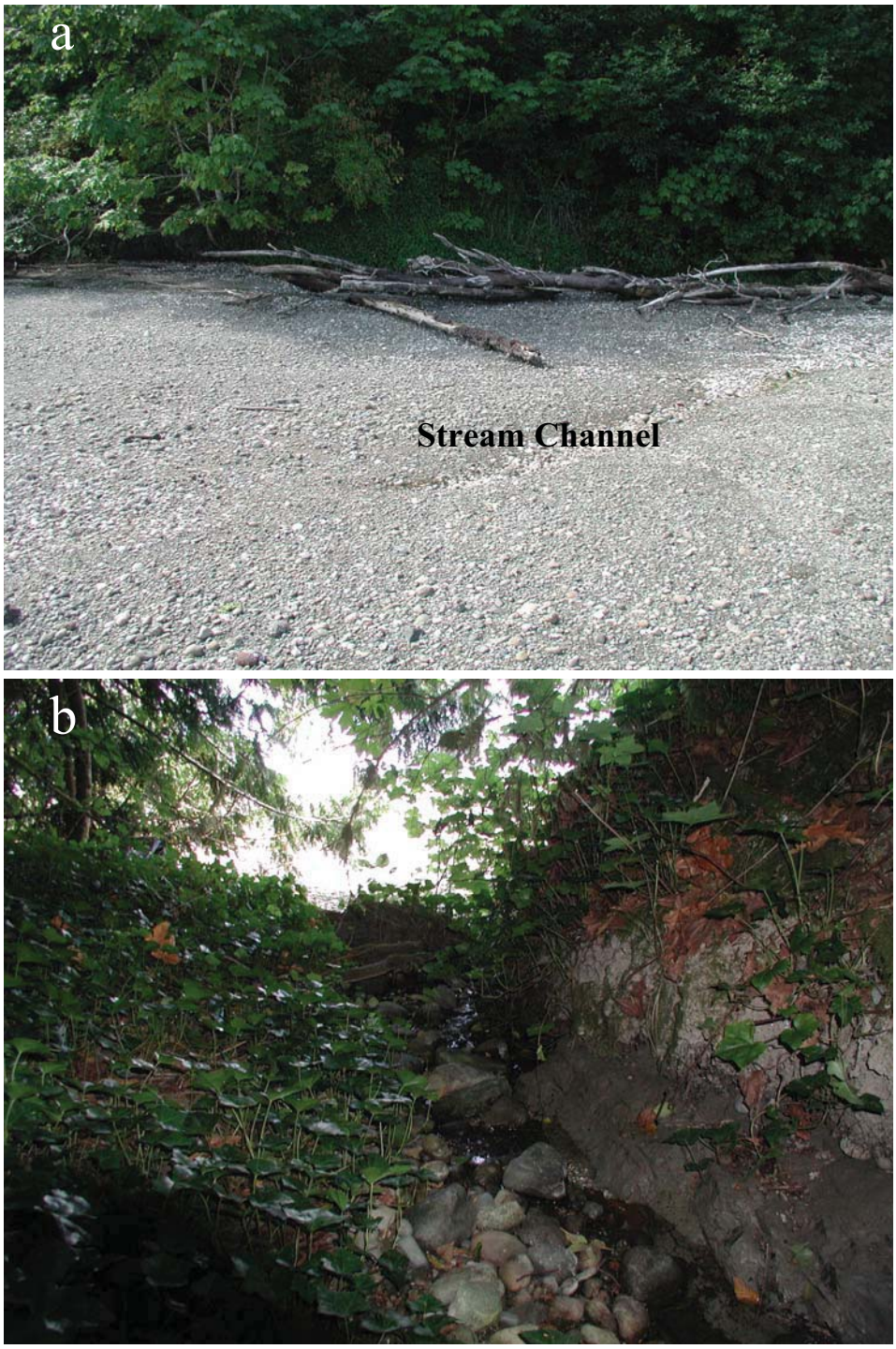


Figure 4-22. Stream channel delta 3 showing (a) shallow stream flow path across the beach and (b) upland channel bed characteristics (cobble dominated substrate). Note undercut clay bluff.

To conclude, none of the three apparent stream deltas investigated was clearly composed of locally-sourced fluvial sediments, in which case the sediments on the beach would be expected to be comparable in size to the coarser sediments within the stream bed. They therefore appear to be delta-like accretional features formed by littoral drift rather than local sediment deposition. It is also possible that deltas 2 and 3 are relict deltas, although in this case the fluvial sediment would have been very coarse (e.g., cobbles) in order for the delta to remain in place once the sediment source was removed.

To summarize, the assessment of the fluvial supply from smaller streams based on their overall watershed area suggests that the small streams are not a significant source of sand or gravel overall. The field investigation of sediment characteristics near the stream mouths also suggests that the smaller streams are generally not the dominant source of sand or gravel locally. (In fact, they may be trapping sediment as appears to be the case in stream delta 1.)

It is possible that small streams may be an important sediment source in some smaller drift cells. However, in general, it appears that the smaller streams are not a significant source of sand or gravel in the area and therefore, are not significantly contributing sediment to support and maintain forage fish spawning habitat.

4.3.4 Mass Wasting Input

The volume of sediment supplied from mass wasting was estimated using the GIS analysis of landslide areas and ages (described in Section 3.2.4), together with field observations of recent landslides suggesting that the landslide depth was typically 3-5 feet. Based on the landslide areas, age ranges, and an average depth of 5 feet, the annual landslide volume was calculated for each inlet. For the purposes of a littoral zone sediment budget, it was assumed that 30 percent of the sediment supplied to the beach by landslides was sand or gravel, and was therefore able to contribute significantly to the littoral sediment supply. This is a very general assumption that is entirely dependent on the local geology. In many sites the percentage would be much higher, particularly outwash or fluvial deposit that consist entirely of sand and gravel. The 30 percent assumption used here is conservative and possibly underestimates the contribution of coarse sediment that mass wasting provides to the littoral zone.

Landslides and mass wasting are also a very important source because all of the sediment they deliver is incorporated directly into the littoral zone. Sediment delivered from streams and rivers may be flushed beyond the littoral zone by peak flows. In large rivers some coarse bedload may never reach the littoral zone as it moves offshore though subtidal channels. For these reasons alone, mass wasting is a very important sediment source to the nearshore environment.

Table 4-7 provides information on the observed landslide frequency and size by inlet within Thurston County, based on the GIS analysis conducted as part of this study. Landslides were observed in both unarmored and armored areas. Landslides are a major source of sediment and woody debris to coastal beaches. Woody debris was rarely delivered to the beach in armored areas. Less than half of the landslides in Budd and Eld Inlets delivered wood debris to the beach,

which is likely due to the high percentage of these shorelines that are armored. It is also likely that a smaller portion of the sediment in these landslides reached the beach, as bulkheads often create a flat area at the base of the slope. Natural landslides are typically characterized by upland disturbance in the forested community and large accumulations of woody debris on the beach (see Figures 4-23 and 4-24). Large-scale landslides that were only apparent on lidar imagery are not included in Table 4-7 because they infrequently deliver sediment and wood to the beach and are not considered to be constant sediment sources.

Table 4-7. Landslide frequency and size by Thurston County inlet or reach.

Inlet Name	Aspect	Number of Landslides	Number of Landslides Delivering Wood	Total Area of Landslides (ft^2)	Average Size of Landslides (ft^2)
Totten	East	52	37	519,382	9,988
Squaxin Passage	North	3	3	14,608	4,869
Eld	East	45	16	269,501	5,989
	West	63	31	701,626	11,137
Budd	East	45	26	485,430	10,787
	West	22	10	143,037	6,502
Dana Passage	North	38	27	514,880	13,549
Henderson	East	28	25	136,723	4,883
	West	44	37	468,218	10,641
Nisqually	West	36	28	258,570	7,183
Total		376	240	3,511,974	9,340

Note: Information in this table does not include deep seated landslides that were visible only on lidar.

Of the landslides identified on Washington Department of Natural Resources geologic maps (WDNR 2003a, 2003b, 2003c, 2203d, 2003e, and 2004), 81 percent of these were also identified in this study. Because all shoreline bluffs with evidence of mass wasting and not just landslides were mapped here, many more sites were identified than those landslides mapped by WDNR (Table 4-8).

Table 4-8. Assessment of landslide mapping for Thurston County marine shoreline.

	Totten Inlet [a]	Squaxin Passage	Eld Inlet [a]	Budd Inlet	Dana Passage	Henderson Inlet	Nisqually Reach
Number of landslides mapped by WDNR (2003a, 2003b, 2003c, 2203d, 2003e, and 2004)	5	1	9	3	3	5	5
Number of landslide mapped in this study	34	4	100	69	39	81	37
Number of WDNR identified landslides not mapped in this study	1	0	2	1	0	1	1

[a] Updated geologic maps were not available at the time this work was completed.

Figure 4-23. Small slides also provide sediment and wood debris to the beach.

Figure 4-24. Example of landslide along Eld Inlet. Riparian vegetation indicates slide is approximately 10 years old. Note abundant wood debris at toe of slope, much of which has not moved since the slide occurred.

The potential coarse sediment supply delivered by mass wasting is summarized in Table 4-9.

Table 4-9. Estimated potential coarse sediment supply due to mass wasting.

	Totten Inlet [a]	Squaxin Passage	Eld Inlet	Budd Inlet	Dana Passage	Henderson Inlet	Nisqually Reach
Mass wasting sediment supply (cy/year)	1,300	50	3,200	1,700	400	2,500	1,100

[a] Thurston County shoreline only.
Note: Coarse sediment (sand size and larger) is assumed to be 30% of the total volume.

The volume of material delivered by landslides is probably lower in the southern ends of the inlets due to lower coastal bluff height. Coastal bluff height tends to increase from south to north, but can vary locally. Figure 4-25 shows a topographic profile recorded 100 feet inland from the edge of the shoreline (as defined by Thurston County's shoreline GIS shapefile) that runs from north to south along the eastern shoreline of Henderson Inlet. This trend was observed qualitatively on other inlets.

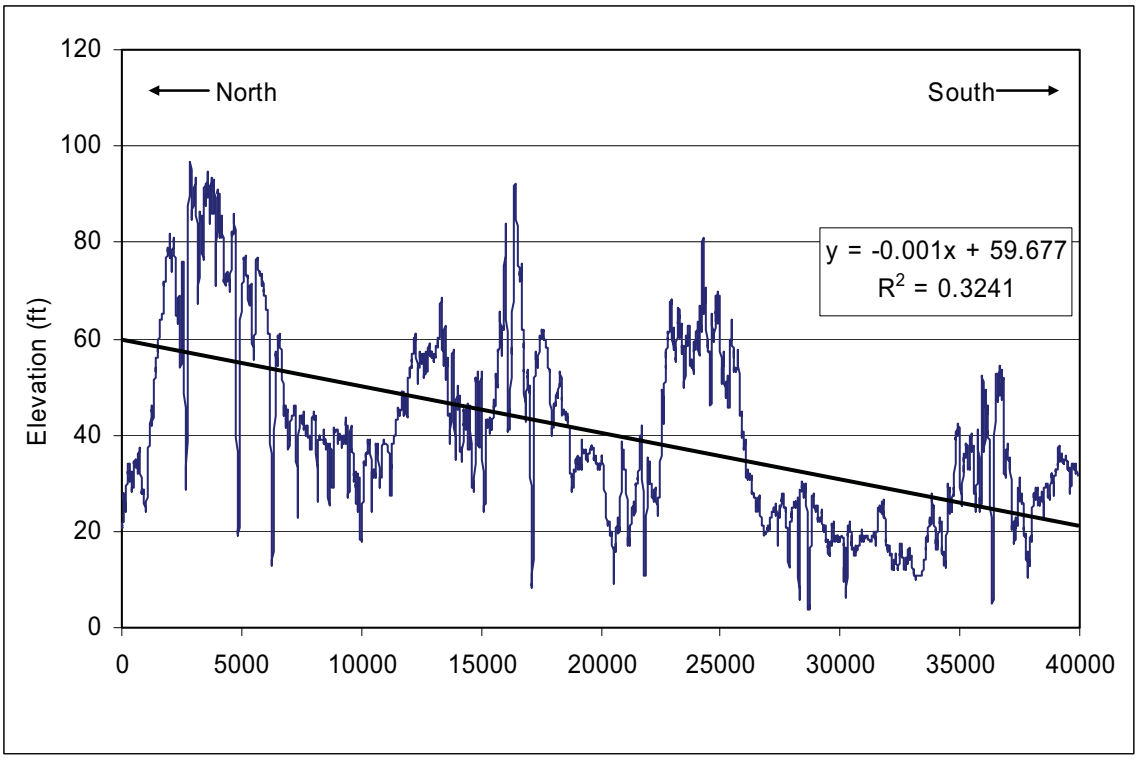


Figure 4-25. Elevations 100 feet inland from the Thurston County shoreline along east Henderson Inlet from north to south.

4.3.5 Closure Depth

The concept of a closure depth is widely used in the development of littoral sediment budgets, particularly sediment storage within the littoral zone. It is defined as the offshore depth beyond

which the nearshore profile does not change over time and is therefore deeper than that portion of the beach profile that changes seasonally. Along coastlines where the closure depth is well defined, sediment budgets need only consider sediment transport and sediment storage in the nearshore above the closure depth. Sediment within the nearshore environment that moves to depths greater that the closure depth is unlikely to re-enter the littoral zone.

Standard estimates (e.g., Hallermeier 1978) suggest that the closure depth in Budd Inlet may be between -5 feet and -15 feet MLLW, although this has been little studied on macrotidal beaches. The estimates of changes in storage due to beach erosion and sea level rise noted below use a nominal closure depth of 10 feet below MLLW. Selecting a nominal closure depth allows order-of-magnitude sediment volumes to be estimated, which in turn allows the relative importance of different contributions to the sediment budget to be evaluated.

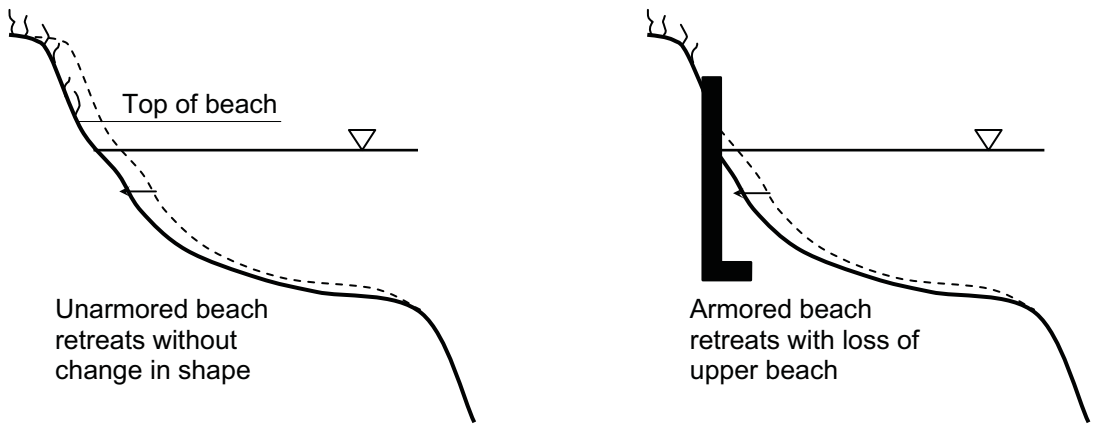
4.3.6 Changes in Storage Due to Beach Erosion

The quantity of sediment released to the littoral system as a whole through beach erosion was estimated from the paired transect measurements, using the concept of passive erosion (see Section 2.5.10). If an unarmored beach and an armored beach both retreat a distance Δx, the unarmored beach will typically maintain its shape (including the upper beach) while the armored beach will typically lose its upper beach. This is illustrated in Figure 2-19. Thus, if the profiles for an unarmored and an armored beach are plotted on top of each other, it will appear that the armored beach has eroded relative to the unarmored beach, and by an amount equal to the retreat distance of both beaches. Figure 4-26 illustrates the appearance of these paired transects; Appendix D shows all the transects measured during the study.

For each transect pair, the beach retreat distance (*br*) was estimated by fitting two straight lines with the same slope to the upper part of the beach profile for each profile in the pair, and calculating the horizontal distance between the two straight line fits. In almost all cases a good straight-line fit to the beach profile could be obtained. There was no statistically significant difference between the measured slopes for unarmored and armored profiles. The retreat distance was not used for further analysis in the few cases where a good fit could not be obtained.

An upper limit was placed on the rate of beach retreat by comparing recent ortho-rectified aerial photography (Thurston GeoData Center 2000) with historical aerial photographs (USACE 1944). (The georeferencing accuracy that could be achieved was limited. The average georeferencing error ranged from 20 to 50 feet due to limited fixed marks and the limited clarity of the older images. Thus, this exercise provided an upper bound and a consistency check on the results of the paired transect measurements rather than an independent estimate of the retreat distance.)

No gross shoreline movement that exceeded the 50 foot georeferencing error was identified. However, shoreline changes over approximately 25 feet were identified in a few areas, such as in areas where embayments were filled over the 56-year time period. This suggests that, in the 56 years between 1944 and 2000, shoreline retreat through most of the study area was well below the 50 foot resolution of the analysis. Thus, shoreline retreat has not exceeded 50 feet over the



By plotting the two profiles together, with the top of beach aligned, the retreat distance and decrease in sediment storage can be estimated

- Broken line: unarmored beach profile
- Solid line: armored beach profile

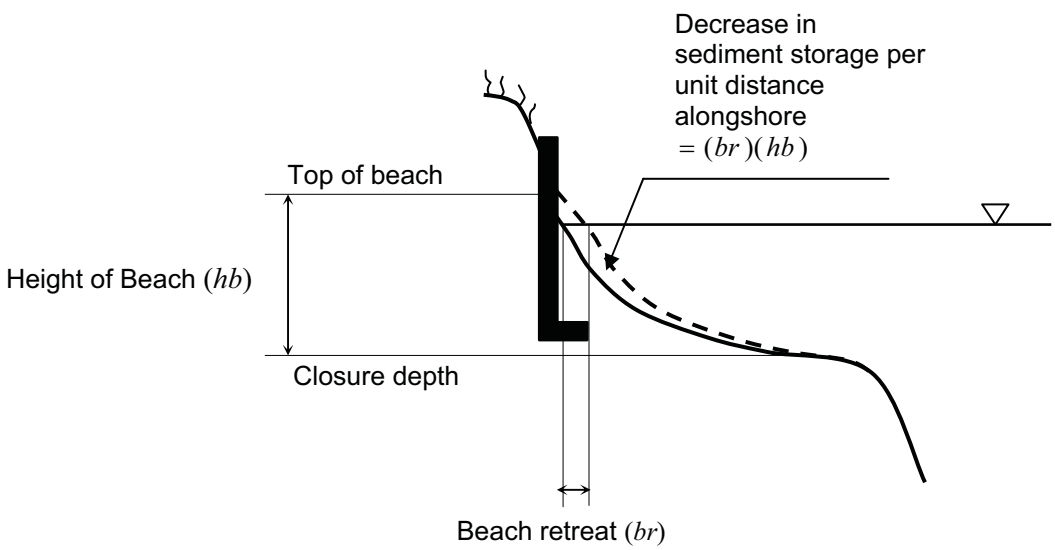


Figure 4-26. Use of paired unarmored and armored beach transects to estimate shoreline retreat, assuming the only effect of the armoring is passive erosion.

last 56 years (i.e., 11 inches/year or 30.5 centimeters/year). This is consistent with the results of the paired transect measurements. Rates of long-term average bluff retreat are probably more on the order of 8-10 cm/yr (3-4 inch/yr) or less (McCormack 2004 personal communication).

To convert the horizontal retreat distance to a sediment volume, the beach retreat distance (*br*) is multiplied by the height of the beach (*hb*), between the top of the beach and the closure depth, and by the inlet length. The top of the beach is defined as the location of any armoring or a bluff edge. Any retreat above the top of the beach is captured through the landslide volumes described earlier. To convert the sediment volume to a rate of change, it is divided by the average age of the bulkheads in Thurston County whose ages are known, or 40 years (TRPC 2003).

Table 4-10 gives the estimated decrease in sediment storage due to beach erosion for each inlet and reach, using the analysis based on passive erosion.

Table 4-10. Estimated change in sediment storage due to beach erosion.

	Totten Inlet [a]	Squaxin Passage	Eld Inlet	Budd Inlet	Dana Passage	Henderson Inlet	Nisqually Reach
Change in storage in beaches (cy/year)	Small	14,800	51,800	Small	22,300	46,500	Small

[a] Thurston County shoreline only.

4.3.7 Change in Storage due to Sea Level Rise

Sea level rise leads to an effective increase in sediment storage on the beach. In order for a beach to remain in equilibrium (with the same width and the same elevation profile) as the sea level rises, additional sediment must be deposited on the beach to build the beach up and keep pace with the sea level.

The volume of sediment needed to keep a beach in balance with the rising sea level, without apparent retreat, can be calculated using as a basis the "Bruun Rule" (Bruun 1983). Bruun developed the rule by assuming that the beach and nearshore zone adjust to maintain a constant "equilibrium profile" above the closure depth.

For beaches typical of Thurston County, backed by a slowly eroding bluff or by armoring, the equilibrium profile should be assumed to be maintained to the top of the beach. This is illustrated in Figure 4-27. If the sea level rises by a distance *slr* each year, the active part of the beach (i.e., between the closure depth and the top of the beach) must also rise by a distance *slr*. The width of this active part of the beach is (*slr*)/*s*, where *s* is the average beach slope. Then, if the alongshore length of the beach (perpendicular to the page) is *alb*, the additional storage each year is:

$$svr = \frac{(slr)(hb)(alb)}{s}$$

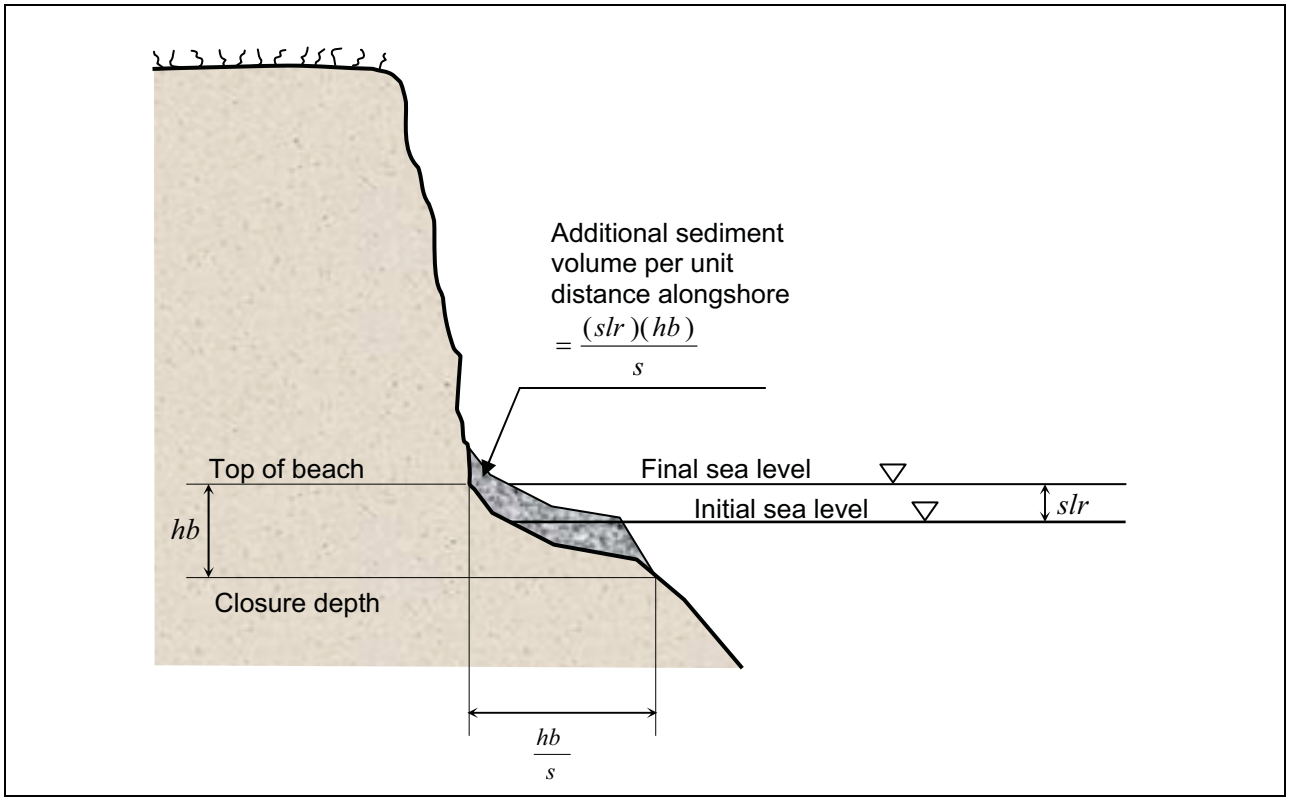


Figure 4-27. Illustration of the additional sediment stored in a beach in order for it to retain a fixed width with a rising sea level.

Table 4-11 gives the estimated increase in sediment storage due to sea level rise for each inlet and reach, using this analysis.

Table 4-11. Estimated change in sediment storage due to sea level rise.

	Totten Inlet [a]	Squaxin Passage	Eld Inlet	Budd Inlet	Dana Passage	Henderson Inlet	Nisqually Reach
Change in storage due to sea level rise (cy/year)	(6,300)	(900)	(15,300)	(9,400)	(3,600)	(8,800)	(8,100)

[a] Thurston County shoreline only.
Note: Negative values are shown in parenthesis.

4.3.8 Sediment Loss due to Alongshore Transport

Sediment sourced within Thurston County is eventually lost to surrounding areas; alongshore drift moves that sediment out of the inlets and eventually into deep water in the channels north of the county. An upper limit to the rate of loss was obtained from the potential alongshore transport rates at the mouths of the inlets identified in the *Coastal Zone Atlas of Washington* (Ecology 1980); the general pattern of transport given in the *Coastal Zone Atlas* at the inlet mouths is confirmed by the later mapping by Schwartz and Hatfield (1982). Results from this

analysis were used during the assessment of the sediment transport and budget to understand the fate of sediment within the study area.

In principle, the alongshore sediment transport rate can be calculated from the offshore wave height, period, and direction together with the nearshore bathymetry and the morphology and grain size of the beach. The offshore wave characteristics in turn can be calculated from the fetch and from wind data. This calculated sediment transport rate is known as the potential transport rate, because it represents the transport possible with an adequate sediment supply. The *Coastal Zone Atlas of Washington* (Ecology 1980) gives the potential transport rate, based on both summer and winter wave conditions, for the entire marine shoreline of Washington State. A more detailed description of the drift cells in Thurston County, based on field observations rather than wind and wave characteristics, is given by Hatfield and Schwartz (1982). This later work could not be used for the sediment budget because it does not attempt to quantify the transport rates.

In an experimental investigation, Wallace (1988) measured the alongshore transport rate from observations such as the quantity of sediment trapped at jetties and groins, and correlated the transport rates with orientation, fetch distance, and size of drift cells present for 26 sites in Puget Sound and the Strait of Juan de Fuca. He found a correlation coefficient of 0.53 between drift rate and cell length. Results from three sites located on the Thurston County shoreline are presented in Table 4-12. These measured transport rates cannot be used directly in the sediment budget development because they do not cover all the specific locations that would capture sediment losses from the inlets; however, they were measured close to those locations so they are likely to be representative of those locations. The tip of Johnson Point is probably less representative than the other two, because Johnson point, at the northwest corner of Henderson Inlet, is the one location in Thurston County where net shore drift is into, rather than out of, the inlet.

Table 4-12. Longshore transport rates for selected sites in Puget Sound.

Site	Wave Approach Direction	Fetch Distance (miles)	Cell Length (miles)	Longshore Transport Rate (cy/yr)
Tip of Hunter Point (Steamboat Island Spit)	SW	3.4	2.5	400
Tip of Cooper Point	S	6.2	4.8	1,000
Tip of Johnson Point (Zittel's Marina)	N	3.0	0.3	100

Source: Wallace (1988).

The calculated potential transport rates are not directly comparable to the above measured transport rates in two ways. First, the calculated potential transport rates are based on medium-fine sand. The precise grain size used is not specified, but a diameter 0.5 mm is typical for medium sand. The dependence of the longshore transport rate Q on grain size D is poorly established; experimental investigations have supported relationships between $Q \propto 1/D$ and

$Q \propto 1/D^{0.25}$ (Komar 1998). The field measurements showed that the beach sediments near these locations were medium to coarse sand (grain size between 0.5 and 2 mm). Depending on the longshore transport model and the grain size selected, this would give longshore transport rates between 25 percent and 100 percent of those listed in Table 4-12.

The second difference between the measured transport rates and the calculated potential transport rates is that the potential transport rate is defined as the rate at which sediment would be transported if it were plentiful. In sediment-starved systems, the actual transport rate is less than the potential transport rate, which provides an upper limit.

With these caveats stated, Table 4-13 lists the potential transport rates in the Coastal Zone Atlas for the locations given, together with the ratio of the measured to the potential transport rate. The actual transport rates lie between 13 percent and 29 percent of the calculated potential transport rate for medium-fine sand. The sediment budget presented here assumes that the actual transport rates were 25 percent of the calculated potential transport rates presented in the Coastal Zone Atlas (Ecology 1980).

Table 4-13. Comparison between measured longshore transport rates and calculated potential transport rates. From Wallace (1988) and Ecology (1980), respectively.

Site	Measured Transport Rate (cy/yr)	Calculated Potential Transport rate (cy/yr)	Measured Transport Rate as a Fraction of Calculated Potential Transport Rate
Tip of Hunter Point (Steamboat Island Spit)	400	1,500	26%
Tip of Cooper Point	1,000	3,600	29%
Tip of Johnson Point (Zittel's Marina)	100	800	13%

Table 4-14 gives the resulting estimates of the loss of sediment due to longshore transport out of each inlet, that is, the net loss due to longshore transport for each reach.

Table 4-14. Estimated output of sediment through alongshore transport.

	Totten Inlet [a]	Squaxin Passage	Eld Inlet	Budd Inlet	Dana Passage	Henderson Inlet	Nisqually Reach
Sediment output through longshore transport (cy/yr)	1,300	Small	4,300	2,500	Small	800	1,000

[a] Thurston County shoreline only.

The blocking structures identified in the GIS analysis performed in this study (see Figure 4-12 for an example of a sediment-blocking, manmade structure) do not appear to affect sediment transport significantly. During the field effort, it was frequently observed that the beach was higher on the updrift side of a blocking structure, either an artificial structure such as a launch

ramp or driftwood; this was the clearest indicator of drift cell direction. However, the aerial photography did not typically show significant accretion on the updrift side, or a significant erosional area on the downdrift side of the identified structures. This suggests that any changes to sediment transport resulting from these structures have reached equilibrium and sediment is successfully bypassing the structures.

4.3.9 Sediment Loss Offshore

Because of the very steep morphology of Puget Sound, sediment can readily be lost offshore, effectively under gravity. This offshore loss is similar to the loss of sediment into submarine canyons along the Pacific coast. The tools that would be required to estimate the rate of offshore loss using slopes, sediment sizes, etc., have not been developed. This investigation therefore takes the approach of assessing the relative magnitude of offshore sediment loss by using that loss term to balance the budget. In areas where the observed erosion is much larger than would be anticipated based on the identified sediment inputs and outputs, it can be assumed that at least some sediment is being lost directly offshore.

4.4 Bathymetric Analysis

Inlet bathymetric cross-sections are shown in Appendix H. The only transect where the deepest measurement was shallower in 2003 than in 1936 was the lower Budd Inlet transect at the dredged navigation channel. Here, the bathymetric measurements suggest that the channel may be filling in, with more of the sediment entering the channel from the west than from the east.

4.5 Field Data Error Analysis

At the end of the 2003 summer field season a protocol was developed to correct measurements recorded with the Impulse 200 rangefinder. The Impulse unit was found to be out of calibration necessitating a procedure to adjust the collected data.

To test the level of angular error, the Impulse 200 and a Leica autolevel (Model NA824) were mounted on tripods, leveled and set to the same height. The level line of the Leica was used to determine the height of the Impulse 200 by centering the line between the two lenses of the Impulse 200. A distance of 30 meters was measured from the Impulse 200. A prism mounted on a monopod was set level to the Leica instrument. Fifteen measurements were taken and recorded with the Impulse 200. For each of these measurements, the red aiming dot of the Impulse was pointed directly at the center of the prism. After every three measurements the Impulse was pointed away from the prism and re-centered. Each measurement was recorded in vertical distance mode, which records the angle and the slope distance simultaneously. Slope distance and the angle were recorded for each measurement. Fifteen measurements were taken in the same manner with prism raised 1.05 meters, 2.09 meters, 3.15 meters, 4.22 meters, and 5.29

meters corresponding to measured angles of 2, 4, 6, 8 and 10 degrees. A total of 90 measurements were recorded. Results were analyzed using the Excel and Statistica software packages.

To determine if angular error for the instrument could be predicted as a function of the measurement angle, the data were analyzed using simple linear regression. Two separate regression analyses were performed using the following data as the dependant variable: 1) the raw angular error, and 2) the mean angular error for each measured angle (i.e., 2, 4, 6, 8, and 10 degrees). In each case, a statistically significant ($\alpha = 0.05$) model could not be developed to relate angular error and measurement angle. Therefore, the angle to each data point was corrected with an average of the error associated with all of the angles tested. A conservative error of plus or minus 0.11 degrees was assumed using the two measurements with the maximum and minimum amount of error.

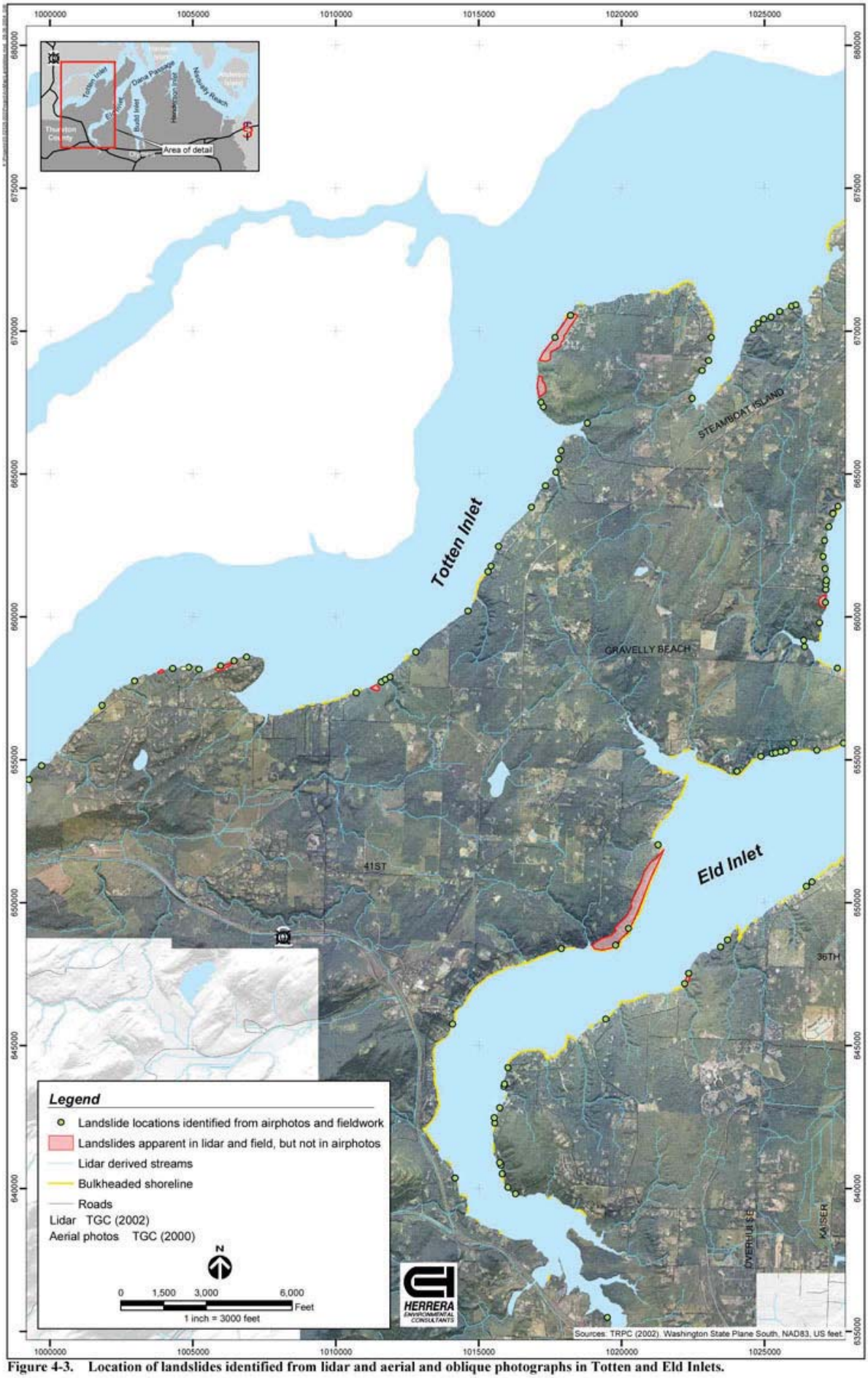


Figure 4-3. Location of landslides identified from lidar and aerial and oblique photographs in Totten and Eld Inlets.

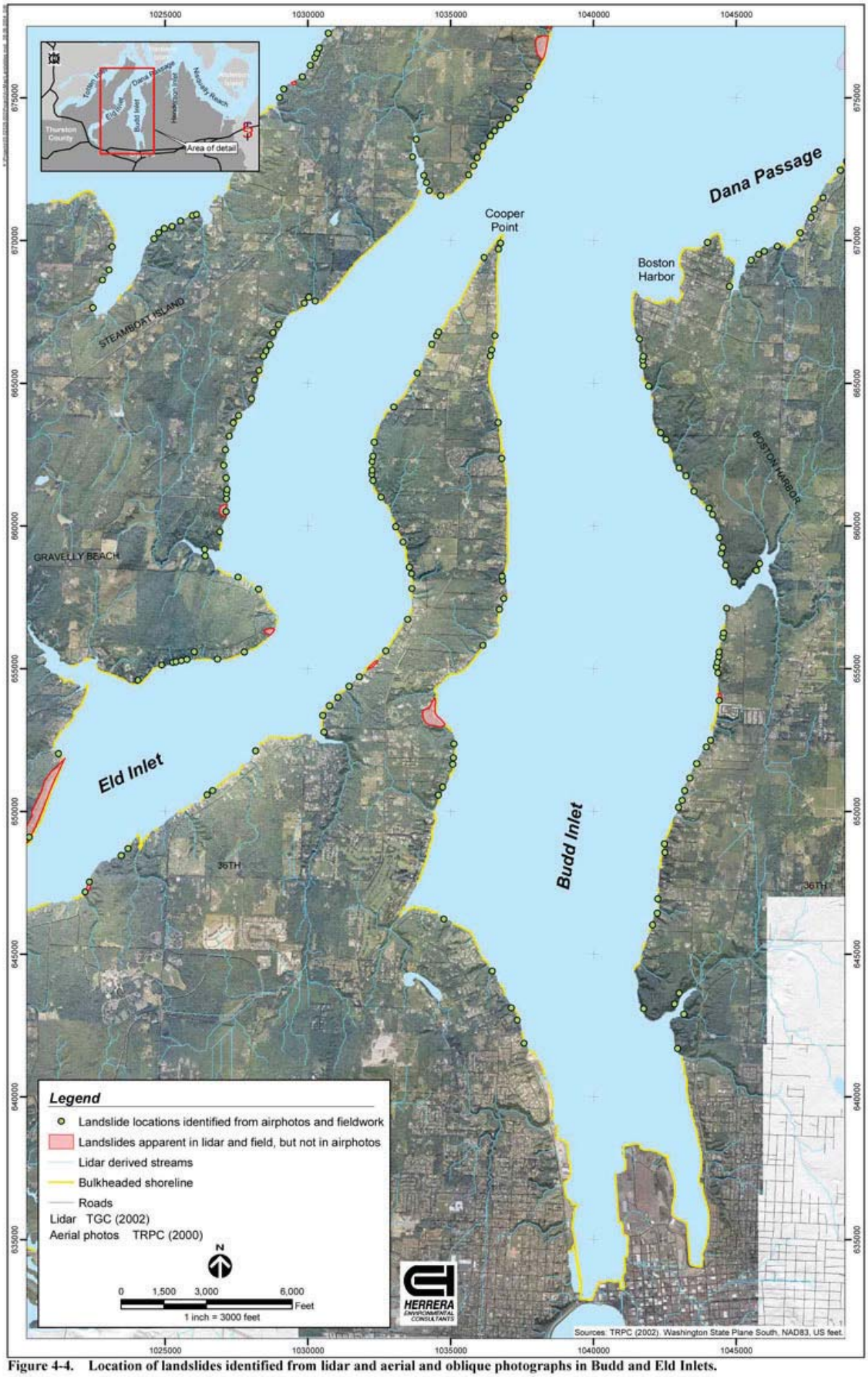


Figure 4-4. Location of landslides identified from lidar and aerial and oblique photographs in Budd and Eld Inlets.

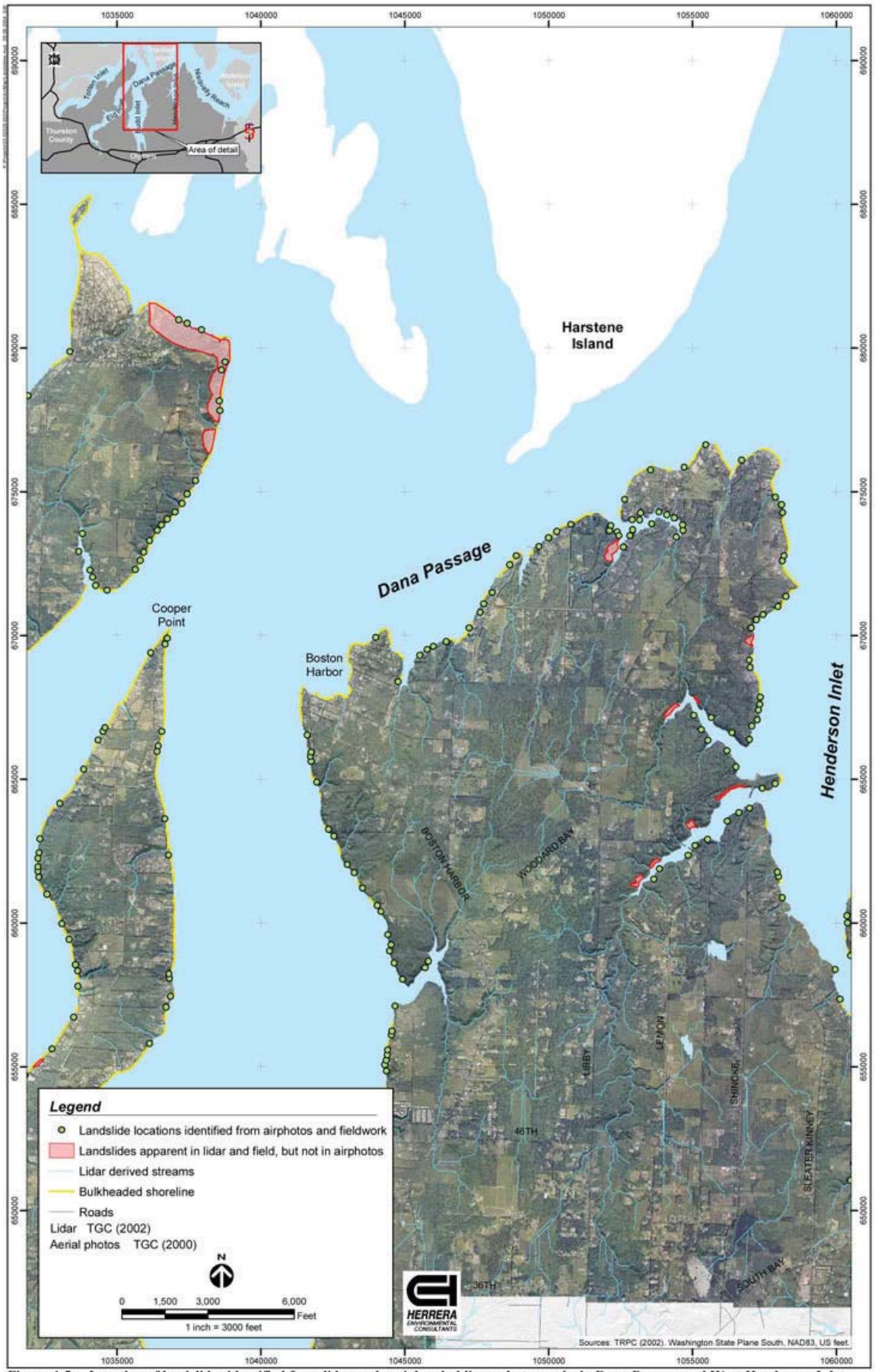


Figure 4-5. Location of landslides identified from lidar and aerial and oblique photographs in Dana Passage and West Henderson Inlet.

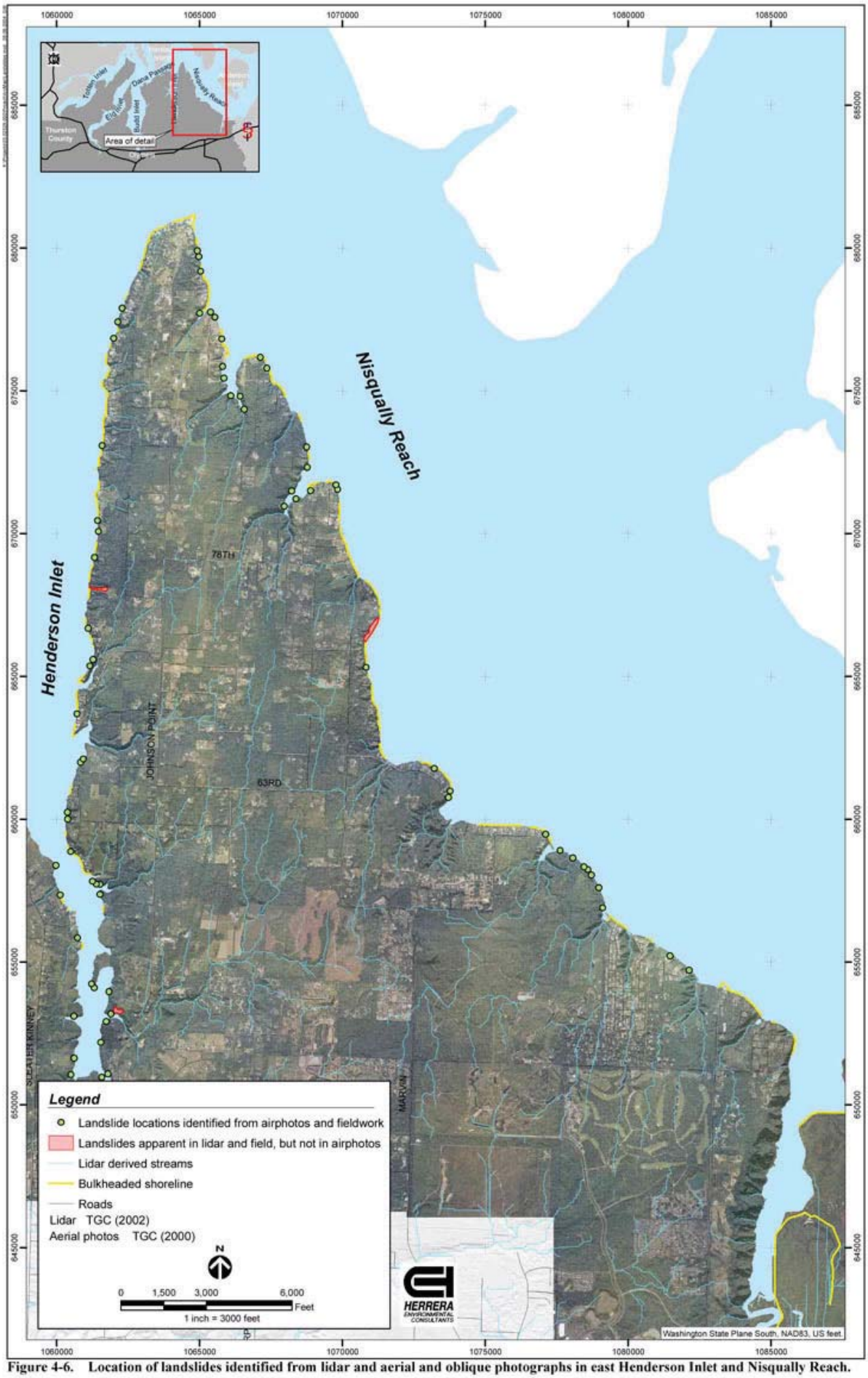


Figure 4-6. Location of landslides identified from lidar and aerial and oblique photographs in east Henderson Inlet and Nisqually Reach.

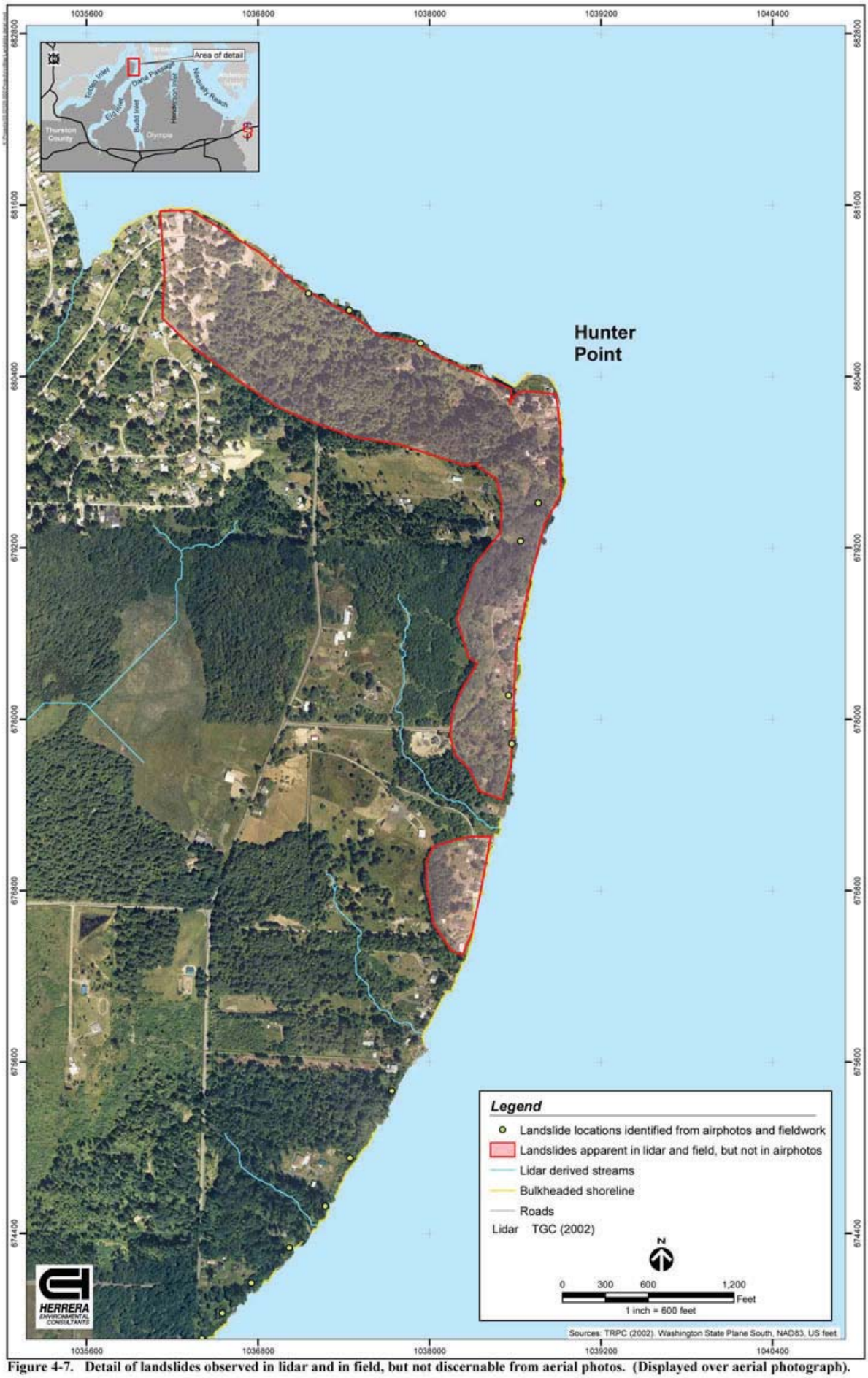


Figure 4-7. Detail of landslides observed in lidar and in field, but not discernable from aerial photos. (Displayed over aerial photograph).

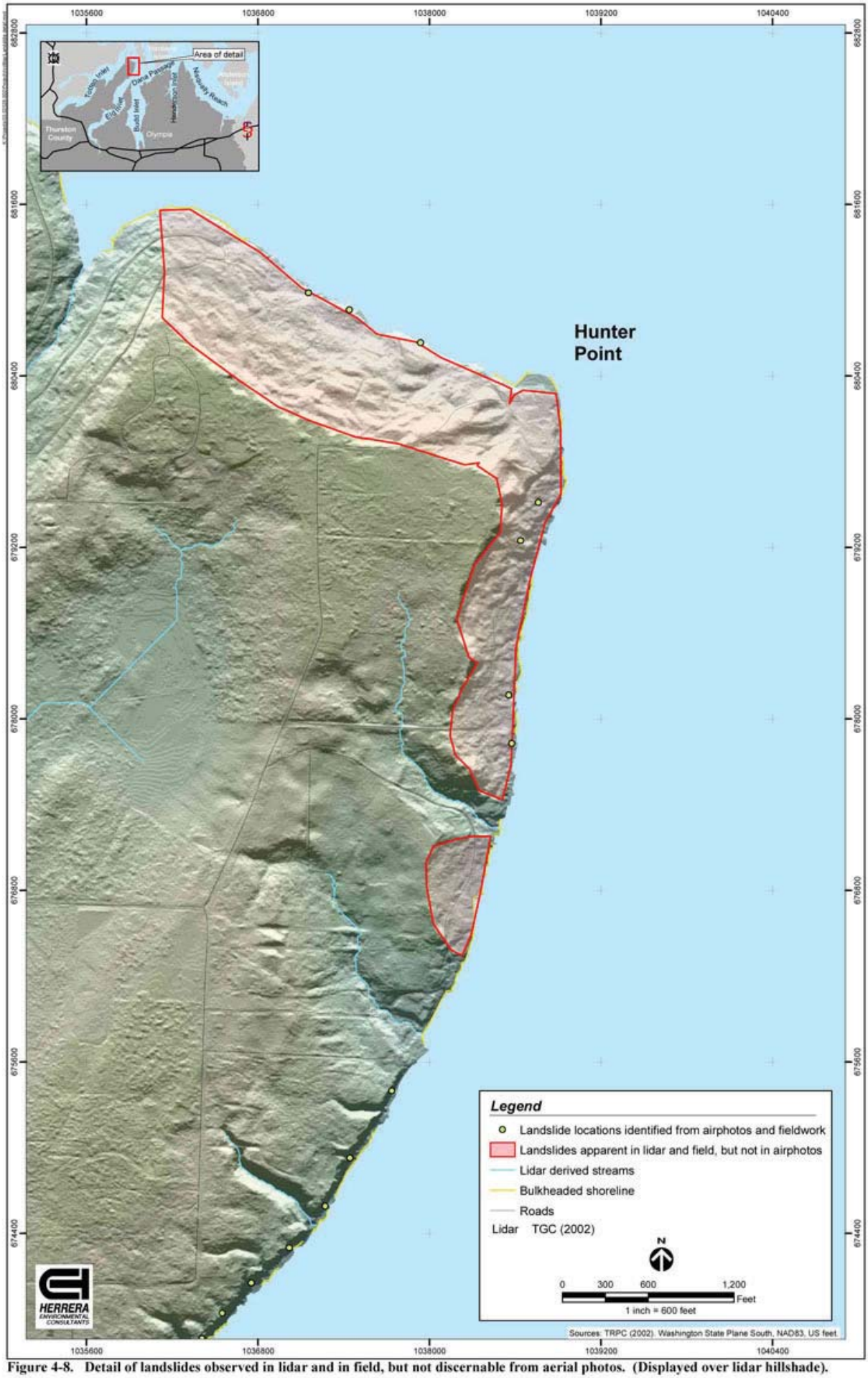


Figure 4-8. Detail of landslides observed in lidar and in field, but not discernable from aerial photos. (Displayed over lidar hillshade).

CHAPTER 5

Discussion

5.0 Discussion

5.1 Introduction

The following section discusses the finding of this study and presents interpretations of study results and potential implications. One valuable tool that ties together much of the field and GIS analysis is the sediment budget. This allows for the identification of sediment sources, sinks, and transport processes for each inlet and reach in the marine shoreline of Thurston County. In addition, it guides the identification of erosional processes that drive the loss of forage fish habitat in the marine nearshore area. A more detailed sediment budget at the drift cell level would be ideal; however, sufficient data are not available to allow such detailed sediment budgets to be prepared. The inlet-level sediment budgets presented here should be considered as averages over the inlets, yielding a general understanding as to the main processes in each inlet.

5.2 Sediment Budget

One of the main reasons to construct a sediment budget is to confirm that all processes contributing to the littoral zone have been identified, and to determine which are the most significant processes. If they have not been identified, or if their contribution has not been adequately estimated, then the sediment budget will not balance. The different elements of the sediment budget were estimated in Section 4.3, which also gives the major underlying assumptions. Only sand and coarser sediment are included in the budget developed for this study; finer sediments are assumed to be transported rapidly offshore or out of the inlet.

5.2.1 Summary of Sediment Budget

Table 5-1 takes the inputs, outputs, and storage changes developed in Section 4.3 to describe the overall sediment budget for each inlet and reach in Thurston County. The sediment budget is balanced if:

$$S_i - S_o - S_s = 0$$

where S_i is the rate of sediment inputs, S_o is the rate of sediment output, and S_s is the rate of change of sediment storage. Inputs and decreases in storage are positive, outputs and increases in storage are negative. Each line in Table 5-1 is estimated independently, with the exception of the offshore transport which is set to balance the budget where possible. In particular, the change in storage due to beach erosion is estimated from the field data, and not as a conclusion arrived at from the sediment budget.

Table 5-1. Estimated sediment budget for Thurston County.

Sediment inputs, outputs, and changes in storage (cy/year)	Totten Inlet [a]	Squaxin Passage	Eld Inlet	Budd Inlet	Dana Passage	Henderson Inlet	Nisqually Reach
Potential input from large rivers	1,900	0	2,300	2,600 [b]	0	2,900	22,000
Potential input from small creeks	Small	Small	Small	Small	Small	Small	Small
Potential input from mass wasting	1,300	50	3,200	1,700	400	2,500	1,100
Change in storage due to beach erosion	Small	14,800	51,800	Small	22,300	46,500	Small
Change in storage due to sea level rise	(6,300)	(900)	(15,300)	(9,400)	(3,600)	(8,800)	(8,100)
Output as longshore transport	(1,300)	Small	(4,300)	(2,500)	Small	(800)	(1,000)
Output as offshore transport (assumed)	Small	(14,000)	(38,000)	Small	(19,000)	(42,000)	(14,000)
Sum (zero to balance)	(4,400)	Small	Small	(7,600)	Small	Small	Small

[a] Thurston County shoreline only.
[b] This value excludes the Deschutes River.
Note: Negative values are shown in parenthesis.

As is typical of sediment budgets, there is a high degree of uncertainty in all of the values in this table. In general, the errors are random and the values are equally likely to be overestimates or underestimates. However, a few remarks regarding likely under- or overestimates can be made:

- The potential input from large rivers is an upper limit and may be an overestimate. Coarse sediment from large rivers can be delivered directly offshore, reaching the deep channels off the marine shoreline without residing in the littoral zone. In particular, the potential input from the Nisqually River is likely to be an overestimate.

- The change in storage due to beach erosion may be an overestimate. These values were estimated based on the assumption that the only effect of armoring is passive erosion, that there was no encroachment when the armoring was constructed, and that the armoring is not actively increasing the rate of erosion through increased wave reflection. If either encroachment or active erosion is occurring, the difference between armored and unarmored beaches would be greater and the corresponding estimate of average beach erosion would be an overestimate.

- In Squaxin Passage, the natural beach in this area extends to an elevation of nearly 20 feet above MLLW, well above MHHW (14.5 feet above MLLW). Even if the bulkheads in this location were originally built at MHHW they would have still encroached onto the beach. Therefore, in this reach alone, encroachment may be a significant contributor to loss of beach.

- In contrast, the beaches along the Nisqually Reach appeared more erosive than is indicated by the paired transect measurements, so the change in storage due to beach erosion along the Nisqually Reach is likely to be an underestimate.

The sediment budgets for Totten Inlet and Budd Inlet could not be made to balance by hypothesizing a net loss of sediment offshore because this would only make the imbalance worse. The most likely reason for the imbalance in these two inlets is that there is beach erosion that was not identified through the paired transect measurements. The limited numbers of paired transects meant that relatively small erosion rates would not be identified.

The field investigations did suggest that some of the beaches in both inlets were erosional. One such indicator of erosion is exposure of bulkhead footings. Exposure of a bulkhead toe implies that erosion has occurred, assuming that the bulkhead toe was originally buried. Figure 5-1 is an illustration of an exposed bulkhead toe. Table 5-2 lists the number of exposed bulkhead toes observed in each inlet and reach.

Table 5-2. Relationship between measured retreat of beaches and number of bulkheads with exposed footing.

Inlet / Reach	Measured Relative Retreat (feet)	Number of Bulkheads with Exposed Footing / Total Number of Bulkheads (%) [a]
Totten Inlet	0	1 / 2 (50%)
Squaxin Passage	50	2 / 2 (100%)
Eld Inlet	10	1 / 5 (20%)
Budd Inlet	0	1 / 6 (17%)
Dana Passage	20	1 / 2 (50%)
Henderson Inlet	20	3 / 3 (100%)
Nisqually Reach	0	1 / 3 (33%)

[a] Some of the armored sites measured had revetment rather than bulkheads. Only those sites with bulkheads that were surveyed in beach profiles are listed here.

The limited number of transect measurements severely limited the accuracy with which the beach retreat could be estimated. Table 5-2 indicates that it would be reasonable to assume that some decrease in sediment storage due to beach erosion has occurred in Totten Inlet, Budd Inlet, and the Nisqually Reach, and that this would be sufficient to balance the sediment budgets.

Observations of exposed bulkhead footings also clearly indicate that the loss of beach width and the consequent loss of forage fish spawning habitat are due to erosion of the shoreline, and not simply to encroachment of ill-sited bulkheads placed low on the beach. Therefore, preservation and restoration activities must include ongoing counters to sediment loss, whether that be beach nourishment, woody debris placed to dissipate wave energy and trap sediment, or measures to reconnect natural sediment supplies to the beach.

5.2.2 General Interpretation

The quantitative sediment budget presented here should be considered as an approximation only. However, based on the orders of magnitude difference of the various sources and sinks, and

taking into account general field observations at each inlet, a qualitative evaluation of the sediment sources and transport processes in each inlet is discussed here. This evaluation has implications for potential restoration activities along the marine shoreline environment of Thurston County, which are also discussed here.

The sediment supply arising from small drainage channels that feed directly into the marine shoreline of Thurston County is not large, even in aggregate, because the watershed area contributing to these drainage channels is much smaller than the watershed area contributing to the larger rivers, and the potential sediment input from the larger rivers is similar in size to that from mass wasting. Therefore, from the point of view of forage fish spawning habitat, a program of culvert removal for these smaller channels may not be particularly valuable.

The elevation of bulkheads directly determines both their direct physical impacts on the beach and the availability of suitable forage fish spawning habitat. Weggel (1988) classified seawalls into six types based on their location within the water column (Table 5-3).

Table 5-3. Seawall classification according to Weggel (1988).

Seawall Type	Seawall Type Description
Type 1	Base of seawall is located landward of the level of maximum wave setup and runup during times of maximum tide and storm surge.
Type 2	Base of seawall is located above water level that occurs at time of maximum combined tide and storm surge, but below level of maximum combined wave setup and runup.
Type 3	Base of seawall is above the maximum predicted tides excluding meteorological effects, but below storm surge plus tide level.
Type 4	Base of seawall is located within normal tide range, and thus the base is under water during part of the normal tidal cycle.
Type 5	Base of seawall is located seaward of the mean lower low water shoreline; it is subject to breaking and broken waves.
Type 6	Base of seawall is located in water so deep that incident waves do not normally break before reaching it.

Almost all of the observed bulkheads in this study were between MTL and MHHW, meaning that they were of Type 4 with the base of the bulkhead under water during part of the normal tidal cycle, and therefore limiting the availability of spawning habitat. For the construction of future bulkheads, a requirement for the elevation of the base of the seawall to be above the maximum predicted tides excluding meteorological effects (Type 3), or above the level of maximum combined tide plus storm surge (Type 2), would eliminate this effect. Waves would still run up to meet the bulkhead, but the toe would not generally be under water.

5.2.3 Totten Inlet

Totten Inlet is not severely erosional, the beaches in front of bulkheads are not significantly narrower than other beaches. There is some erosion, as evidenced by bulkhead toe exposure

Figure 5-1. Exposed bulkhead toe or footing, Totten Inlet. Such an exposure is evidence of beach lowering because bulkhead toes are buried below ground surface when constructed. Undercutting of the toe threatens the structural integrity. August 25, 2003.

observed during the field assessment. The sediment supply is approximately evenly divided between the fluvial supply (primarily Kennedy and Schneider Creeks) and landslides (including bluff erosion). There is no strong evidence that sediment is being lost offshore into the inlet.

The sediment deficit appears to be relatively small, on the order of 4,000 cubic yards per year of sand-size and coarser sediments. Because the sediment deficit is relatively small, it could be offset by a program of beach nourishment. A relatively small quantity of sediment would have to be introduced into the system in order for the sediment budget to be brought into balance.

Relatively little of the inlet shoreline (i.e., 19 percent of the Thurston County side) is armored, reflecting its relatively low erosion potential as well as the relatively limited level of development. Increased setback requirements for any new bulkheads would reduce the impact of these structures.

5.2.4 Squaxin Passage

The north-facing beaches of Squaxin Passage receive the highest wave energy in Thurston County. The majority of this reach (i.e., 71 percent) is armored, and the area continues to erode as evidenced by the high proportion of exposed footings on bulkheads in this area.

Encroachment of bulkheads onto the beach is a significant issue. Because of the high wave energy and relatively large wave runup, the unarmored beach reaches an elevation of 5 feet or more above MHHW. Therefore, bulkheads that have been constructed with a base at MHHW immediately encroach some tens of feet onto the beach.

Another impact of the high wave energy in the area is that the alongshore transport rate is relatively high. Thus, sediment added to beaches in this area rapidly moves north and away, past Steamboat Island.

These combined effects mean that Squaxin Passage is a difficult area for restoration. It may be more cost-effective to concentrate on other areas of the Thurston County marine shoreline.

5.2.5 Eld Inlet

Eld Inlet is similar to Totten Inlet in that the sediment supply is approximately evenly divided between the fluvial supply (Perry and McLane Creeks) and landslides (including bluff erosion). There is more shoreline erosion in Eld Inlet compared to Totten Inlet, and the level of armoring is greater (36 percent in Eld Inlet compared to 19 percent in Totten Inlet). However, this is not a severely eroded or armored area.

It appears likely that there is some loss of sediment offshore into Eld Inlet. This is based upon the observation of excess of shoreline erosion in Eld Inlet compared to the other identified inputs and outputs. As a result, shoreline erosion and thus applications to armor the shoreline in Eld Inlet are likely to continue. Furthermore, beach nourishment alone will be more expensive as a

restoration method in Eld Inlet compared to Totten Inlet: more sand and gravel will be needed, and it will be lost offshore more rapidly. Beach nourishment design here, while feasible, should consider mechanisms to retain any sediment placed. Drift sills (that is, low groins at the level of the nourished beach) can retain sediment nourishment while allowing longshore drift to carry sediment normally down the beach (Zelo et al. 2000). Drift sills should not be used without beach nourishment. Sediment traps intended to slow offshore, rather than longshore transport, should also be considered.

5.2.6 Budd Inlet

Budd Inlet is the only inlet in Thurston County that is fed by a large river, the Deschutes. More sediment is transported by the Deschutes River than by any other stream in Thurston County except for the Nisqually River; this sediment is now trapped in Capitol Lake.

Budd Inlet is the most heavily developed and most heavily armored of the four inlets. Forty five percent is armored, including 71 percent on the western side of the inlet. The amount of measured erosion is surprisingly small given the level of development. On average, there is relatively little narrowing of armored relative to unarmored beaches: the transects showed values ranging between a narrowing of 13 feet and a widening of 5 feet, with an average narrowing of 2 feet. (Table 5-3 presents the average as zero because this is not statistically different from zero.) However, particularly on the western, more developed side, beaches are narrow and are cut off below MHHW and generally do not provide desirable spawning habitat for forage fish.

These observations are representative of a sediment-starved system backed by relatively unerosive materials. Along the western part of Budd Inlet, it appears that there is little bluff or backshore erosion even in unarmored areas. The sediment budget suggests that little sediment is being lost offshore into Budd Inlet.

The Deschutes River has the potential to make a significant contribution to the sediment budget of Budd Inlet. Opening the tide gate has the potential to greatly improve sediment availability in Budd Inlet. (This would be only one of many environmental benefits to be gained from such an action.) However, because of the existing morphology and development, particularly the navigation channel and berths at Olympia Harbor, simply opening the tide gate and reconnecting Capitol Lake to Budd Inlet would not effectively connect the sediment supply to the littoral zone and beaches.

Sediment transport in many nearshore areas, including Budd Inlet, is primarily wave-driven. Both breaking and non-breaking waves can suspend sediment. In and near the surf zone, waves tend to transport sediment in their direction of travel. If the waves approach the shore at an angle, there is a net longshore transport of sediment.

Most wave-driven sediment transport occurs in the intertidal and upper subtidal zones. On many beaches, a closure depth can be identified beyond which there is essentially no net sediment transport. Sediment movement beyond this depth may occur, but there is no net longshore or

onshore transport. Standard estimates (e.g., Hallermeier 1978) suggest that the closure depth in Budd Inlet may be between -5 feet and -15 feet MLLW, although this has been little studied on macrotidal beaches. Structures that can block longshore sediment transport include groins and similar structures that approach or reach beyond the depth of closure. There is also little longshore transport adjacent to a bulkhead if its toe is close to or below the closure depth. Bulkheads in the upper intertidal area do not appreciably change the characteristics of wave-driven sediment transport.

Sediment can also be transported offshore under the combined influence of waves and gravity. Sediment that is suspended or agitated by waves can drift, roll, or slide offshore. Once this sediment reaches beyond the closure depth it is unlikely to move onshore again. This is significant in areas with steep offshore slopes, including much of Puget Sound and at submarine canyons along the Pacific coast. Fine sediments (silts and clays) are lost offshore more rapidly simply because they tend to remain in suspension. Strong currents (e.g., due to major river flows), can also entrain sediment. This is particularly significant for fines.

Given the sediment transport mechanisms described above, three cautions must be made relating to the restoration of the sediment supply from Budd Inlet (i.e., restoring Capitol Lake to an estuary). First, the deep draft navigation channel and deepwater berths at the Port of Olympia would effectively block transport from the river mouth (in West Bay) to East Bay, and to the eastern shore of Budd Inlet generally. The water depth along the deepwater berths is well beyond the closure depth in Budd Inlet, so little longshore sediment transport is expected. Without major construction efforts, such as opening a second channel from Capitol Lake to East Bay, the improvement in sediment supply can be expected to benefit only the western shore of Budd Inlet.

West Bay Marina and the nearby log-boom areas may also block sediment transport, although Ecology's oblique aerial photographs of the shoreline (Ecology 2000) suggest the presence of a low-tide beach, and therefore the potential for sediment transport through this area.

Second, careful design of the channel opening would be needed so that sediment is not immediately lost down the steep slope into the navigation channel or otherwise offshore. It is possible that this would require structural modifications beyond opening the tide gate. For example, the channel opening could be moved to the northwest of its present location so that the sediment was delivered directly to the west shore of Budd Inlet rather than to the center of the deep channel. Alternatively, a training wall could be constructed to divert the flow and sediment towards west shore. At present, the net shore drift in the southern part of Budd Inlet is to the south. Net shore drift is a consequence of the prevailing wave patterns, the morphology, and the available sediment supply. It may not be possible to construct the channel opening in a way that would allow significant transport to the north. Very careful analysis is needed to determine whether this is possible. A detailed study of the hydrodynamics and sediment transport in the southern part of Budd Inlet would be necessary, and it may be that no acceptable solution can be found to the problem of directing the sediment away from the deep channel and towards the littoral zone.

Finally, it is necessary to recognize that opening the tide gate and restoring the sediment supply would not be a near term fix. It would take years or even decades for the new sediment transport patterns throughout Budd Inlet to become reestablished.

5.2.7 Dana Passage

Dana Passage is similar to Squaxin Passage, although it is less erosional. Localized restorations in pocket beaches or at inlets along Dana Passage could be effective. Beach nourishment on a reach-wide basis would be less effective; the nourished sediment would rapidly be lost offshore.

5.2.8 Henderson Inlet

Uniquely, among the four inlets in Thurston County, Henderson Inlet traps some sediment from outside the inlet due to littoral drift. The drift direction directly northwest of the inlet along Dana Passage is to the south into the inlet. Henderson Inlet also appears to be the most rapidly eroding of the four inlets and is similar to the much more exposed Dana Passage. For example, bulkhead footings were observed to be exposed at all of the bulkhead transects in Dana Passage. This suggests that significant amounts of sediment are being lost offshore.

Even though Henderson Inlet is relatively lightly developed at present and it has the least armoring (19 percent), pressure for further armoring is likely to grow. This is an area where softer measures such as beach nourishment should be particularly encouraged. The alongshore transport is relatively slow over much of the inlet, so that sediment will generally remain where it is deposited. Management measures that take into account that this area will remain erosional, together with targeted restorations, are appropriate here.

5.2.9 Nisqually Reach

There is no one predominant drift direction along the Nisqually Reach, suggesting that much of the beach sediment in this area is locally sourced. Field observations suggest that this reach is more erosional than indicated by the statistical analysis of beach profile performed in this study. Hardpan and other qualitative evidence of erosion were observed in several transects, and 40 percent of the reach is armored.

Within the Nisqually Reach, targeted restoration at inlet and pocket beaches should be designed taking into account the fact that at present there is a sediment deficit.

In summary, the sediment budget analysis conducted for this study and discussed above can be summarized as follows:

1. Both large rivers and mass wasting (landslides as well as bluff failures) have the potential to supply significant quantities of sediment to the marine shoreline of Thurston County. The Deschutes River has the potential to make a significant contribution to the sediment supply to the

west shore of Budd Inlet if a connection to the littoral zone can be achieved. Relatively little sediment is available to enter the system from small creeks.

2. Sediment is lost both alongshore to the north, eventually reaching the deep channels to the north of Thurston County, and offshore into the inlets of Thurston County. A large fraction of this shoreline is naturally erosional.

3. Bulkheads and other armoring structures can invoke physical changes to beaches that would otherwise not occur.

4. Bulkheads and other armoring structures affect sediment recruitment by decreasing or obstructing sediment input from actively eroding bluffs and landslides, thus likely adversely affecting forage fish habitat throughout partially bulkheaded drift cells.

5.3 Future Sediment Supply

Future changes to the sediment supply are likely to be mixed and to depend more on land uses than on direct actions at the shoreline (construction or removal of bulkheads). From a qualitative perspective, it appears that a decrease in sediment supply will likely continue to occur unless reasonable planning-level precautions are taken.

Restoration of the Deschutes River as an estuary has the potential to make a significant contribution to the sediment supply to the western shore of Budd Inlet, although very careful analysis and design of the restoration would be needed and any change would likely take decades to be fully realized.

Other fluvial sediment sources are likely to remain essentially constant, in that no major dam construction or removal efforts are anticipated and that current stormwater management requirements do not allow developments to introduce significant changes to river and stream hydrology.

5.4 Beach Profiles

Twenty-nine paired beach profiles were surveyed at sites representative of Puget Sound shorelines in Thurston County. Each pair of beach profiles consisted of an unarmored and armored (vertical concrete bulkhead or rock revetment) site. Results clearly showed that beaches backed by armoring tend to have lower top of beach elevations (different morphology), less habitat, less beach between MLLW and MHHW, and are less likely to be shaded when compared to unprotected beaches. In addition, bulkheads placed below MHHW cause a physical elimination of upper beach habitat, including forage fish spawning habitat.

Figure 5-2 illustrates the difference between a shoreline with and without an upper beach. The beach is entirely submerged along the bulkhead at this location while about 15 feet of beach profile remains exposed at the adjacent site. The concrete wall extending perpendicular from the bulkhead may be acting as a barrier to littoral drift, possibly contributing to loss of beach adjacent to the bulkhead. However, because the beach surface is level with the wall, sediment is clearly being passed over the wall to the bulkheaded beach. This figure also illustrates the physical habitat elimination that takes place when a bulkhead is placed below MHHW.

The results of this study show that beach profile (morphology) in Thurston County is affected by the presence of armoring through beach encroachment. The effect of encroachment on beach morphology is illustrated by two Budd Inlet beach profiles, each with bulkheads that extend to different distances onto the beach (Figure 5-3). The bulkhead at site 27 extends only about 5 feet onto the beach, whereas the bulkhead at 27A extends 20 feet onto the beach. The horizontal distance (Δx) difference from the top of beach at site 27A to the point of intersection of the site 27 transect is approximately 18 feet. These two profiles show no difference in beach slope but do demonstrate that encroachment reduces the extent of upper beach habitat and lowers the beach elevation (profile).

5.4.1 Beach Profile and Sediment Characteristics

Results from beach profile analysis performed in this study showed that both beach width and the width of habitat were significantly shorter and lower in elevation between MTL and MHHW in front of bulkheads. However, the beach profile analyses showed no statistically significant difference in substrate type between the unarmored and the armored shorelines regardless of their beach profile (morphology) characteristics. In spite of this, this study found a slight, statistically nonsignificant shift from sand to gravel and (to a smaller degree) to cobble at armored shoreline areas (see Figure 4-13 in Chapter 4).

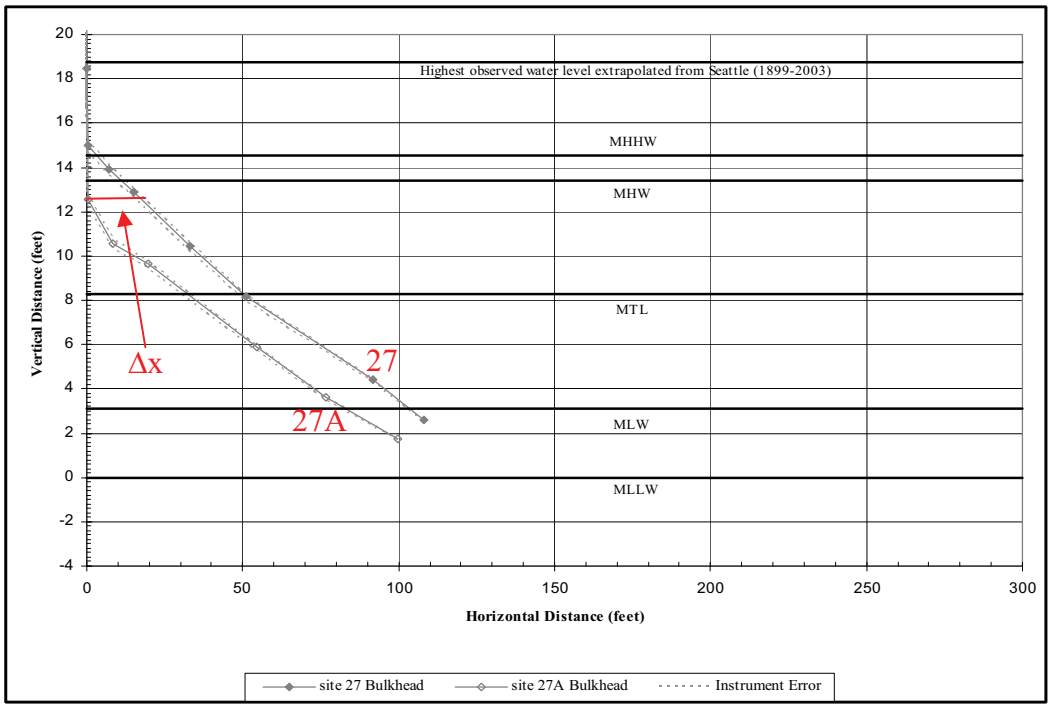
Although this study did not find a statistical significant difference in sediment size between unarmored and armored sites, scientific quantitative evidence exists (Sobocinski 2003) showing that armored sites have coarser sediments (dominated by gravel) than unarmored sites (which have a mixed-medium grain size). A recent study on the impact of shoreline armoring on supratidal beach fauna in central Puget Sound found that sediments were dominated by gravel (<2000 μm diameter) at altered beaches and medium sand (<250 μm diameter) at unarmored beaches, based on a sediment grain size analysis conducted at paired sites. In addition, all but one of the unarmored beaches sampled had more uniform sediment size distribution (sorting) than altered beaches based on core samples analyzed for sediment grain size (Sobocinski 2003).

5.5 Shoreline Retreat and Bulkheads

The amount of shoreline retreat was estimated (see Table 5-2) using the concept of passive erosion. Passive erosion is the narrowing of a beach due to the retreat of a generally recessional shoreline towards a fixed point such as a bulkhead. Passive erosion (as distinguished from active

Figure 5-2. Illustration of adjacent beaches with and without an upper beach; Northwest Eld Inlet, September 8, 2003.

Paired beach profiles, Budd Inlet.



Site 27A

Site 27

Figure 5-3. Paired armored transects in Budd Inlet showing bulkhead encroachment at sites 27 and 27A and their horizontal distance difference (Δx) as measured from the top of beach. Bulkhead 27A encroaches on beach more than bulkhead 27. Photos and cross-sections recorded on August 27, 2003.

erosion) is an increase in the retreat rate due to interactions between a bulkhead and the waves and currents responsible for sediment transport (e.g., toe scour). As described previously, the relative retreat in the shoreline was evaluated for each pair of beach sites. Assuming that the paired sites are equivalent in every way except for the presence of armoring, this shoreline retreat is precisely equal to the distance that that the shoreline has retreated during the lifetime of the armoring.

This measure of retreat distance tends to overestimate the typical retreat distance for an inlet in two ways. First, it is generally the case that the more erosional stretches of beach are more likely to be armored. This means that the rate of shoreline retreat at armored locations is likely to be greater than at unarmored locations, but this is because property owners are more likely to go to the expense of constructing bulkheads if they observe rapid erosion threatening their property. At locations that naturally have a low erosion rate, property owners are less likely to perceive a threat to their property and are more likely to leave the shoreline in a natural state. Second, if a bulkhead was constructed on fill, then there is a fixed contribution to the loss of beach through encroachment and this encroachment loss will add to the loss due to passive erosion. Fill and encroachment can sometimes be identified from current or historical photographs.

The differences between unarmored and armored transects may be caused by various processes. Bulkheads may prohibit landslides and could consequently starve the beach of sediment. Also, bulkheads may increase wave action on the beach surface and remove sediment from the beach.

The difference between encroachment and erosion (active or passive) in front of a bulkhead cannot be determined from examining the transect plots alone; additional information is needed, such as exposure of bulkhead toe, estimation of encroachment distance, and beach surface coarsening (a thin layer of coarse sediment on the beach face). Photographs and field notes were reviewed in order to quantify this information. Exposure of bulkhead toe was noted for each transect where present; encroachment distance was estimated from the field and aerial photographs and then compared to the surveyed top of beach retreat distance. Results are summarized in Figure 5-4. Results showed six out of the 29 paired transects display exposure of the bulkhead toe; 13 out of 29 paired transects displayed beach retreat distance greater than encroachment distance; three out of the 29 displayed beach retreat distance less than encroachment distance; and seven out of 29 displayed no apparent change. The average distance of bulkhead encroachment onto the upper beach for each inlet is summarized in Table 5-4.

5.6 Wave Reflection and Energy

Active erosion refers to the process by which bulkheads actually accelerate the rate of shoreline erosion, presumably through increased wave reflection. Wave energy delivered to shorelines is either dissipated onto the shoreline as breaking or surging waves and swash or reflected offshore. Shoreline characteristics that influence how wave energy is dissipated include: 1) slope (steeper slopes lead to greater reflection), 2) roughness (smoother slopes lead to greater reflection), 3) sediment, and 4) orientation relative to wave crests.

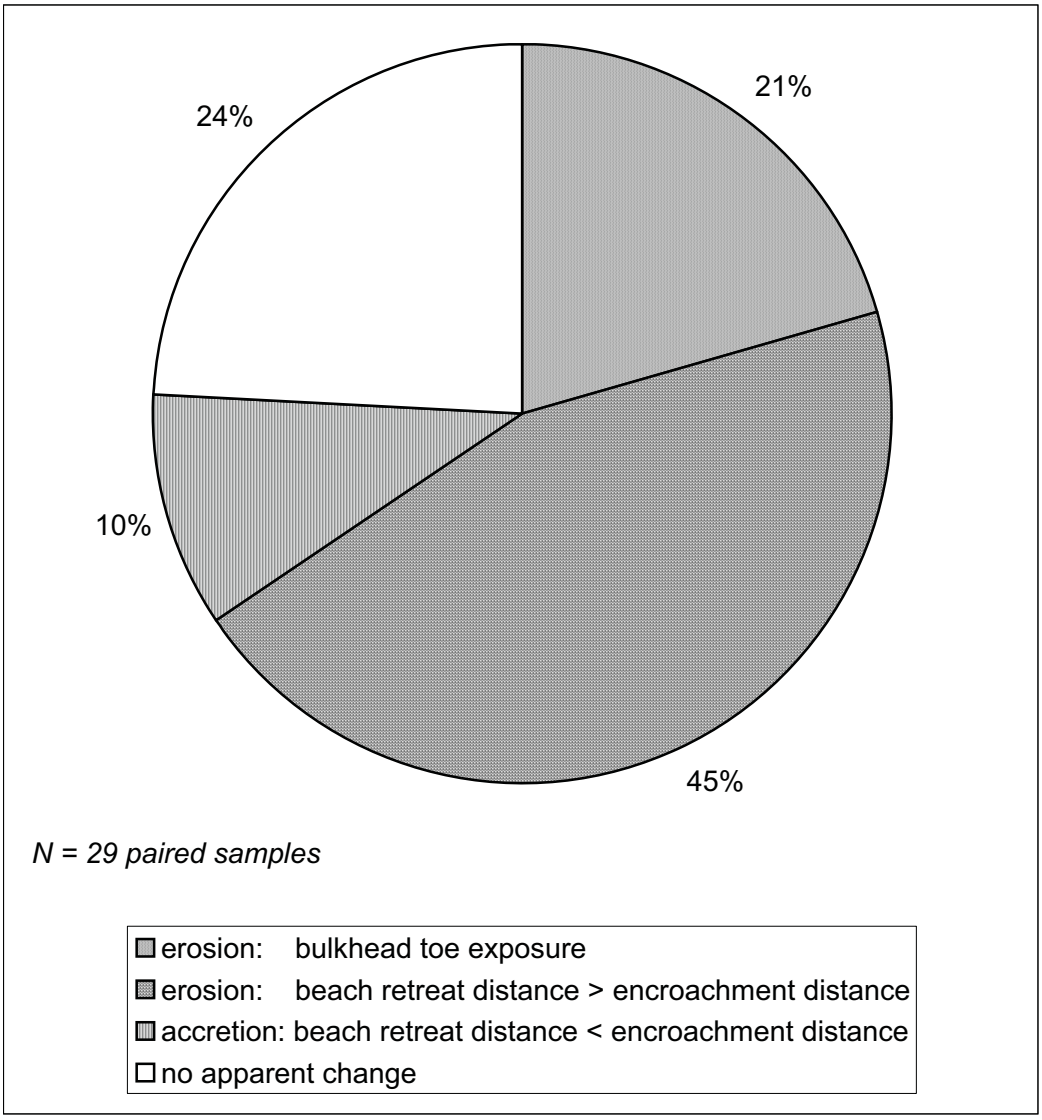


Figure 5-4. Pie chart summarizing the percent of erosion and accretion occurring in the 29 paired Thurston County beach transects.

Table 5-4. Average bulkhead encroachment distance onto upper beach, by inlet.

Inlet	Side of Inlet	Length of Shoreline (ft)	Length of Bulkheads (ft)	Percent of Shoreline Armored	Area of Beach Covered by Bulkheads and Related Fill (ft^2)	Average Encroachment onto Upper Beach by Bulkheads (ft)
Totten	East	81,657	15,328	19%	125,347	8.2
Squaxin Passage		12,435	8,834	71%	48,308	5.5
Eld	East	90,633	30,149	33%	129,133	4.3
	West	109,176	42,109	39%	145,646	3.5
Budd	East	54,071	13,138	24%	193,190	14.7
	Olympia [a]	24,517	23,102	94%	–	–
	West	43,334	30,886	71%	629,801	20.4
Dana Passage		44,613	16,614	37%	96,279	5.8
Henderson	East	50,795	13,397	26%	244,445	18.2
	West	62,177	7,995	13%	168,877	21.1
Nisqually Reach [b]		62,836	25,111	40%	501,549	20.0
All inlets		636,246	226,663	36%	2,282,575	10.1

[a] Bulkhead encroachment along the Olympia shoreline could not be estimated because the natural shoreline location could not be determined.
[b] A portion of the Nisqually River shoreline is excluded from this and other tables because it is not strictly marine in nature.
Data source: TRPC 2003a.

The ratio of reflected wave height, H_r, to incident wave height, H_i, referred to as the reflection coefficient, χ, provides a measure to evaluate the effect of shoreline armoring. Reflection coefficients depend on the composition, geometry (e.g., slope and curvature), and relative depth of a structure and the incident wave characteristics. Relative depth is defined as water depth at toe of the structure, d_s, over the wavelength of incident waves, L. Reflection coefficients range from 0 (no reflection) to 1 for total reflection (CERC 1984).

Typically only a fraction of the incident wave energy is reflected since wave energy is dissipated during its approach and after it is reflected (Figures 5-5 and 5-6). Vertical walls, whether natural or artificial, tend to reflect wave energy offshore. An illustration comparing an unarmored alluvial beach and vertical concrete bulkhead that encroaches into the upper tidal zone is illustrated in Figure 5-7, near high tide. Bulkheads with vertical or re-curved slopes can deflect wave energy downward, and can cause scouring of the bottom sediment at the bulkhead toe and periphery (Engineering Science 1981, Zabawa and Ostrom 1982, CERC 1984). This in turn may increase the erosion rate in front of a bulkhead, although the field evidence of this is inclusive (Kraus and McDougal 1996; Wiegel 2002).

The study results presented here do not conclusively show that active erosion caused through wave reflection is occurring along the shoreline of Thurston County. In order to demonstrate active erosion, it would be necessary to directly measure wave reflection energy and the erosion rate at an unarmored and an armored site (and, if possible, at a comparable site armored by revetment). This has not been possible during a single season's field effort. However, this does not diminish the other potential impacts that may result from armoring, including passive erosion and shoreline simplification that can degrade habitat quality.

5.6.1 Effect of Armoring and Wood Debris on Wave Energy Dissipation

There are theoretical reasons to believe that increasing the roughness and decreasing the slope of shoreline armoring structures can help to dissipate wave energy, in contrast to smooth, steep (vertical) structures such as concrete bulkheads that reflect wave energy. These concepts have been integrated into published guidelines for designing shoreline protection structures that minimize wave reflection (CERC 1984). The Army Corps of Engineers recommends that seawalls, bulkheads, and revetments inside harbors dissipate rather than reflect wave energy whenever possible and note the value of "natural" conditions:

> *Natural beaches in a harbor are excellent wave dissipators, and proposed harbor modifications which would decrease beach areas should be carefully evaluated prior to construction* (CERC 1984).

Figure 5-7 illustrates two types of wave energy reflection: a) wave breaking and dissipating energy on beach, b) wave reflected off a vertical bulkhead.

The following discussion describes the role of roughness elements in dissipating wave energy and the potential implications with regards to stable wood debris accumulations located on the upper beach. In theory, a stable deposit of multiple large tree boles could act as an effective structure for dissipating wave energy. Wave reflection would be inversely proportional to the number and size of tree boles deposited on the beach.

The magnitude of wave reflection for particular beach or structure conditions is measured as the ratio of the reflected wave height, Hr, to the incident wave height, Hi:

$$\chi = \frac{H_r}{H_i}$$

where χ is the reflection coefficient (Figure 5-8). Wave reflection is dependent on the slope, roughness and permeability of the beach or structure and the angle of wave approach and wave steepness (CERC 1984, p. 2-116). The reflection coefficient of rubble breakwaters or revetments can be estimated using empirical guidelines:

$$\chi = \alpha_1 \, \alpha_2 \, X_i$$

where X_i is estimated reflection coefficient and α_1 and α_2 are reflection factors that take into account structure slope, rock diameter, and the number of rubble layers (CERC 1984). For waves approaching a beach orthogonally (wave crests parallel to shoreline), Battjes (1974) incorporated beach or structure slope (θ) and wave steepness into a surf similarity parameter, ξ, which can then be used to estimate χ, for different shoreline conditions representing different roughness and permeability (Figure 5-8). The surf similarity parameter is expressed as:

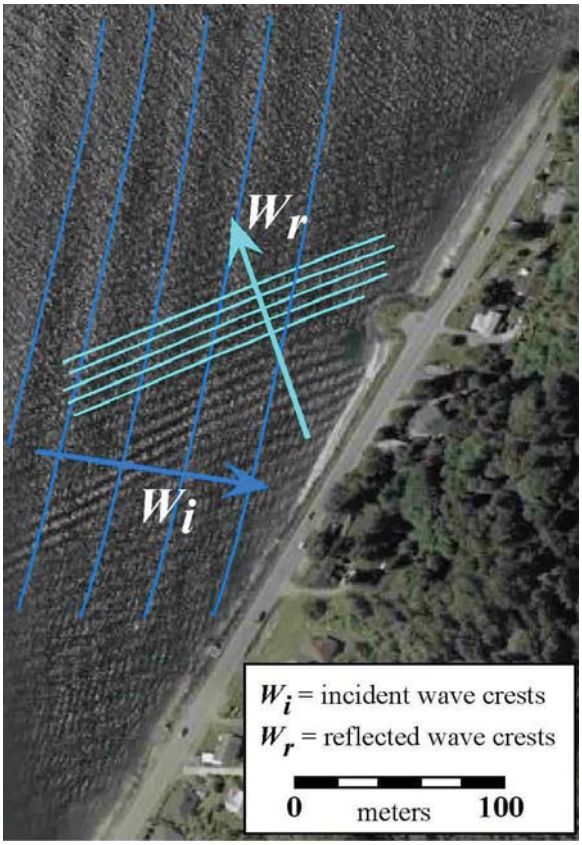


Figure 5-5. Example of wave reflection along a shoreline revetment, Sinclair Inlet, Puget Sound, June 20, 2002 (USGS 2002).

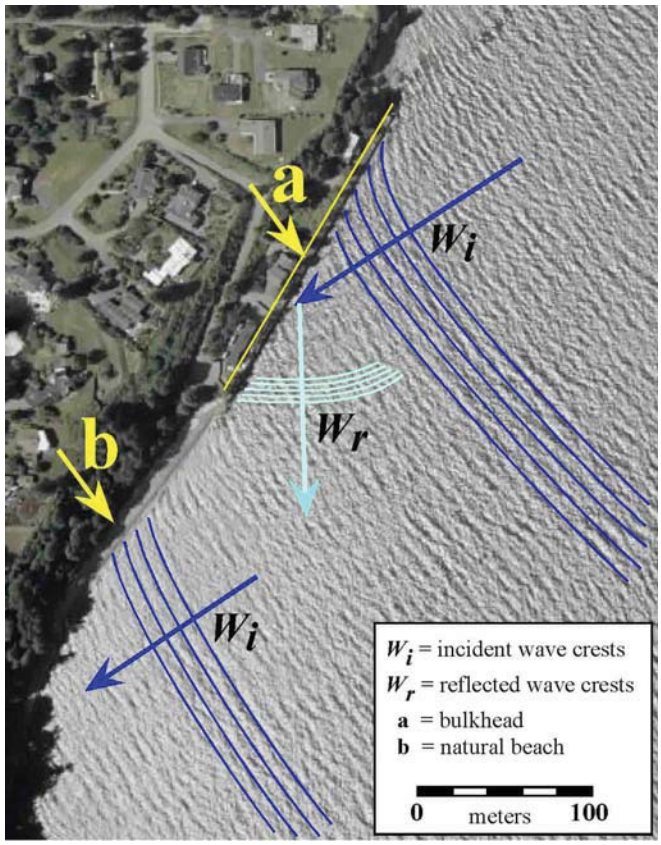


Figure 5-6. Example of wave reflection along a shoreline revetment, Sinclair Inlet, Puget Sound, June 20, 2002 (USGS 2002).

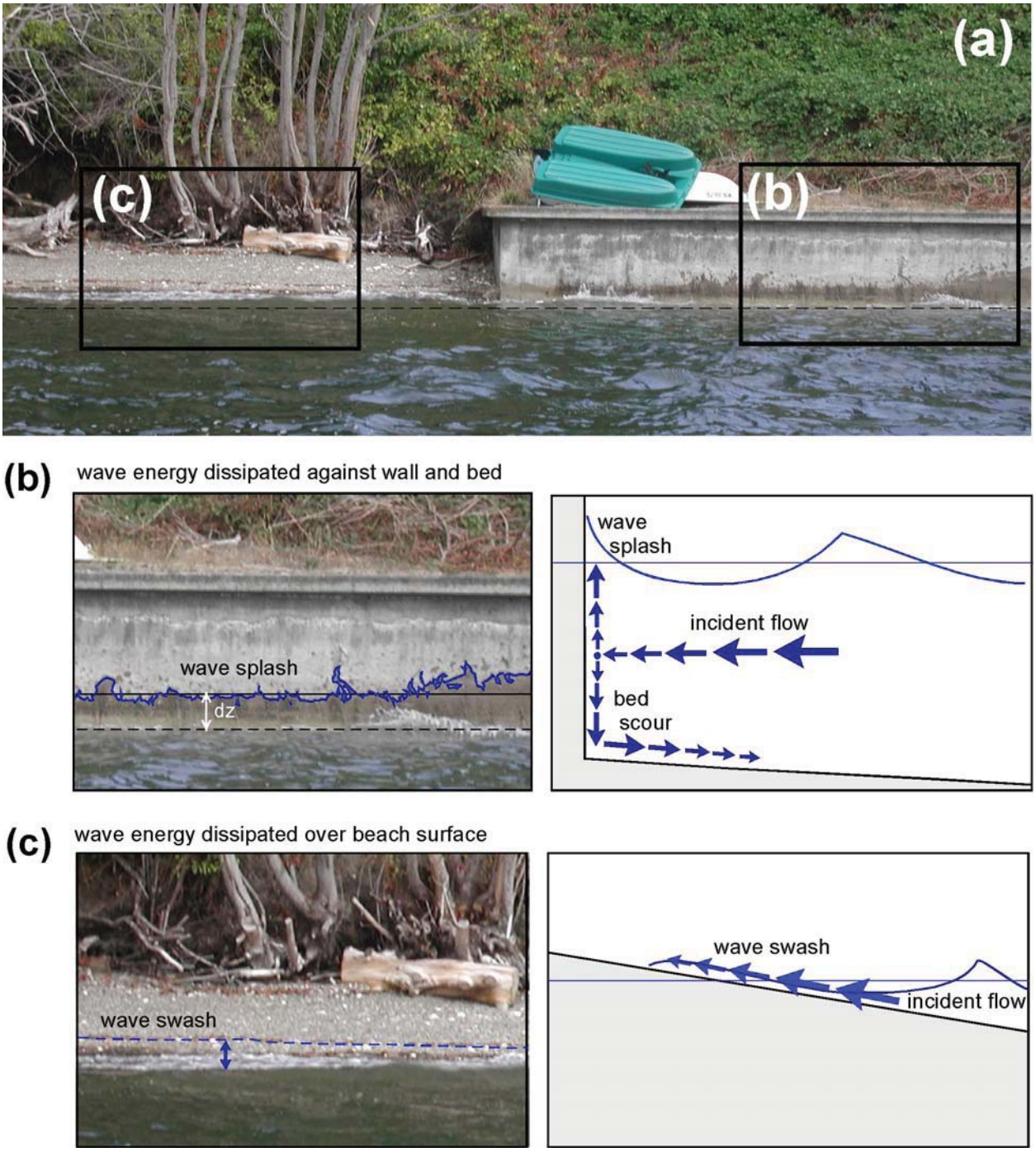


Figure 5-7. (a) Wave energy dissipation along unarmored beach and bulkhead encroaching onto beach. (b) Flow into the bulkhead is deflected upward and downward against the wall. (c) At the unarmored beach, wave energy is dissipated across alluvial sediments through percolation and friction over wood debris and riparian vegetation.

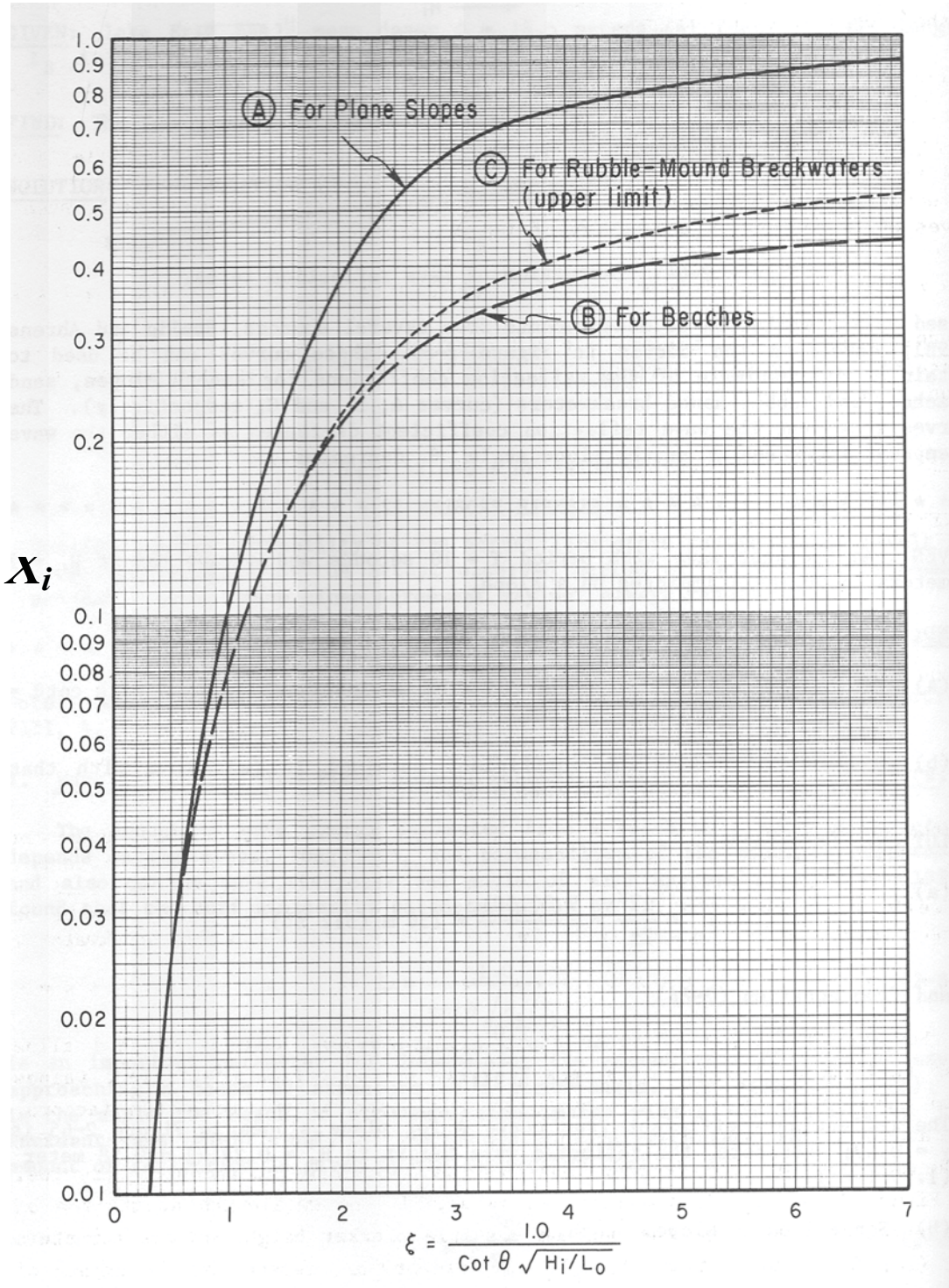


Figure 5-8. Wave reflection coefficients, X_i, for slopes, beaches, and rubble-mound breakwaters as a function of the surf similarity parameter ξ (CERC 1984).

$$\xi = \frac{1.0}{\cot\theta\sqrt{H_i/L_0}}$$

$$= \frac{\tan\theta}{\sqrt{H_i/L_0}}$$

where θ is the angle the beach or structure forms with the horizontal, H_i is incident wave height of incident wave and L_0 is deepwater wavelength of incident wave. The surf similarity parameter rapidly increases with the slope of the structure (Figure 5-9). Design guidelines for rock revetments show that reflection coefficients can be lowered by increasing the diameter and number of layers of rock (Figure 5-10). These basic design principles can be used to show that multiple layers of large wood debris along a shoreline can provide effective energy dissipation, decreasing the amount of wave reflection during higher high water levels, by increasing the roughness of the shoreline and by decreasing its slope relative to a vertical bulkhead.

Stable accumulations of large wood debris occurred on 79 percent of the unarmored beach transects and only 3 percent of the armored transects. Therefore, stable multi-layer placements wood debris may provide a means of providing shoreline armoring that may preserve more upper beach habitat.

Based on the wave energy dissipation factors described above and observations made in this study, it is worth considering whether constructing stable structures along existing bulkheads that emulate natural wood debris accumulations could improve upper beach conditions by trapping sediment or simply by limiting or slowing erosion along the bulkhead. A potential restoration strategy based on these findings is presented in Chapter 6.

5.7 Implications for Forage Fish Spawning Habitat

Surf smelt and Pacific sand lance spawning habitat is created and maintained by natural processes such as beach erosion/accretion and littoral transport which this study shows are locally altered by the presence of bulkheads. The habitat elements specifically identified as affected by the presence of bulkheads includes beach shading/cover along the upper beach area, abundance and distribution of woody debris, and the spawning substrate (sand and pea size gravel) abundance and distribution. The following sections discuss each of these habitat elements.

5.7.1 Beach Shading/Cover

The fact that this study found a significantly (p= 0.0094) higher number of unarmored beaches with shade relative to armored beaches is not necessarily an obvious result. Field observations demonstrated that shade-casting riparian vegetation (forests) can grow at armored sites

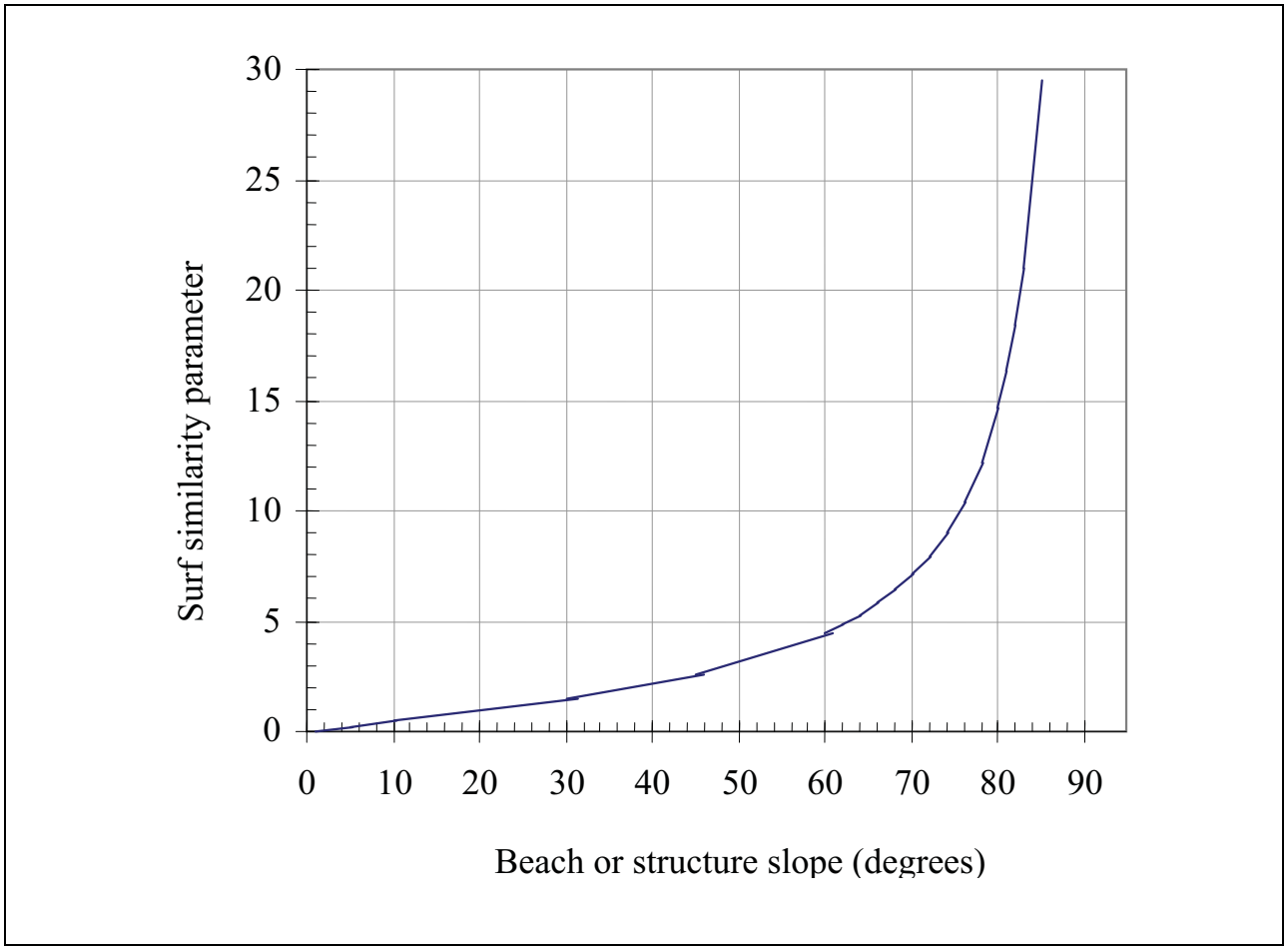


Figure 5-9. Example of exponential increase in surf similarity parameter (SSP) as a function of beach or structure slope, assuming incident H_i=1.5 m and L_0=10 m (adapted from CERC 1984). Higher SSP values are indicative of greater wave reflection.

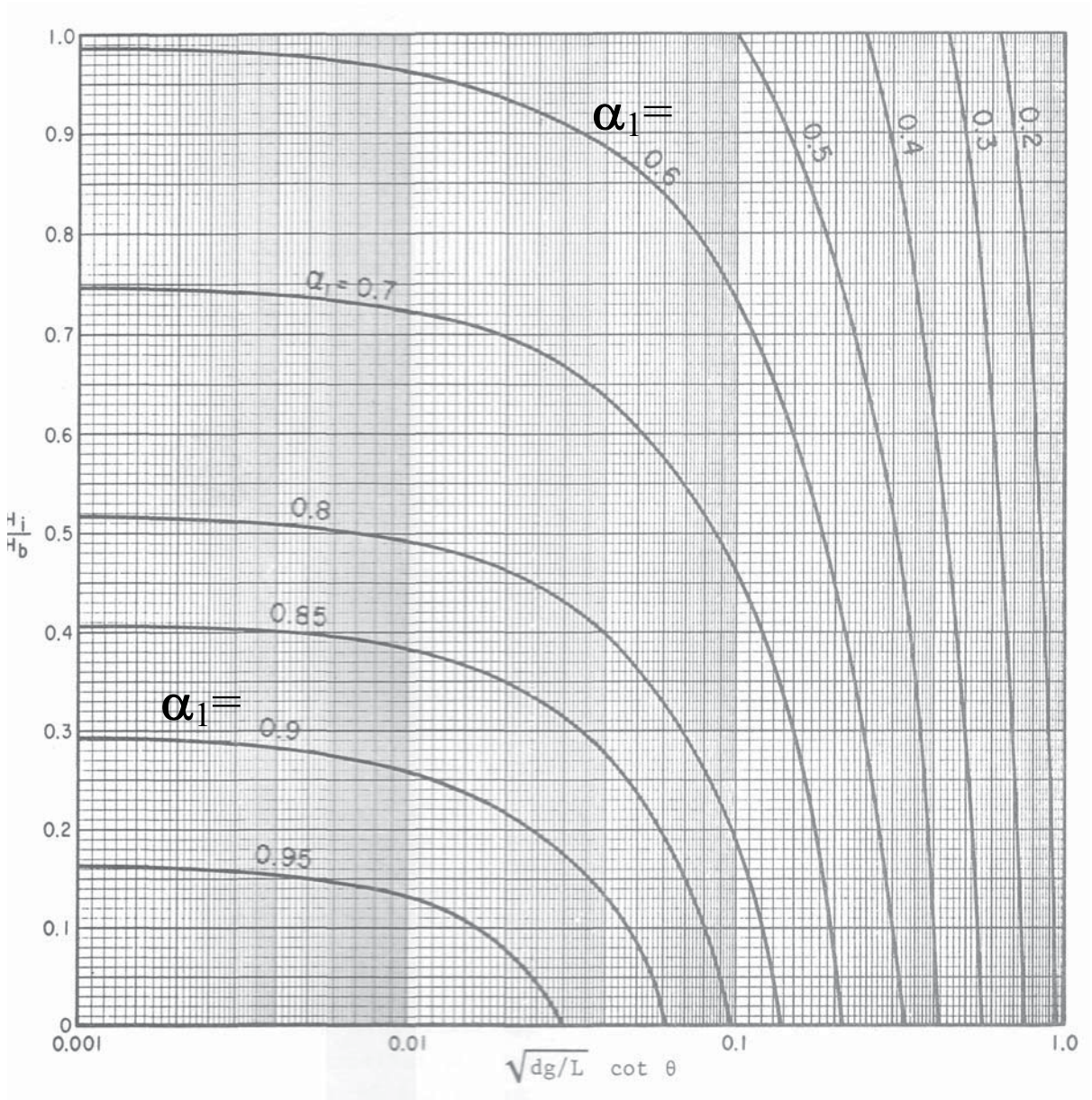


Figure 5-10. Reflection factor α_1 as a function of ratio of incident wave height, H_i, to breaking wave height, H_b, and median diameter of armor elements, dg, deepwater wavelength of incident waves, L, and beach slope θ (CERC 1984).

regardless of the presence of bulkheads (see Figures 5-11a, 5-11b, and 5-12). Also, it appears that the lack of riparian vegetation (and thereby shade) observed at most armored sites is the result of lawn "beautification" and view enhancement activities by the property owner (indirect effects), and not a direct effect of the armoring itself.

Unshaded (sun-exposed) forage fish spawning sites have been found to have significantly higher egg mortality than shaded spawning sites. Furthermore, reduced substrate moisture (increasing the potential for desiccation) in addition to direct solar radiation (direct sun exposure and elevated temperatures) may be important factors influencing forage fish egg viability (Penttila 2001). Therefore, the loss of overhanging riparian vegetation along the Thurston County marine shorelines is likely reducing the survival of forage fish eggs and larvae, and affecting the recruitment potential (abundance) of LWD. In turn, the decline in LWD abundance is likely affecting forage fish habitat by reducing the accretion potential for sand and small gravel.

5.7.2 Abundance and Distribution of Woody Debris

The findings of this study indicate that presence or absence of wood debris was the most significant single factor distinguishing unarmored and armored shorelines. Wood debris was present at 76 percent of unarmored beaches, but only at 3 percent of the armored shorelines. This difference is likely due to a loss of local recruitment capacity along protected shorelines. As noted previously, armoring does not require the removal of riparian forest, and several sites were observed where mature riparian forest has been left intact along bulkheads and where riparian re-forestation was occurring along bulkheads (see Figures 5-11 and 5-12). Field observations performed in this study clearly indicate that where mature trees (particularly with rootwads intact) fall onto the beaches of Thurston County, they tend to stay where they fall. Unfortunately, along with other riparian vegetation, woody debris is typically removed by property owners as part of "beautification" activities performed after the construction of bulkheads. Hence, while local wood recruitment appears to be the principal factor controlling wood accumulation on the beach, human removal may also play a significant role in its loss.

The placement of bulkheads, particularly those that extend below the MHHW elevation, likely also contributes to the loss of woody debris. This loss may be induced by creating deeper water along the bulkheads and by promoting higher wave energy, edge waves, and currents along bulkheads thus limiting the natural anchoring capacity of woody debris as the upper beach area is physically eliminated. In addition, bulkheads likely affect woody debris recruitment by reducing erosion along the toe of bluffs, which is one of the intrinsic functions of these types of man-made shoreline features.

Wood debris accumulations can dramatically increase the physical complexity and hydraulic roughness of the upper beach. Wood debris deposits dissipate wave energy delivered to the upper beach and can be a factor in retarding shoreline erosion (Teriche 1977). Wood debris provides numerous ecological functions by diversifying the composition and size of beach substrate, trapping nutrients and sediment, and providing cover, thus protecting forage fish spawning habitat area. Accumulations of wood debris depend on the supply from upland,

littoral, or offshore sources and on factors such as beach slope, substrate size, size and shape of wood debris, wave energy, currents, and water depths. Allochthonous wood debris accumulations consist of "driftwood" that is delivered from offshore or through littoral transport. Allochthonous wood is subjected to mechanical wear and abrasion that reduces a tree to relatively smooth, straight sections of the original tree. Conversely, autochthonous wood debris accumulations form close to where the wood debris first entered the marine environment, such as a landslide deposit.

In addition, woody debris can: 1) stabilize beaches and help build berms and backshore areas (Brennan and Culverwell 2004) that provide substrate and a source of sediment for forage fish spawning; and 2) provide a source of organic matter, moisture, and nutrients that assist in the establishment and maintenance of dune and marsh plants (Williams and Thom 2001) which can contribute to the maintenance of forage fish spawning habitat.

Therefore, the loss of woody debris and their recruitment potential from the Thurston County marine shorelines is likely reducing the area of existing forage fish habitat. This is a long-term cumulative effect that occurs in addition to the physical habitat loss that takes place when a bulkhead is constructed.

5.7.3 Spawning Substrate Characteristics, Abundance, and Distribution

As noted previously, results from this study show a slight, statistically nonsignificant shift from sand to gravel and (to a smaller degree) to cobble at armored shoreline areas. Other studies have found more significant differences between unarmored and armored beaches. For example, Sobocinski (2003) found unarmored beach sites to be composed predominantly of medium-grained mixed sand, with altered beaches being dominated by gravel. The small difference observed in the present study likely reflects the fact that the bulkheads in Thurston County are typically high on the beach, meaning that they would have less direct impact on the fronting beaches than bulkheads set low on the beach. The sampling methodology used in this study, where only broad grain size classifications were recorded, does not allow the identification of more modest changes such as a shift from fine to coarse sands.

The abundance and distribution of forage fish spawning substrate is altered by the presence of bulkheads through direct and indirect mechanisms. A direct mechanism occurs during the placement (construction) of an armoring structure and results from the physical elimination of spawning area and thereby the loss of suitable substrate to spawn (i.e., sand and pea-size gravel). In this regard, the results from this study show that both beach width and the width of available habitat were significantly less between MTL and MHHW in front of bulkheads when the data from all inlets were analyzed.

Appendix G contains forage fish maps of spawn surveys performed by WDFW along Thurston County marine shorelines in 1996, and between August 2002 and March 2004 (TRPC 2004). According to these maps, the spawning habitat for surf smelt is distributed broadly across the study area. Based on the GIS analysis performed for this study (see Table 2-3 in Chapter 2),

a)

b)

Figure 5-11. Riparian reforestation along bulkheads can provide overhanging vegetation, shade and wood debris to the upper beach, a) Eld Inlet, August 26, 2003, b) Budd Inlet, June 16, 2003.

Figure 5-12. Example of wood debris recruitment despite presence of bulkhead, showing that bulkheads do not preclude sediment delivery and wood recruitment to the upper beach. Northwest Eld Inlet, September 8, 2003.

36 percent of the Thurston County marine shoreline has been armored with bulkheads and rock revetments, which on average, encroach 10.1 linear feet onto the upper beach. (The average distance that is covered by the bulkhead and associated fill from the toe of the bluff to the beach is 10.1 feet.) Where this filled area would otherwise have sand and gravel, forage fish spawning habitat has been lost.

Another mechanism altering the abundance and distribution of forage fish spawning substrate is the beach lowering that occurs at an armored site. In this regard, this study found the top of beach height to be significantly lower in front of bulkheads and other armoring (see Table 4-1). Given that surf smelt and Pacific sand lance typically spawn between the MTL and the MHHW elevation, spawn deposited at armored shorelines is likely subjected to an increased period of tidal inundation. Figure 5-13 presents an inundation frequency curve depicting the percent time that various beach elevations experience inundation. Because this frequency curve changes exponentially between the MTL and the MHHW elevation, a small change in elevation causes a significant increase in inundation or, conversely, tidal exposure time that is experienced by eggs deposited in this area. In this regard, the ecological significance of surf smelt and Pacific sand lance preference for the upper beach area (subject to shorter periods of tidal inundation) to spawn has not been addressed in studies evaluating the effects of shading upland vegetation on surf smelt egg survival on upper intertidal beaches of Puget Sound (Penttila 2001). However, this preference may be a species adaptation to avoid egg predation by aquatic predators and also potentially to minimize egg disturbance due to the increased tidal exchange experienced at lower tidal elevations.

Consequently, beach lowering at armored beaches could have indirect effects on forage fish egg-to-larva survival rate by decreasing the exposure time as compared to that experienced in unarmored beaches. However, no studies exist on the effect of decreased exposure time on egg-to-larva survival rate. Restoration projects, designed to regain some of this exposure time loss, could feasibly improve beach conditions and thereby help to restore a more natural inundation frequency of the upper beach area. This could be achieved by facilitating natural sediment accretion in front of bulkheads, thus regaining some of the loss beach elevation and thereby the time of tidal exposure. This potential restoration strategy is discussed in Chapter 6.

An indirect mechanism that affects the abundance and distribution of forage fish spawning substrate, and investigated in this study, is the loss of woody debris and its recruitment potential through the removal of riparian forests. Field observations made in this study clearly showed woody debris providing structural support for sediment accretion and as a natural sand stabilizer. Depending upon the location, logs high in the intertidal become imbedded and alter the deposition patterns of sand and small gravel. Figure 5-14 shows a typical site where naturally deposited woody debris has contributed to the accretion of substrate and the stabilization of sand in the upper beach area. As noted previously, the presence or absence of woody debris was the most significant single factor distinguishing unarmored and armored shorelines. Therefore, the loss of woody debris associated with bulkheads has likely contributed to the loss of forage fish spawning substrate. In this regard, it has been suggested that impacts on invertebrate assemblages may result from changes in beach elevation, reduced deposition of organic debris, coarsening of sediments, and vegetation removal. This is based on results from previous

synoptic and paired sampling regime analyses that demonstrated the impacts of shoreline armoring on invertebrate assemblages (Sobocinski 2003).

Finally, given that copepods (as well as other forage fish food sources) are important food items for surf smelt that inhabit shallow exposed gavel-cobble and sand-eelgrass habitats (Simenstad et al. 1979), any alteration to these habitats resulting from the effects invoked by bulkheads, would likely also indirectly affect these forage fish species. In this regard, it has been found that shoreline armoring decreases abundance and taxa richness in both benthic infaunal invertebrate and insect assemblages in the supratidal zone, particularly when bulkheads are installed below MHHW and where backshore vegetation has been removed (Sobocinski 2003).

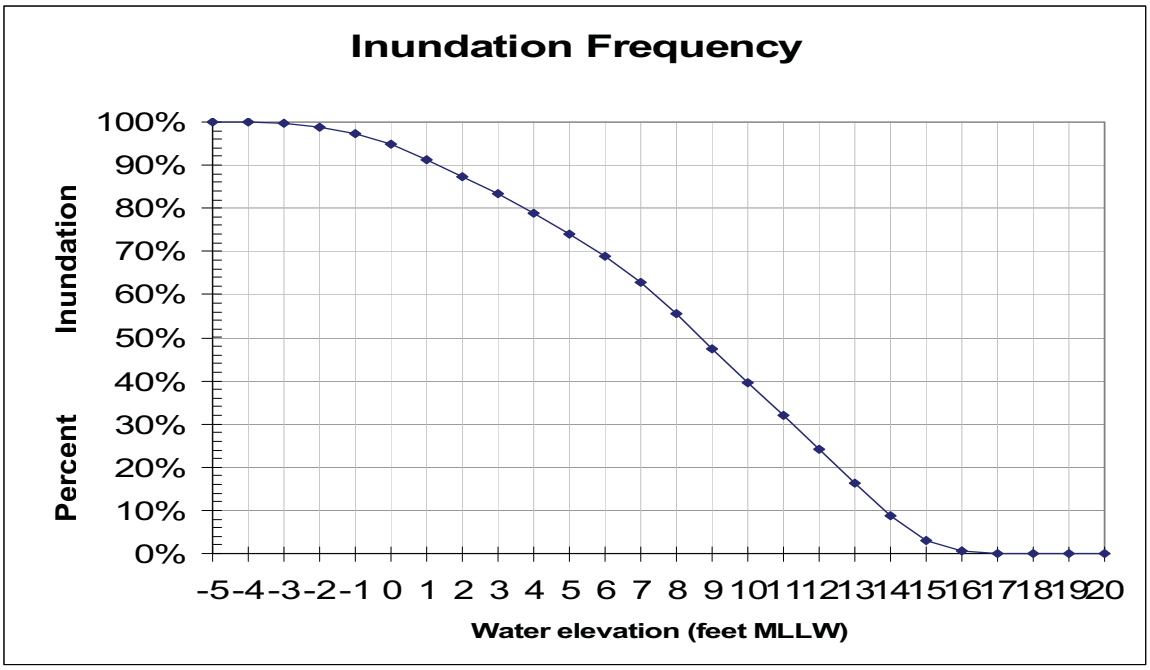


Figure 5-13. Inundation frequency curve depicting the percent time that various beach elevations experience inundation, based on the average mean tidal range for Southern Puget Sound. Source: NOAA Data for 1983–2001 Epoch.

Figure 5-14. Naturally deposited woody debris contributing to the accretion of substrate and the stabilization of sand in the upper beach area. Nisqually Reach, Transect 57. August 28, 2003.

CHAPTER 6

Conclusions and Recommendations

6.0 Conclusions and Recommendations

The majority of Thurston County's marine shoreline lies along coastal bluffs within protected inlets. These bluffs consist of glacial and inter-glacial deposits that are primarily composed of sediment ranging in grain size from clay to coarse cobble. Both rivers and bluff erosion, principally through landsliding, provides a significant source of coarse sediment to Thurston County beaches.

Development along the marine shoreline of Thurston County has led to extensive erosion control measures, dominated by vertical concrete bulkheads. Less than half of the county shoreline associated with gravel and sand beaches remains unarmored. Unarmored sand and gravel beaches extend above MHHW; the upper beach of a naturally eroding shoreline is maintained as the upland area retreats. Armoring along marine shorelines can prevent retreat of the upland behind the structures but does not stop erosion of the beach in front of such structures. Continued erosion of the beach in front of the structures can result in a significant loss in the area of shallow water habitat present during higher high tides.

Much of the marine shoreline of Thurston County is erosional due to regional sediment starvation. This sediment starvation is partly natural and, to a lesser extent, a result of sediment impoundment behind bulkheads. The restoration and preservation opportunities identified in this report include the following:

- Reconnection of the natural sediment supply to the littoral zone, through reconnection of landslides and bluff failures to the beaches. A discussion regarding the possibility of improving the sediment supply to the west side of Budd Inlet by removal of the Capitol Lake dam is included in this report.

- Pilot projects to improve sediment trapping and decrease the rate of erosion and littoral drift through placement of woody debris, alone or in conjunction with beach fills.

- Localized restoration and preservation actions to improve the quality of specific habitat areas through actions such as the reintroduction and preservation of riparian vegetation.

- Planning actions to diminish the regional impact of future development and armoring in the area.

It should be noted that the preservation and restoration recommendations discussed here do not give consideration (or knowledge) of property ownership, the past history of the site, or future plans of property owners.

6.1 Key Findings

Following are several key findings of this study regarding the geomorphic characteristics of the marine shoreline in Thurston County.

1. Shorelines with armoring, particularly bulkheads, differ significantly from unarmored shorelines with regard to the following characteristics:
   - Reduced beach area and thereby reduced forage fish spawning habitat in the upper tidal zone
   - Reduced local sediment recruitment potential
   - Lowered elevation profile of beaches
   - Reduced sand and small gravel areas in relation to the beach width
   - Lack of woody debris from adjacent riparian areas and from offshore
   - Reduced shade/cover along upper beach
2. No significant differences between unarmored and armored shorelines were found with regards to the following characteristics:
   - Beach slope
   - Substrate grain size, although a statistically non-significant coarsening was observed along armored shorelines, which warrants further investigation
3. The following trends were observed regarding the geomorphology of Thurston County shorelines:
   - Coastal bluff height tends to increase from south to north, as does the frequency of landsliding.
   - Armoring has had the likely effect of stopping landslides and may reduce upland inputs of sediments over years or decades.
   - There is a general coarsening of beach sediments from south to north in Totten, Eld, and Henderson Inlets, which generally reflects an increasing potential wave energy from south to north.
4. Development of a general sediment budget for each inlet within the marine shoreline of Thurston County's marine shoreline indicates the following:

- Landslides and larger rivers both have the potential to provide a significant source of sediment.
- Small, typically unnamed creeks do not and have not historically provided a significant source of sediment to the littoral zone of Thurston County.
- If sediment transported by the Deschutes River could be delivered to the littoral system of Budd Inlet through restoring Capitol Lake to an estuary, the nearshore environment of the western shore of Budd Inlet could be significantly improved. Careful study would be needed to determine whether this is possible, given the present morphology and south-directed shore drift in the area.
- Most of the sediment sourced in Thurston County is eventually delivered out of the inlets to the north and into the deep channels to the north of Thurston County. A significant fraction of the sediment, particularly in Eld Inlet and Henderson Inlet, is being lost offshore within the inlet.

5. The loss of upper beach habitat is positively correlated with increased local shoreline armoring (i.e., more bulkheads in an area are associated with increased loss of beach area).
6. Preservation of unarmored shorelines will minimize further impacts to upper beach habitat.
7. Restoration action should focus on evaluating potential solutions for reducing upper beach loss along armored shorelines.

6.2 Data Gaps

Limited information was available regarding sediment discharge to southern Puget Sound either from fluvial systems or coastal erosion. A literature review of fluvial sources was performed to estimate the discharge from fluvial systems based on relative watershed areas; however, no consistently calculated set of areas for the watersheds discharging to southern Puget Sound could be found. A reconnaissance level survey of landsliding was conducted in this study using aerial photographs, digital elevation models, field observations, and published maps.

In addition, this study identified the following data gaps and needs:

1. Repeated topographic surveys of beach profiles over time are needed to obtain more accurate estimates regarding the rate of beach erosion and accretion, including both seasonal and long-term effects. The profiles established in this study could provide a baseline for future surveys. However, it would be necessary to obtain explicit permission from

landowners to set up a fixed survey marker, particularly in unarmored areas where the back beach may not be fixed.

2. Additional data collection is necessary to quantify the effect of bulkheads on wave reflection and to determine if these structures contribute actively to erosion of the upper beach. The repeated topographic surveys recommended in (1) above are a significant element of this. More intensive direct studies of sediment transport (e.g., Abbe 1990) at unarmored and armored shorelines, and areas with and without wood debris should also be performed. Note that most such studies to date (e.g., Miles et al. 2001) have investigated bulkheads that extend much further out into the intertidal zone than those typically observed in Thurston County.

3. Statistically unbiased forage fish surveys are needed better correlate fish utilization with the physical beach characteristics observed in this study. (Existing fish sampling was found to be biased based on beach substrate type.)

4. The role of wood on coastal beaches needs to be investigated, particularly within the context of forage fish spawning habitat maintenance. This should include the role of wood in trapping sediment and in dissipating wave energy for water levels at or above MHHW.

5. Measurements of bedload transport on the beach for various wave conditions are needed to better estimate the sediment mobility of representative beach profiles and substrates.

6. The significance of alternative shoreline armoring techniques needs to be investigated through the use of prototype armoring structures (i.e., "prototype bulkheads"), in order to assess the effectiveness of that technique at rehabilitating the Thurston County marine shoreline.

7. The role of littoral drift in shoreline erosion requires additional investigation in which more sample sites are examined than were possible in this study.

Although this study found no significant differences in substrate grain size distribution between unarmored and armored shorelines, this may have been an artifact of the sampling methodology that only noted grain size classification. The methodology did not, for example, distinguish between fine and coarse sands. Other studies, e.g., Sobocinski (2003), have found more significant differences between unarmored and armored shorelines.

In order to better visualize the existing substrate grain size distribution at unarmored and armored beaches, additional graphic analysis could be performed (see example presented in Figure 6-1). This analysis could provide insights into substrate trends within the upper beach on different beaches, if applied to all the beach profiles (Appendix D).

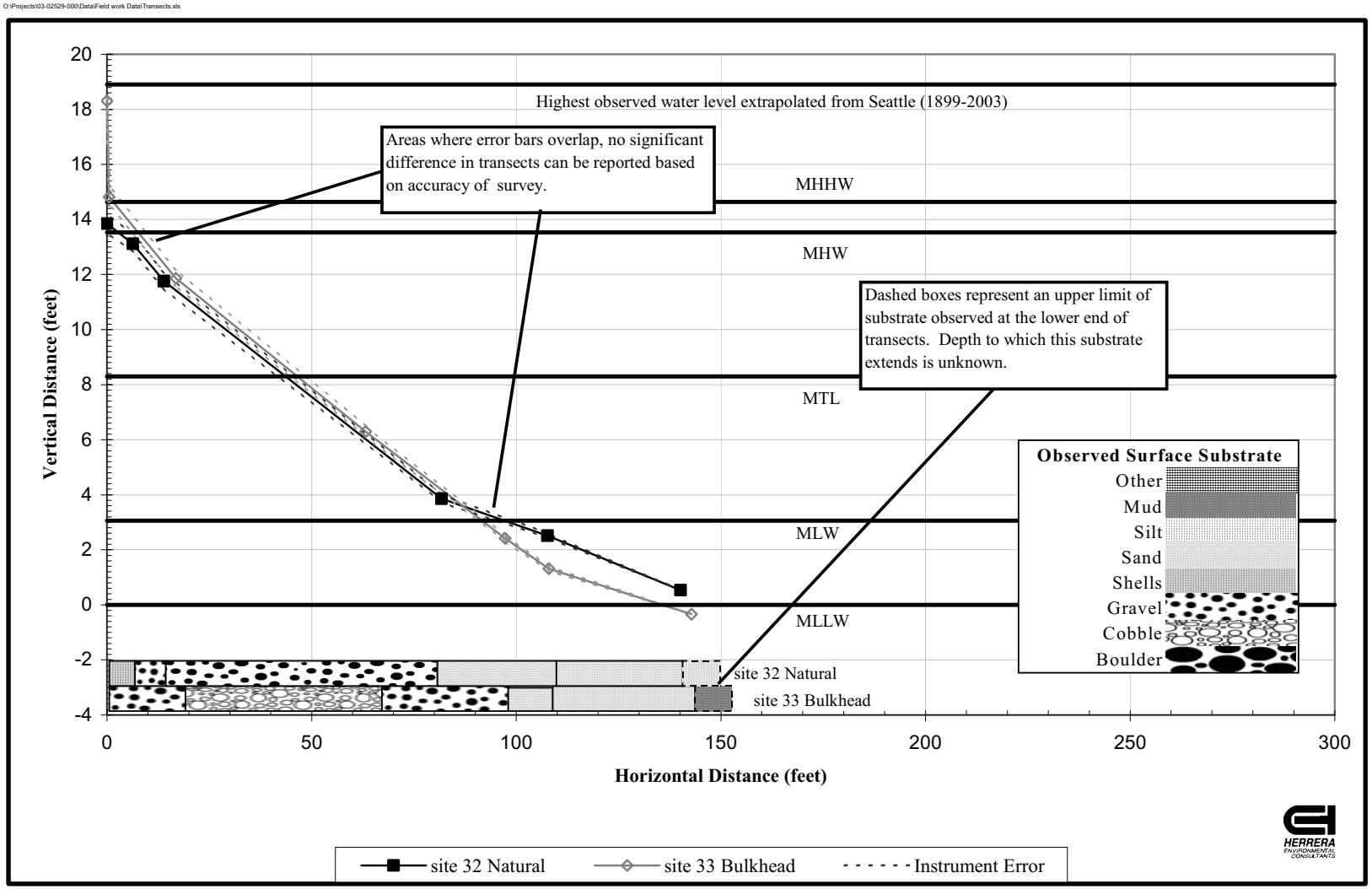


Figure 6-1. Substrate grain size distribution at paired, unarmored and armored beach transects from Budd Inlet sites 32 and 33. Datum: MLLW at Olympia tidal station. Vertical exaggeration is approximately 8:1. Horizontal bars at bottom of figure present observed surface substrate along the transect recorded during the field survey.

6.3 Identification of Preservation and Restoration Sites

Thurston County marine shorelines have undergone significant physical modifications over the last 100 years that have included artificial encroachment into intertidal and even subtidal areas (port facilities in Southern Budd Inlet), shoreline protection measures, and clearing of riparian forests. A variety of shoreline protection measures have been applied in Thurston County, such as: (i) timber pile walls, (ii) horizontal log walls, (iii) log cribs, (iv) rock revetments, and (v) concrete bulkheads, which account for the vast majority of structures observed. Bulkheads are typically located along the upper beach at the toe of adjacent uplands, but it is not uncommon for bulkheads to encroach into the beach profile.

Unarmored beach sites still occur in isolated spots throughout the County on private land and within parks and conservation areas (e.g., Priest Point and Burfoot Parks on the east side of Budd Inlet, Woodard Bay Conservation area on west side of Henderson Inlet, Tolmie State Park along southeast shoreline of Nisqually Reach).

Restoration efforts can focus on both regional and local actions. Regional actions may include reconnecting drift cells with sediment sources, for example, by removing barriers to sediment transport. Local actions may also include restorations that improve forage fish habitat in a single location, such as by restoring riparian vegetation. Local actions, by their nature, do not necessarily affect the broader littoral system.

6.3.1 Erodability of Coastal Bluffs

Coastal bluffs in Thurston County are predominantly quaternary glacial outwash of varying ages and composition. The erodability and composition of coastal bluffs can impact the availability of forage fish spawning habitat areas. Coastal bluffs that are highly erodable and contain coarse sediment may significantly contribute to the formation and maintenance of forage fish habitat.

As noted in Chapter 2 (see section 2.5.2), the most prevalent shoreline material identified by the Washington DNR geology maps is unstratified Vashon till (Qgt), which is composed of highly compacted clay, silt, sand, and gravel (see Table 6-1 for locations). Unstratified Vashon till is not highly erodable. The coastal bluffs of East Budd Inlet, West Eld Inlet, and Squaxin Passage also contain some areas of sand and of Pre-Vashon gravel (Qpg), which is made up of gravel that is relatively resistant to erosion.

Most Thurston County coastal bluffs that are not Vashon till or Pre-Vashon gravel are erodable. Squaxin Passage and Totten Inlet contain large areas of coastal shoreline mapped as landslide deposits (Qls), which are typically made up of rock, soil and organic matter. These deposits are only mapped where landslides are large or landslides obscure the underlying geology. Landslide deposits are indicative of frequent landsliding and are highly erodable. Coastal bluffs along West Budd inlet and East Eld inlet are comprised of Vashon advance outwash (Qga), which consists of sand, gravel, silt, and clay deposited during glacial advance. The Vashon advance outwash is erodable. Coastal bluffs along Henderson inlet and the Nisqually Reach have long

reaches of Latest Vashon fine-grained sediments (Qgof) which is made up of lacustrine clays to fine sandy silts with sparse dropstones. This geologic unit is mapped where it is over 5 feet thick. This unit often fails along bluffs. Pre-Vashon sand-size or finer deposits (Qps) dominate the coastal bluffs of West Budd Inlet, Dana Passage, and Nisqually Reach. These non-glacial deposits of massive to cross-bedded sand are interbedded with silt and gravel. This gravel supports forage fish spawning habitat. This unit is erodable and often fails along bluffs.

Table 6-1. Dominant and subdominant geology observed on Thurston County shorelines.

Inlet Name	Side of Inlet	Dominant Geology	Subdominant Geology
Budd	East	**Qps**	Qpg
	West	**Qga**	Qgt
Dana Passage		**Qps**	Qgt
Eld	East	Qgt	**Qga**
	West	Qgt	Qpg
Henderson	East	Qgt	Qgof
	West	Qgof	Qgt
Nisqually	West	**Qps**	Qgof
Totten	East	Qgt	Qls
Squaxin Passage		Qls	Qpg

Bolded geologic units are erodable sources of coarse sediment.

Of these geologic units, those that are highly erodable and contain sand and gravel are very important contributors to forage fish spawning habitat. Hence, those areas along the Thurston County marine shoreline characterized by the presence of these highly erodible geologic units, likely contribute significantly to the formation and maintenance of this type of habitat.

6.3.2 Forage Fish Spawning Habitat: Suitability, Creation, and Maintenance

A general protocol for prioritizing sites for preservation and restoration was developed specifically with regard to beach sediment, sediment input, and upper beach habitat (Table 6-1). The purpose of this protocol was to identify those sites that provide (i.e., are suitable) and/or have the capability to create and maintain forage fish spawning habitat. Many high priority sites provide necessary substrate for forage fish spawning habitat some of which can be transported to documented forage fish spawning sites. The first factor influencing upper beach environments consisting of coarse sediment (grain sizes equal to and larger than sand) is the sediment supply to sustain these conditions. Sediment supply is provided by either local sources of coarse sediment such as bluffs, streams and rivers, or littoral drift that conveys sediment to the site in question. Because littoral drift and beach erosion are both directly affected by wave energy, site exposure and fetch need to be factored into an assessment of preservation or restoration (see Table 6-2). Additionally, sites with low wave energy typically retain finer sediment (silts), which provide unsuitable substrate for spawning. Sites lacking a major source of coarse sediment and wave energy therefore offer limited opportunity for providing upper beach forage fish habitat. Such areas include much of the low-relief shorelines found at the southern ends of Totten, Eld, and

Henderson Inlets. Priority sites are generally located toward the northern end of Thurston County. These sites are characterized by high bluffs, sources of coarse sediment (e.g., glacial outwash and inter-glacial fluvial deposits) that are susceptible to mass wasting, and high rates of littoral drift due to their exposure and fetch (see Table 6-2). While some areas recommended for preservation or restoration may not host documented forage fish spawning, these areas likely contribute coarse sediment that can be transported to forage fish spawning sites. Spawning sites depend on the preservation of sediment sources as well as the preservation of the sites themselves. In addition to these general observations, there is considerable local variability in habitat quality along the northern portion of the Thurston County shoreline.

Table 6-2. Prioritization criteria for preservation and restoration areas in Thurston County, based on the potential for an area to contribute to forage fish spawning habitat.

Site Characteristic	High Preservation Priority High Restoration Potential	Low Preservation Priority Low Restoration Potential
I. Sediment Supply		
A. Bluff geology		
i. Particle size	Sand and gravel	Smaller than sand
ii. Particle cohesion	Low (i.e., outwash)	High (i.e., till)
iii. Bluff height	High bluff	No bluff
B. Fluvial input		
i. Grain size	Sand and gravel	Smaller than sand
ii. Littoral connection	Yes	No [a]
iii. Proximity to site	Close	Far
II. Wave Energy		
A. Shoreline aspect	Direct exposure to incoming storms (e.g., facing southwest and northward)	Sheltered (leeward) (e.g., east facing)
B. Fetch	Long	Short
C. Bathymetry	Steep and deep	Gradual and shallow
III. Ecological Attributes	High Preservation Priority Low Restoration Potential	Low Preservation Priority High Restoration Potential
A. Overhanging vegetation and woody debris	Mature trees to toe of bluff [b]	No trees [c]

[a] Areas with low littoral connection have high restoration potential if connection can be restored (such as opening Capitol Lake).
[b] High priority for preservation but **low** priority for restoration.
[c] Low priority for preservation but **high** priority for restoration.

Areas along marine shorelines in Thurston County that met most or all of the criteria listed in Table 6-2 are shown as high priority restoration or preservation areas in Figure 6-2. All areas with shoreline armoring that meet most of the high preservation/restoration criteria in Table 6-2 are delineated as restoration sites in Figure 6-2. Sites without shoreline armoring that meet most of the high preservation/restoration criteria are delineated as preservation sites. Restoration and preservation areas were delineated in a general manner using qualitative observations of relief and geology. One implication of this is that some local anomalies such as low elevation areas located near high elevation areas may have been included in the restoration and preservation

delineation. Local variability in site conditions may mean that some areas delineated as preservation sites may require some restoration.

Preservation of shoreline and upland environments is recommended in areas with little disturbance and development. In these areas, much of the shoreline maintains its natural structure with overhanging riparian vegetation, a wide vegetated riparian buffer, large woody debris, and no shoreline armoring. Restoration of shorelines is recommended where bulkheads cover much of the shoreline and where older vegetation has been removed. Conceptual restoration recommendations are discussed below in Section 6.4.

6.3.3 Potential for Preservation and Restoration Actions: Recommendations by Inlet

The potential for successful preservation and restoration varies by inlet and as a result of the differing sediment supply, wave energy, and development practices within each inlet. The following recommendations identify the most suitable approach to preservation and restoration in each inlet:

- Totten Inlet is relatively non-erosive and relatively lightly developed. As a result, the level of armoring is also low. The focus in Totten Inlet should be on preservation actions, particularly through planning actions that limit new armoring. Beach nourishment could also be effective in restoring upper beach habitat, both locally and as a regional (inlet-wide) action.

- Squaxin Passage is very highly developed and receives the highest wave energy in Thurston County. The shoreline is very erosive and heavily armored. The shoreline is also susceptible to deep-seated landslides. These landslides have historically provided significant sediment to the littoral system. However, the sediment does not remain in Thurston County—it rapidly moves north and is lost offshore, past Steamboat Island.

  The focus in Squaxin Passage should be on slowing sediment transport, possibly through the introduction of woody debris, and on the reconnection of landslide-generated material to the littoral zone. However, given the high level of development, this area may not be cost-effective for restoration.

- Eld Inlet is more erosional than Totten Inlet, and the level of development and armoring is higher. Restoration and preservation actions should consider a combination of beach nourishment and slowing sediment transport. For example, it appears likely that there is some loss of sediment offshore into Eld Inlet. This is based upon the high level of shoreline erosion observed in Eld Inlet compared to the other identified sources and sinks. Shoreline erosion in Eld Inlet is likely to lead to more shoreline armoring, and thus Eld Inlet should be targeted for improved

bulkhead siting and more complex bulkhead structures that dissipate wave energy and trap sediment.

The area to the north of Frye Cove is a significant source of sediment through landsliding. However, this sediment is relatively fine. This means that the coarse fraction is important in supplying sediment to the littoral system as a whole, so that the connection of the landslides to the littoral system should be preserved.

- The west shore of Budd Inlet is the most heavily developed and heavily armored shoreline within Thurston County, with the exception of Squaxin Passage. It appears that the bluffs in Budd Inlet are relatively non-erosive. Unarmored and armored sites exhibit poor upper beach habitat conditions. The scope for local restoration is limited here.

- A regional restoration action with significant potential for the west shore of Budd Inlet would be to open up Capitol Lake in such a way as to make the sediment supply from the Deschutes River available to the littoral zone of Budd Inlet. If this could be achieved, the nearshore environment of the western shore of Budd Inlet could be significantly improved. Careful study would be needed to determine the actual level of improvement, given the present morphology and south-directed shore drift in the area.

- The eastern shore of Budd Inlet is less heavily armored than the western shore. In this area, it is critical to preserve the connection between erosive bluffs and the littoral zone: reconnection of the bluffs to the shore through bulkhead removal would also be extremely valuable here. The northern part of this shore is characterized by tall bluffs subject to toe erosion. This means that even relatively benign shore protection, if it is successful in reducing toe erosion, is likely to reduce the sediment supply to this inlet. This is an area where conservation easements may be particularly valuable in preserving the sediment supply.

- Dana Passage is similar to, although less erosional than, Squaxin Passage. Localized restorations in pocket beaches and at estuaries could be effective, and measures to slow sediment transport could be tested. Improvements to the sediment supply would be difficult because of the high rate of littoral transport. Sediments sourced here would rapidly be lost offshore without restoration measures to retain them.

- Henderson Inlet is lightly developed and lightly armored at present. However, it is the most erosive of the four inlets. This means that pressure for further armoring is likely to grow. This area, along with the eastern shore of Budd Inlet, should be a particular focus of soft protection measures.

- Finally, the fact that there is no one predominant drift direction along the Thurston County portion of the Nisqually Reach suggests that much of the beach sediment in this area is locally sourced, despite the presence of the Nisqually River to the east. The tall bluffs towards the north part of this reach provide a source of sediment through bluff toe erosion. The reach is actively eroding and local restorations at pocket beaches and at estuaries could be effective. Limitations and criteria for new bulkhead construction are recommended to help sustain current conditions.

6.3.4 Specific Sites for Preservation and Restoration

Two specific sites have been identified for preservation and restoration actions. Additional factors make these specific sites particularly critical for preservation or restoration. Descriptions of these sites follow:

> Sites A and B are located at the base of deep-seated landslides (Figure 6-2). Preservation and restoration should be considered at these sites for a number of reasons. Bulkheads will not dramatically slow erosion or protect development in this area. Bulkheads that are built here have been, and will continue to be, damaged by landsliding and are ineffective at slowing earth movement over the long term. (Figure 6-3 shows a bulkhead damaged near Site B.) In addition to being ineffective at slowing earth flows, bulkheads have resulted in a loss of upper beach habitat at these sites by reducing the beach width and maximum beach height. Removal of bulkheads at these sites would result in a larger area of habitat. Additionally, in the areas where landsliding is successfully slowed, large woody debris and coarse sediment contributions to the beach are currently restricted. Any fine sediment delivered to the beach from landslides has been and likely will continue to be winnowed away from these high energy areas.

6.4 General Recommendations for Improving Beach Conditions

The results of this study suggest that riparian forests play an important role in maintaining forage fish spawning habitat through the recruitment of woody debris. Therefore, attention should be given to the proper management, preservation, and restoration of marine riparian forest areas along the marine shorelines of Thurston County because the forested areas support habitats that are heavily impacted by the construction of bulkheads and other human activities. Active programs of reforestation for affected shorelines would be expected to enhance and restore intertidal beach habitats for forage fish species. Improved shade and overhanging vegetation can be established even along armored shorelines through riparian reforestation and limiting tree clearing.

Changes in land use practices can also improve some conditions influencing forage fish habitat. For example, discouraging ground improvement on unstable bluffs and encouraging larger

setbacks can increase the sediment supply to the littoral zone by allowing landsliding to continue. In addition, leaving fallen trees on the beach is also likely to improve habitat conditions, particularly if located in front of a bulkhead.

6.4.1 Recommendations Regarding Future Sediment Supply

Bulkheads have two potential impacts on landslides as a source of sediment. First, landslides and upper bluff failures that would otherwise deliver sediment to the beach can be interrupted by bulkheads; the mass wasting continues but the materials are trapped behind the bulkhead. It is recommended that property owners be required to place such materials on the beach, rather than using them to rebuild a bluff (perhaps with a new retaining wall) or transferring the materials to a landfill.

Second, if the mechanism of bluff failure is undercutting the bluff toe followed by failure of the bluff face, then bulkheads can significantly reduce the rate of mass wasting. It appears that this is not the primary mechanism of bluff failure for the majority of the Thurston County shoreline. The main exceptions to this are in the northern parts of the Nisqually Reach, the northeastern shore of Budd Inlet, and the northeastern tip of Totten Inlet. With these exceptions, failures throughout the bluff face are commonly observed. This assessment is supported by evidence of bulkheads that have been damaged by landslides and deep-seated slumps.

The impact of bluff-top land use changes, i.e., deforestation and development, is likely to be mixed. Deforestation tends to increase erosion (and the sediment supply) as the stabilizing effects of the vegetation cover and root system are lost. However, development is often associated with ground improvement intended to decrease mass wasting. A focus on setbacks in geologically unstable areas, rather than on ground improvement or upper bluff armoring, is recommended.

The only significant future changes to the sediment supply are likely to be associated with possible restoration actions at Capitol Lake. Relatively straightforward planning and regulatory actions related to the disposal of landslide-generated sediments and ground improvement at bluff-top sites are likely to maintain the landslide-related sediment supply in its current state. However, these actions alone would not halt the decline in forage fish spawning habitat in Thurston County because much of the marine shoreline in its current state (and likely its natural state) is generally erosional.

6.4.2 Recommendations Regarding Shoreline Protection Measures

To preserve and protect forage fish habitat, all future shoreline protection along beaches suitable for forage fish spawning (sand or gravel) should extend no lower than the maximum astronomical tide (i.e., Weggel Type 3, see Table 5-3). For long-term protection, given sea level rise and land subsidence, this limit should be raised by 1.2 feet to protect habitat through 2050 or 2.9 feet to protect habitat through 2100.

Figure 6-3. Bulkhead cracked by deep-seated landslides (Restoration Site B, Squaxin Passage, August 26, 2003). Note exposed footing at base is evidence of erosion. Bulkheads are ultimately likely to fail without maintenance. Bulkhead failure will trigger new sediment input to the littoral zone.

Erosion control structures should be designed to minimize impacts to the upper beach by effectively dissipating water energy and retaining sediment between MHW and MHHW. Significant decreases in inundation (see Figure 5-13) or, conversely, increases in tidal exposure time (to resemble more natural conditions) could be obtained by small increases in beach elevation through sediment trapping. This means that any restoration action, such as placement of sediment-trapping woody structures in front of bulkheads that has the potential to increase the beach elevation, also has the potential to yield substantial benefits in terms of forage fish egg-to-larva survival rate.

A variety of measures could be employed to preserve and increase the area of upper beach, including discouragement of additional shoreline armoring, removal of existing shoreline armoring, addition of intertidal sills, beach nourishment, and placement of sediment retention structures on the upper beach. Where bulkheads are deemed necessary, wood should be incorporated into restoration projects where possible. The lack of wood is one of the most dramatic differences between unarmored and armored shorelines. Where bulkheads are removed, restoration may result in increased upper-tidal zone area.

Pilot projects incorporating complex driftwood revetments in areas where bulkheads are threatened (such as restoration sites A and B) should be constructed and evaluated. As noted previously, beaches in front of bulkheads often erode, lack shade, have less area covered by sediment on which forage fish spawn, and experience increased periods of tidal inundation. This pilot project should attempt to reverse these trends by creating complex structures that emulate natural wood debris accumulations at the top of the beach. (A conceptual image of this is shown in Figure 6-4.) Driftwood at the top of the beach may slow sediment transport and erosion by reducing wave energy and wave reflection energy and by creating pockets where larger sediment will accumulate. These types of structures would be similar in principle to existing coastal protection structures using inter-locking elements such as “dolos” (CERC 1984).

In a separate or combined pilot project, beach nourishment in combination with drift sills composed of woody debris should also be constructed and evaluated. These drift sills would consist of woody debris placed perpendicular to the shoreline on the upper beach, with sediment (a beach fill) placed on the updrift side of the beach. Shore-perpendicular woody debris is typical of locally recruited wood. In areas of significant longshore drift (particularly along the northern part of Thurston County), shore-perpendicular woody debris may be more successful at trapping sediment compared to shore-parallel woody debris. Drift sills constructed of rock have been tested elsewhere in Puget Sound (Zelo et al. 2000).

Beach response, as measured by sediment types, beach profiles, and forage fish habitat utilization, should be monitored to measure the efficacy of any pilot project. While the structures should resemble complex accumulations of wood debris, they would need to be stable and could be constructed using real logs or concrete logs. Applying several treatments in similar settings is recommended.

Both shore-parallel and shore-perpendicular installations of woody debris can have a relatively large footprint on the beach. In highly eroded beaches, this can be a significant encroachment,

both from the point of view of public access (it becomes more difficult to walk the beach at all but the highest tides), and from the point of view of forage fish habitat (the potential habitat is covered by a driftwood revetment and is no longer present). It is therefore recommended that any wood-based shoreline armoring pilot project be performed in a location where the beach is relatively wide. If the technology is successful in trapping sediment, then it can be tested on more heavily eroded beaches.

Beach nourishment, either alone or in combination with woody debris, should be seriously considered as a shore protection and habitat restoration measure in areas where the wave energy is relatively low. These areas are typically located in the central parts of the inlets, rather than the most northerly parts. This is particularly recommended in Totten and Eld Inlets, because the erosion rate is relatively low in these locations.

6.4.3 Riparian Vegetation and Woody Debris

Observations in this study clearly indicate that where mature trees (with intact rootwads) fall onto the beaches they tend to stay where they fall. The quantity of wood debris found on the beach appears to be proportional to the quantity of local recruitment delivered through tree fall, bank erosion, or mass wasting (primarily the latter). Trees laying perpendicular or oblique to the shoreline with intact branches and barnacles typify stable wood whereas driftwood deposits from offshore typically consist of simple cut logs stacked up parallel to the shoreline.

Woody debris accumulation along the upper beach is one of the most distinctive and widespread characteristics of natural shorelines in southern Puget Sound. As described above, it may also trap sediment and decrease the rate of sediment transport and erosion relative to a “clean”, armored beach. Local wood recruitment appears to be the principal factor controlling wood accumulation on the beach. However, human removal may also play a significant role, because it appears to be a relatively common practice. (See Figure 6-5 for an example of wood cutting.)

Wood cutting and removal from the beach should be discouraged. Restoring wood accumulations, particularly in front of bulkheads, should be encouraged as an important aspect of restoring upper beach habitat. Public education may help to change perceptions, particularly if it can be shown that woody debris both improves habitat and slows erosion.

Where possible, marine shoreline riparian forests along armored shorelines should be re-established. Armoring does not require the removal of riparian forests and several sites were observed where mature riparian forest has been left intact along bulkheads. At other sites, riparian forests are clearly being established along bulkheads (see Figures 5-12a, 5-12b, and 5-13). Re-establishing shoreline riparian forests will improve shading of the upper beach and increase wood recruitment potential.

6.5 Monitoring

Monitoring of beach changes along the Thurston County marine shoreline is a critical need in order to understand what is happening to shoreline habitat and the effects of existing erosion

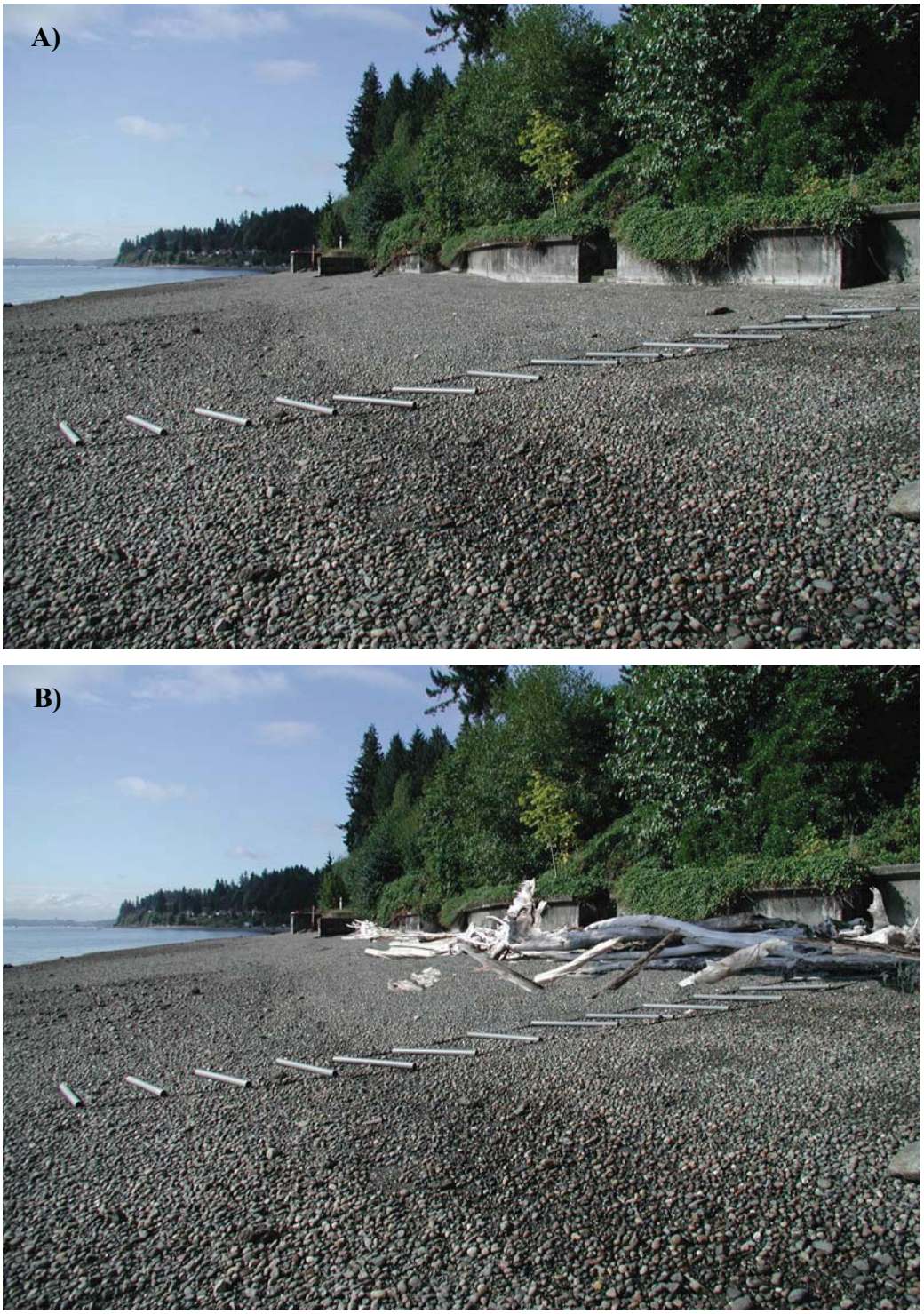


Figure 6-4. Conceptual image of complex driftwood revetment in front of bulkheads (site 27, Budd Inlet, August 2003). A) Bulkheads before treatment. B) Conceptual wood placement after treatment, but without expected sediment response; i.e., sandy areas would be expected to form behind wood.

Figure 6-5. The presence of wood debris on the upper beach appears to be primarily a function of local wood recruitment which is dependent on a source of mature trees and erosion. Human removal of wood may also be a significant factor, such as in this case where cutting and removal has occurred. Unarmored shoreline, Northwest Eld Inlet, September 8, 2004.

control measures. This is particularly important in the preservation, restoration, and control of sites identified in this report. Beach profiles obtained in this study represent a baseline from which future studies should build upon to further investigate and monitor beach sediment changes along Thurston County marine shorelines. Additional beach profile sites (permanent georeferenced transects) should be established at locations within the preservation and restoration areas.

It is strongly recommended that a beach width monitoring program be initiated to measure erosion rates directly. This should include both the erosion rate due to regional sediment starvation and any increased (active) erosion caused directly by shoreline armoring.

However, if a permanent monitoring program is to be implemented, it would be necessary to obtain explicit landowner permission. For example, it would be preferable to establish fixed survey markers for the transects (rather than measuring from the back beach, as was done in this study. Access through the landowner's property rather than from offshore would also allow for more rapid travel between sites. Our experience during the field work for this study was that some (by no means all) landowners would be willing, and indeed enthusiastic, about such a monitoring effort.

Beach response, as measured by sediment types, beach profiles, and forage fish habitat utilization, should be monitored to measure the efficacy of any pilot project. While the structures constructed in a pilot project should resemble complex accumulations of wood debris, they would need to be stable assemblages of real logs or concrete logs. Applying several treatments in similar settings is also recommended.

Useful monitoring could take place at several levels of effort. A useful minimum level of effort would include the following.

- Beach width measurements should take place quarterly, typically in September, December, March, and June. The September and March measurements would represent the widest and narrowest beaches respectively, while the intermediate measurements would give information relating to the rate of seasonal variation. If only two sets of measurements can be recorded annually, they should be in September and March.

- Measurements should include a pair of sites (armored and unarmored) in the northernmost drift cell on each shore of each inlet and the Nisqually Reach, for a total of eight pairs of sites.

- The simplest measurement, which could be performed as a volunteer effort, would be the width of dry beach at high tide. Beach width would be measured from a fixed point. This would include a defined point on the armoring structure for the armored site in each pair. In addition, a pole or other fixed point would need to be established for many unarmored sites. At the unarmored site, the distance from the fixed point to the back of the

beach would also be measured to establish the rate of bluff erosion. The date of the measurement would be selected to give a consistent high tide datum (e.g., the high tide is predicted to occur at MHW). The benefit of a volunteer effort is that multiple sites could be measured simultaneously. If limited numbers of staff were used, then the work would have to be performed over several days and several tidal cycles. All measurements should be combined with a photographic record of the condition of the site(s).

- The next step in cost and complexity would be to perform transect measurements similar to those performed in this study.

- Finally, full bathymetric transects (to -20 feet MLLW or below) could be performed to investigate the extent of the offshore transport of sediment.

Ongoing shoreline development in Thurston County, particularly the illegal construction of bulkheads that encroach upon beach habitat and the removal of riparian forest, will further destroy the upper beach habitat. To evaluate the extent of these practices, an aerial monitoring effort could be conducted periodically. Aerial monitoring could take place using a small aircraft with a pilot (as a left side observer), a data recorder (as a right side observer), and an onboard GPS system used to record locations. Flights can take place on an annual or semi-annual basis. A laptop computer can be used to collect information from the aircraft's GPS unit. Data on shoreline changes can then be collected visually or by using a video camera. When a sighting is called out, the data recorder immediately registers the coordinates with a single keystroke on the computer. Once the flight crew returns, the day's data can be reviewed using a spreadsheet program and data can be then imported into an ArcView basemap. Where unexpected shoreline modifications are discovered, the legality of those modifications would be verified during a field inspection (by boat) and further investigated through Thurston County and state permitting authorities.

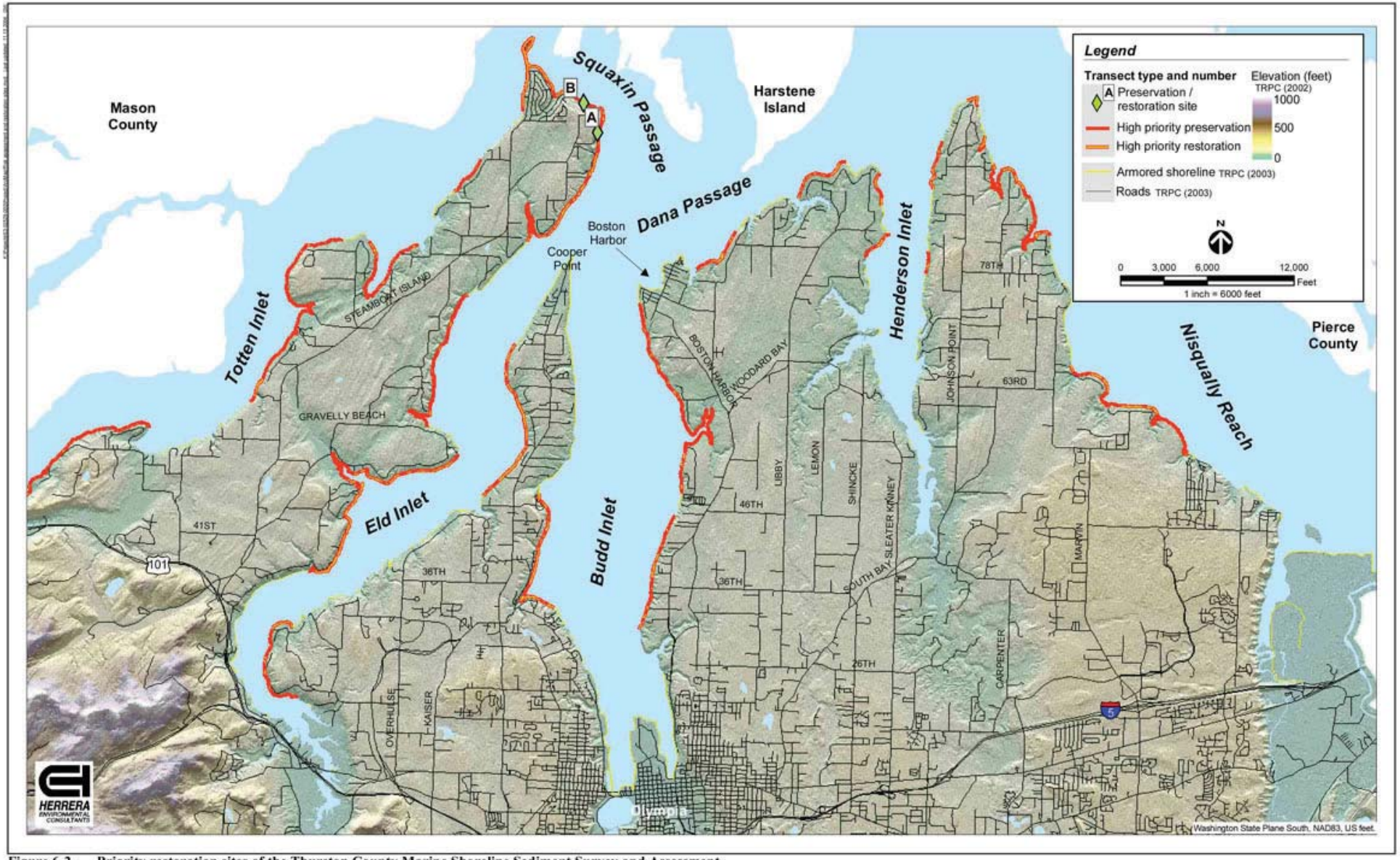


Figure 6-2. Priority restoration sites of the Thurston County Marine Shoreline Sediment Survey and Assessment.