Marine Shorelines Design Guidelines for Puget Sound

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INTRODUCTION

Shore armor—the construction of bulkheads and seawalls—has become a significant environmental issue in the Puget Sound region. Approximately thirty percent of the Puget Sound shore is already armored, and every year approximately 1.5 mi of new shore armor is built and about 2.5 mi of old armor is replaced (Simenstad et al. 2011, Carman et al. 2010). It is the most commonly applied engineering approach for addressing erosion in the Puget Sound region and comes in many forms from revetments to concrete vertical bulkheads.

Armor is typically installed to preclude shoreline erosion (when a landward structure is threatened), however it is infrequently the most appropriate management technique for the problem at hand. Armor often provides more fortification to the shoreline than necessary to protect landward infrastructure or is used largely for landscaping purposes. In other cases, armor is installed where setback distances are insufficient or to preclude bluff recession that is driven by upland geology (as well as waves, Figures 0-1, 0-2). In addition, vegetation clearing, deforestation, invasive species, and poorly managed surface water runoff can exacerbate bluff erosion, amplifying the perceived need for shore protection. In reality, hard armor is typically not necessary to slow erosion throughout much of the sheltered shores of Puget Sound. Yet the extensive application of armor as a "one-sized fits all" solution has resulted in widespread impacts to nearshore processes (Schlenger et al. 2011).

Figure 0-1. Examples of hard armor in the Puget Sound. Armor required due to inadequate setback distance and high fetch (left) and armor ineffective at preventing landslides in unstable area with development (right).

Many armored shores been in place for decades and are losing their structural integrity. For the many unnecessarily armored shores, this is an opportunity for bulkhead removal or to build a more suitable alternative for that particular site with fewer impacts on nearshore resources. Considerable shore armor was installed throughout the region before the implementation of the Shoreline Master Programs (SMP, in the mid-1970s), when viable alternatives were less apparent.

Case study results (Appendix A) and applications of alternative approaches to managing erosion on Puget Sound marine shores have proven several "softer" solutions to be effective if appropriately designed and installed. It is the goal of this document to guide property owners to solutions that match site conditions with design techniques that have fewer costs to nearshore ecosystem functions, goods, and services.

Coastal erosion is a natural process, the sediment from which is essential for ecological processes and nearshore ecosystem health. Shorelines are dynamic features that naturally migrate over time. Building structures too close to the shore can create the perceived need to halt these natural processes of shoreline erosion and bluff recession, which sustain the regions beaches and nearshore habitats. Armor alters nearshore processes, fundamental beach characteristics, coastal ecology, and reduces the resilience of the coast to rising sea level (Williams and Thom 2001). Precluding erosion along individual parcels results in the incremental degradation of various nearshore processes, the cumulative effect of which can result in widespread impairment to nearshore ecosystem functions, goods, and services (Johannessen and MacLennan 2007, Simenstad et al. 2011).

A broad spectrum of shoreline management approaches exist that are appropriate for Puget Sound shores ranging from passive management approaches that require minimal engineering to soft shore protection and hard shore armor. No Action alternatives are characteristically more passive approaches that preserve natural processes and have few to no negative impacts on nearshore ecosystem functions, goods, and services. Soft shore protection approaches preserve the natural beach and typically rely only on natural materials (at least above grade). Soft shore approaches include projects in which gravel and sand are added to the beach (beach nourishment), large wood is installed to curb erosion in the backshore, or the bank is regraded and revegetated to reduce bank erosion.

Table 0-1. Range of approaches, associated design techniques, elements, and impacts.

TYPE OF APPROACH	DESIGN TECHNIQUES	KEY ELEMENTS	IMPACTS
No Action	▪ Best management practices ▪ Managed Retreat	▪ Non-engineered management practices ▪ Preserves/enhances natural processes ▪ Move structures at risk	None
Soft Shore Protection	▪ Large Wood ▪ Beach Nourishment ▪ Reslope/ Revegetation	▪ Preserves shoreline dynamics ▪ Use of natural materials ▪ Slows rather than eliminates erosion	Low
Hard Armor	▪ Revetments ▪ Vertical Bulkhead	▪ Static shoreline ▪ Loss in beach substrate, end erosion ▪ Habitat areas reduced or simplified	Mod- High

Alternative techniques to hard armor have been applied in the Puget Sound for decades, however there has been no previous effort to comprehensively monitor and compare the different techniques or develop a standard of care for their proper design. Phase 1 of the MSDG effort entailed detailed data collection from 25 individual sites across the 5 major design technique types. Design elements and approaches were developed for each technique and criteria were developed to measure project success. These data were integral in forming the guidance and recommendations found throughout this document.

The over-arching objective of the Marine Shoreline Design Guidelines document is to:

- Present alternatives to traditional armoring that could avoid or minimize ecological impacts to Puget Sound nearshore habitats.

- Facilitate better decisions by resource managers and restoration planners about siting and design of alternative erosion control projects that minimize ecological impacts and/or provide greater ecological benefits over traditional armoring.
- Help local jurisdictions and willing citizens to understand and properly care for the aquatic and riparian ecosystems in their communities and watersheds.

Within the Marine Shores Design Guidelines (MSDG) report the reader will be provided with a background on the Puget Sound nearshore environment, the values of stewardship, and comprehensive guidance on how to effectively manage and protect Puget Sound shores for the improvement of the larger nearshore ecosystem. Guidance material and design recommendations integrate the results of assessing the relative success of different shoreline design techniques, which was an earlier phase of the larger MSDG project.

The design methodology for shore protection includes: detailed guidance on how to perform site and coastal processes assessments, measure cumulative risk, identify appropriate design alternatives for site conditions, avoid and mitigate for negative habitat impacts, and the design process entailed for each of the major marine shoreline design techniques (Figure 0-1).

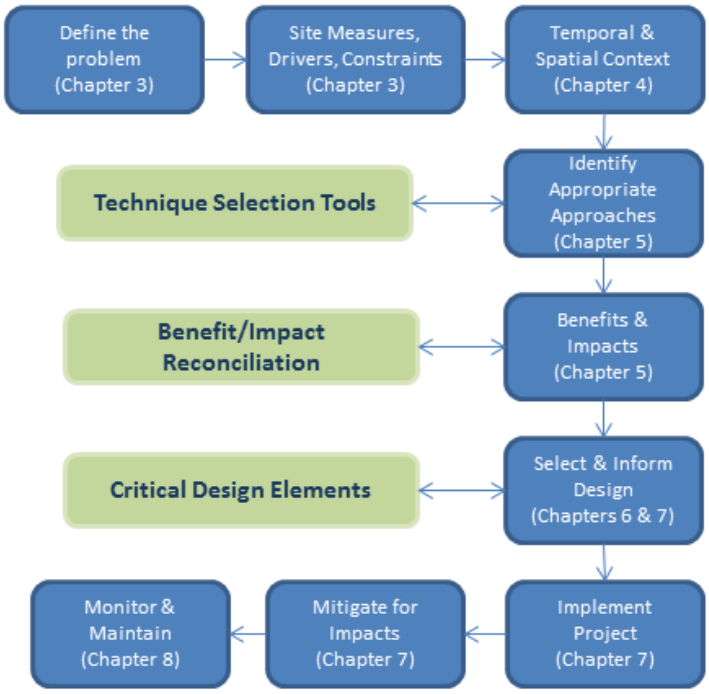

Figure 0-2. Components of the MSDG process for implementing shore protection in the Puget Sound region.

The MSDG was produced through The Aquatic Habitat Guidelines program, which is a group of state agencies and stakeholders whose mission includes the promotion, protection, and restoration of fully functioning marine, freshwater, and riparian habitat through comprehensive and effective management of activities affecting Washington's aquatic and riparian ecosystems. Project participants include the Washington Departments of Fish and Wildlife, Ecology, Transportation, and Natural Resources; the Interagency Committee for Outdoor Recreation; and the Puget Sound Partnership. This broad group produces guidance that has become essential in the design and permitting of aquatic projects.

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GLOSSARY

Accretion: The gradual addition of sediment to a beach or to marsh surface as a result of deposition by flowing water or air. Accretion leads to increases in the elevation of a marsh surface, the seaward building of the coastline, or an increase in the elevation of a beach profile (the opposite of erosion) (Shipman 2008).

Accretion shoreform (AS): Sediment sinks or depositional shores.

Adjacent shores: The adjacent shores are generally considered the immediate vicinity of the project site itself from the project boundary to approximately 100-200 ft alongshore to either side. The length of adjacent shore should extend beyond the area of apparent impacts from the project.

Anchored or Embedded: Characteristics describing LWD placement. Anchoring refers to attachment and embedment refers to depth of LWD below surface.

Anthropogenic: Caused or produced by humans. In the context of this document this term can be described as filling, dredging, armoring or development actions taken in the coastal environment.

Area regraded: Total area that has been reshaped to meet a slope or grade that is in more equilibrium with the surrounding geomorphic conditions.

Armor: Rigid, permanent design techniques used to stabilize shorelines and prevent erosion.

Assessment: Processes that involve analyzing and evaluating the state of scientific knowledge and, in interaction with users, developing information applicable to a particular set of issues or decisions.

Backfill: The materials found immediately behind or landward of a coastal structure. Typically this includes cobbles from the beach, quarry spall, or earth.

Backshore: The upper zone of a beach beyond the reach of normal waves and tides, landward of the beachface. The backshore is subject to periodic flooding by storms and extreme tides, and is often the site of dunes and back-barrier wetlands (Clancy et al. 2009). Width is measured cross-shore from the waterward extent of the backshore to the waterward extent of upland vegetation or anthropogenic modifications.

Bank or Bluff: A steep slope rising from the shore, generally formed by erosion and mass wasting of poorly consolidated material such as glacial or fluvial sediments. The term bluff is typically used in the Pacific Northwest for a steep sea cliff composed of unconsolidated sediment that has no to moderate amounts of vegetation. The term bank is typically used in the Northwest for slower elevation sea cliff with a well vegetated bank face. Within this document bank and bluff may be used interchangeably.

Bank face: The steep section of the bank/bluff sloping towards the beach or shore.

Barrier beach: A linear ridge of sand or gravel extending above high tide, built by wave action and sediment deposition seaward of the original coastline. Includes a variety of depositional coastal landforms, including spits, tombolos, cuspate forelands, and barrier islands (Shipman 2008).

Batter: Backward (landward) slope

Beach: The gently-sloping zone of unconsolidated sediment along the shore that is moved by waves, wind, and tidal currents. Width is measured cross-shore from the break in slope between the upper beach and the low-tide terrace and the waterward extent of the backshore.

Beachface: The section of the beach normally exposed to the action of waves. This is typically the sloping beach between the low tide terrace and the backshore.

Beach scarp: A steep slope produced by wave action.

Beach profile: A vertical cross section of a beach perpendicular to the shoreline.

Bedding: The arrangement of sediments or rock in beds or layers of varying thickness and character.

Bluff: see *bank*

Bulkhead: A hard armor technique usually vertical that maintains soil and abates erosion from waves and currents using rigid material.

Crest elevation: Elevation of upper vertical extent of design, usually referring to hard armor structures.

Crenulated: An undulating or irregularly wavy stretch of shoreline.

Cyclical erosion: Wearing away of the nearshore that tends to occur on a periodic basis through processes that repeat over time (e.g. transport of colluvium resulting in exposure of the bluff toe and subsequent wave-induced mass wasting)**.**

Deep-seated (instability/landslide): Sub-surface conditions that make the slope susceptible to failure/landslide associated with the area's geologic processes and features.

Delta: A deposit of sediment formed at a stream or river mouth, or other location where the slowing of water flow results in sediment deposition (Clancy et al. 2009).

Depth of beach: The vertical thickness of beach sediment veneer on the upper intertidal beach.

Depth of footing: The depth of burial of the toe of the structure.

Detritus: 0rganic materials (seeds, leaf litter, insects) that provide food for marine organisms.

Drainage control: Anthropogenic surface water management devices such as pipes, swales, and drains.

Drift aligned: A beach that is orientated differently than the predominant incoming waves at breaking (after refraction in the shallow nearshore).

Drift cell: A littoral [drift] cell is a coastal compartment that contains a complete cycle of sedimentation including sources, transport paths, and sinks. The cell boundaries delineate the geographical area within which the budget of sediment is balanced, providing the framework for the quantitative analysis of coastal erosion and accretion. See Johannessen and MacLennan (2007) for further description of drift cells.

Drift sill: Low elevation groin, typically constructed of rock, installed along with beach nourishment filled up to height of sill which is sometimes used to hold or slow littoral transport of placed sediment.

Ecosystem: A dynamic complex of plant, animal, and micro-organism communities and their nonliving environment interacting as a functional unit. An ecosystem can be of any size—from a log, pond, field, or forest, to the earth's biosphere—depending upon the organisms that are the frame of reference, but it always functions as a whole unit. Ecosystems are commonly described according to the major type of vegetation, for example, forest ecosystem, old-growth ecosystem, or marine ecosystem.

Ecosystem function: The specific mechanisms through which we benefit from Puget Sound, such as production of forage fish, or wave attenuation. Functions are roughly synonymous with goods and services. Ecosystem functions are delivered through the interaction of processes and structures (Simenstad et al. 2006).

Ecosystem structure: The position and character of the physical components of an ecosystem; the character or "state" of the system. Structures are created through the effects of ecosystem processes, and in turn provide ecosystem function goods and services.

Embayment: An indentation of the shore larger in size than a cove but smaller than a gulf.

Embedded: see *Anchored*

End effects: Erosion immediately adjacent to a hard armor structure due from wave refraction, bank/beach geology, wave energy at the site, the angle of wave approach, angle of the return wall, up-drift sediment supply, and the construction material of the structure.

Enhancement: Any improvement of a structural or functional attribute of an ecosystem.

Erosion: The wearing away of land by the action of natural forces. Pertaining to a beach, the carrying away of beach material by wave action, tidal currents, littoral currents, or deflation (wind action) (opposite of accretion). Erosion may be separated into two categories: long-term erosion, which occurs over decadal or greater scales, and short-term erosion, which occurs at less than decadal scale due to individual storm events or seasonal variability.

Estuary: A semi-enclosed coastal body of water that has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage. Sometimes it is defined more broadly to include other coastal inlets that connect lagoons and swamps to the sea.

Eustatic: Of or pertaining to worldwide changes of sea level.

Extent: A description, to include length and width, of the project area.

Feeder bluff (FB): Coastal bluff with active erosion and/or mass wasting which periodically supplies moderate volumes of sediment to the nearshore with a longer recurrence interval than feeder bluff exceptional segments. The bluff face typically has vegetation indicative of disturbance with evidence of landslides and toe erosion (MacLennan et al 2013)

Feeder bluff exceptional (FBE): Coastal bluff with active erosion and/or mass wasting which periodically supplies substantial volumes of sediment to the nearshore in greater quantities with a shorter recurrence interval than feeder bluffs. The bluff face typically has little to no vegetation with active landslides and toe erosion, and may include colluvium and toppled large woody debris (MacLennan et al 2013).

Fetch: Open water distance over which waves are formed.

Geotextile: Permeable filter fabric.

Gully: A small channel produced by running water in soil or unconsolidated material.

Habitat: The physical, biological, and chemical characteristics of a specific unit of the environment occupied by a specific plant or animal. Habitat is unique to specific organisms and provides all the physical, chemical and biological requirements of that organism within a specific location (Fresh et al. 2004).

Headscarp: A steep surface on the undisturbed ground at the upslope limit of the landslide, caused by movement of the displaced material away from the undisturbed ground. It is the visible part of the surface of rupture.

High tide beach: The sloping portion of the beach profile located above and landward of the low-tide terrace and below mean higher high water.

Hillshade: Cartographic portrayal of topographic relief.

Hummocky: Mounded topography that is the result of landslide activity or debris

Hydrophilic: Having a strong affinity to water

Infrastructure: Anthropogenic upland primary and secondary structures/improvements.

Inundation:

Landslides: A general term covering a large variety of mass wasting and processes involving the downslope transport of soil, sediment, or rock.

Landward: A description meaning towards the land.

Large woody debris (LWD): Large logs with or without root masses attached, and can also include separate root masses.

Large woody debris Recruitment: LWD being actively/recently recruited or eroded from adjacent uplands.

Littoral: Relating to the shore or a region along the shore.

Longshore transport: Transport of sediment parallel to the shore by waves and currents, also called littoral drift.

Low tide terrace: A broad flat portion of the beach profile located near the mean lower low water level.

Man rock: Size of stones roughly based on how many men it would take to move.

Marine riparian: The transitional zone between the uplands and aquatic environments adjacent to marine waters, where marine riparian vegetation is often located.

Mass wasting: A general term for the downslope movement of soil and rock debris.

Morphology: The shape or form of the land surface or of the seabed and the study of its change over time.

Native bank material: The sediment composition of native soils within the marine bank/bluff.

Nearshore: As defined by PSNERP, includes the area from the deepest part of the photic zone (approximately 10 meters below Mean Lower Low Water [MLLW]) landward to the top of coastal bluffs, or in estuaries upstream to the head of tidal influence (Clancy et al. 2009).

No appreciable drift (NAD): Areas in which no appreciable littoral drift occurs.

Overtopping: Waves breaking over the top of a structure or berm and the resulting scour or debris left behind. This can be indicated by drift wood, wrack deposits or scour behind the feature being overtopped.

Permeability: The capacity of a porous rock, sediment, or soil for transmitting a fluid; a measure of the relativity ease of fluid flow under unequal pressure. This most commonly relates to groundwater flow through a bluff or bluff sediments.

Pocket beach: A beach that is contained between two bedrock headlands that essentially functions as a closed system in terms of littoral sediment transport.

Pocket estuary: Term used in the Puget Sound region to describe small estuaries and lagoons (types of embayments) partially isolated by their configuration from the main body of Puget Sound (Shipman 2008).

Primary structure: An element of anthropogenic upland infrastructure/improvements of fundamental importance. Home or residential building.

Process-based restoration: Intentional changes made to an ecosystem to allow natural processes such as erosion, accretion, accumulation of wood debris, etc., to occur. Process-based restoration aims to return the landscape to its pre-disturbance, self-sustaining state. Also defined as the restoration of processes that shape an ecosystem, such as sediment transport or erosion, rather than the restoration of ecosystem features, such as tidal marshes or species populations (Van Cleve et al. 2004).

Progradation: The process where a coast is built waterward by deposition and accumulation as at a spit of a delta.

Protection: Safeguarding ecosystems or ecosystem components from harm caused by human actions.

Quarry Spalls: Rock used for chinking and bedding layer. Typically from broken stone or concrete and approximately 4-8" diameter of each rock.

Relative permeability: The difference in fluid transport properties or capacity between two or more geologic media, affecting fluid flow direction and rate within a given geologic sequence.**Resilience:** The ability of an entity or system to absorb some amount of change, including extreme events, and recover from or adjust to the change or other stress.

Restoration: Returning an ecosystem to a close approximation of its pre-disturbance state in terms of structure and function (NRC 1992). This includes measures needed to protect and preserve restored systems in perpetuity.

Retrogress: A process by which the removal of material from the base of a slope removes support from the slope immediately above it, causing it to fail. This type of failure may gradually extend up the slope in the direction opposite to the movement of the displaced material. Retrogressive landslides are most common in sea cliffs experiencing continuing removal of material from the toe by coastal processes.

Return wall: A section of bulkhead that extends towards land, typically from the end of a shore-parallel bulkhead, and ties into the bank or backshore.

Revetment: A hard armor technique using stone placed on a sloping bank to protect against waves or currents.

Rilling: Small channels eroded into soil or sediment by rivulets of water.

Riprap: A layer of stone installed for erosion control.

Risk: The relative need for the given infrastructure in terms of setback distance, infrastructure type and estimated erosion rate. Erosion rates estimated from maximum measured fetch and shoreform type.

Runup: The rush of waves up the face of a beach or structure produced by breaking waves. The maximum vertical height of water above still water level is the measure of this.

Secondary structure: Element(s) of upland infrastructure that support the primary infrastructure and are not fundamental. Septic systems, patios, non-living residential, gazebo, recreation/park infrastructure, minimal foundation.

Sediment input: Delivery of sediment from bluff, stream, and marine sources into the nearshore. Depending on landscape setting, inputs can vary in scale from acute, low-frequency episodes (hillslope mass wasting from bluffs) to chronic, high-frequency events (some streams and rivers). Sediment input interacts with sediment transport to control the structure of beaches.

Sediment transport: Bedload and suspended transport of sediments and other matter by water and wind along (longshore) and across (cross-shore) the beach. The continuity of sediment transport strongly influences the longshore structure of beaches.

Seepage: Ground water seeps on the marine bank or bluff face.

Setback: Distance of the nearest major infrastructure element (primary or secondary structure) from the coast, measured from bluff crest landward where present, or from OHWM for no-bank sites.

Scour: The removal of sediment in the vicinity of a coastal structure that results in loss of hydrodynamic forces of the structure.

Sheet pile: A pile in a row of piles driven side by side to retain earth and prevent erosion.

Shoreform: A term often used in Puget Sound to describe a coastal landform. The term is generally used to describe landscape features on the scale of hundreds to thousands of meters, such as coastal bluffs, estuaries, barrier beaches, or river deltas.

Significant wave height: The average height of the top 33% of waves.

Slope: The gradient of the beach or bluff face, measured as the vertical rise over a horizontal distance (H:V); may be more than one slope for complicated reslope projects.

Slope failure: An area of mass wasting at the marine bank. Identify indicators and measurements of slope failure on the site, including alongshore width of the failure, height, and approximate age.

Shoreline Process Unit: PSNERP change analysis designation for segments of Puget Sound shoreline where beach sedimentary processes are confined by drift cell indicators of sediment transport zone and adjacent divergence and convergence zones, or areas of no appreciable drift.

Shoretype: The Shipman typology classification for the project area (Shipman 2008). BLB=Bluff backed beach, BAB=Barrier Beach, BE=Barrier estuary, BL=Barrier lagoon, OCI=Open coastal inlet, CLM=Closed lagoon/salt marsh, PB=Pocket Beach, RP=Rocky platform, PL=Plunging rocky shore. The CGS typology classification for the project area (MacLennan 2013). FBE (feeder bluff exceptional), FB (feeder bluff), FB-T (feeder bluff – talus), TZ (transport zone), AS (accretion shoreform), MOD (modified), NAD-B (no appreciable drift – bedrock), NAD-LE (no appreciable drift - low energy), NAD-D (no appreciable drift – delta), NAD-AR (no appreciable drift – artificial).

Storm Surge: Storm surge is a rise of water associated with low pressure weather systems.

Solar radiation: Altered solar patterns due to hotter summers, colder winters.

Still water depth (SWD): The depth of water if there were no waves

Stratigraphy: The arrangement of strata (geologic layers or bedding) relative to geographic position and chronologic order of sequence and including the character of the stratified rock or sediment. The study of stratigraphy encompasses the origin, distribution, composition, succession of the geologic material.

Subsidence: The gradual caving in or sinking of an area of land.

Substrate density: The density and composition of the sub-surface sediment/geology, which will inform that appropriate selection of LWD anchoring mechanism. Loose, less consolidated material would be amenable to deadman anchor. In moderately consolidated material LWD could be effectively anchored with an auger anchor. While, for sites with higher density or lithified subsurface geology (e.g. bedrock), ballasted LWD would represent the best LWD anchoring mechanism.

Surficial (stability/landslide): Surface layer (top layer of earth/ soil) Sub-surface conditions that make the slope susceptible to failure/landslide associated with the area's geologic processes and features.

Swash aligned: A beach that is generally parallel or near parallel to the predominant waves at breaking (after refraction in the shallow nearshore).

Transgression: Overall landward and upward shift due to sea level rise relative to the land.

Tidal flow: see *tidal hydrology*

Tidal hydrology or tidal flow: Localized tidal effects on water elevation and currents, different significantly from regional tide regimes mostly in tidal freshwater and estuarine ecosystems.

Transport zone: A bluff or bank which supplies minimal but not appreciable sediment input to the nearshore from erosion/mass wasting, and does not have an accretion shoreform present. Littoral sediment is typically transported alongshore. The bluff face typically has considerable coniferous vegetation with few signs of disturbance from landslide activity or is of very low relief such that sediment input is very limited.

Toe elevation: The tidal elevation of the beach in front of the structure. May be recorded relative to local water level (with time notes in local time), ideally at or near a low or high tide.

Toe erosion: Erosion at the base of the marine bluff caused by wave attack.

Uplift: A geologic term to describe post-glacial rebound and is a rise in a land mass.

Vegetation maturity: The approximate level of establishment of a plant community.

Vertical Bulkhead: *See* bulkhead

Waterward: A description meaning towards the water.

Wave Hindcasting: A method of generating a reasonable approximation of the long-term wind wave climate at a given location using historic wind records from a nearby location.

Wave runup: see *runup*

Width: The cross-shore dimension of the structure, include separate measurements of return walls or other associated structures.

ACRONYMS and ABBREVIATIONS

- **AS** Accretion Shoreform
- **BAB** Barrier Beach
- **BE** Barrier estuary
- **BL** Barrier lagoon
- **BLB** Bluff backed beach
- **BN** Beach nourishment
- **BR** Bulkhead Removal
- **CAO** Critical Areas Ordinance
- **CEM** Coastal Engineering Manual
- **CGS** Coastal Geologic Services
- **CLM** Closed lagoon/salt marsh
- **DEM** Digital Earth Model
- **DOE** Washington Department of Ecology
- **ESA** Endangered Species Act
- **FB** Feeder Bluff
- **FBE** Feeder Bluff Exceptional
- **GIS** Geographic information systems

- **HOWL** Highest Observed Water Level
- **LiDAR** light detection and ranging
- **LW** Large wood
- **LWD** large woody debris
- **MHHW** mean higher high water
- **MHW** mean high water
- **MLLW** mean lower low water
- **NAD** no appreciable drift
- **OCI** Open coastal inlet
- **OHWM** ordinary high water mark
- **PB** Pocket Beach
- **PL** Plunging rocky shore
- **PSNERP** Puget Sound Nearshore Ecosystem Restoration Project
- **RE** Re-slope and revegetation
- **RP** Rocky platform
- **RV** Rock revetment
- **SLR** sea level rise
- **SMP** Shoreline Master Program
- **SPM** Shore Protection Manual
- **SWD** Still water depth
- **SWL** Still water level
- **TZ** Transport Zone
- **TAG** technical advisory group
- **USGS** United States Geological Survey
- **WDFW** Washington Department of Fish and Wildlife
- **WDNR** Washington Department of Natural Resources (also noted as DNR)
- **WRIA** Water Resource Inventory Areas
- **WSDOT** Washington State Department of Transportation
- **USACE** United States Army Corps of Engineers
- **USFWS** United States Fish and Wildlife Service
- **VB** Vertical bulkhead

Chapter 1. PUGET SOUND SHORELINES

Puget Sound is a unique region and in order to appropriately design shoreline projects it is best to understand its features and processes. This chapter will give the reader an overview of these processes, but with the understanding that more in-depth research will be required to fully understand the topic. There are several good reports on Puget Sound fully referenced at the end of this chapter (Suggested Reading).

Puget Sound lies between the Cascade Mountains on the east and the Olympic Peninsula on the west. In this trough glaciers have advanced and retreated over the millennia, scouring and depositing sediment forming the now familiar bluffs and beaches and on the shorelines (Figure 1-1) There are rock outcroppings, like parts of the San Juan Islands, but mostly the Puget Sound lowland is composed of sediment of one sort or another – from fine clay deposited at the bottom of lakes long-drained, to huge boulders rafted in on the glaciers.

Figure 1-1. Photo montage showing a feeder bluff and a series (intertidal) bars, and spits deposited down-drift. Useless Bay, Whidbey Island (Dept. of Ecology Washington State Coastal Atlas).

Puget Sound is an inland sea connected to the Pacific Ocean through the Straits of Juan de Fuca. Tides in Puget Sound have two highs and two lows each day, with a range increasing from about 8.5 feet at Port Townsend to 14.5 feet in Olympia. Low atmospheric pressure and sustained winds can contribute to local tidal surge, which can elevate water levels generally up to two feet above normal levels.

Figure 1-2 shows tidal elevations from the Port Townsend NOAA tidal station for early February, 2006. The blue line is the predicted tide and the red line the observed elevation. In the absence of storm effects, these two lines are close together, as it is later in the day on the 5th. But during a storm the low barometric pressure allows the tide to surge higher than normal. In addition to these storm effects, annual sea level is subject to variability as a result of periodic El Nino events, which may result in sea level as much as a foot higher along the west coast (Subbotina et al. 2001).

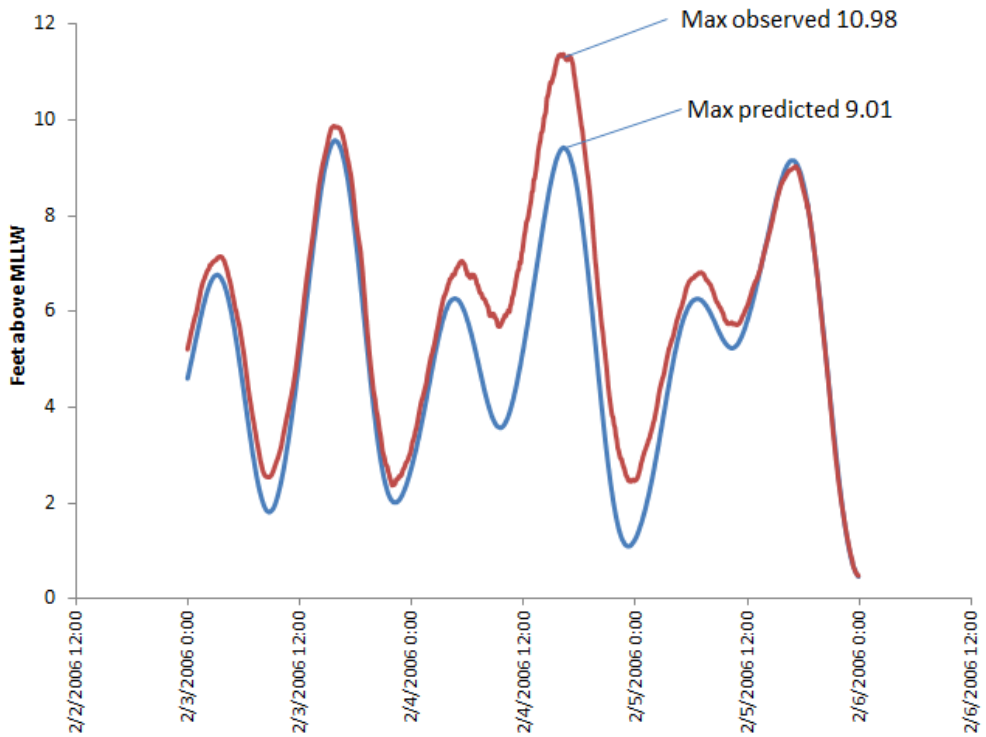

Figure 1-2. Predicted and observed tides for Port Townsend, Sta 9444900, February 3-5, 2006. (NOAA NOS data)

The mixed tides are skewed towards the upper half of the tidal range, so waves most commonly break on the upper portion of the beach (Finlayson 2006) (Figure 1-3). This means that the highest rate of longshore sediment transport takes place at the top of the beach, as well as the greatest amount of erosion. This is also the location of most shore protection projects (bulkheads and seawalls).

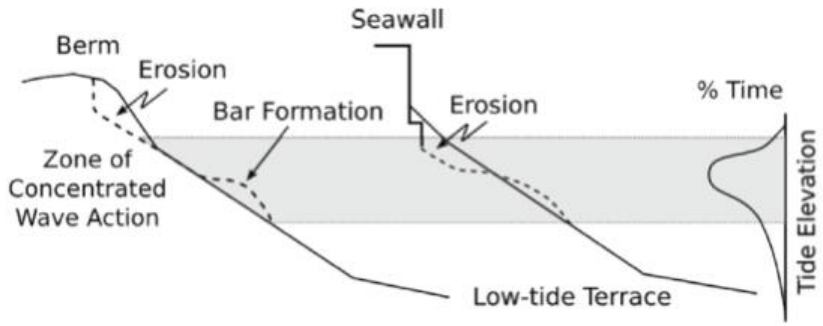

Figure 1-3. Schematic showing tides are most often at the higher portion of the beach. At left, a natural beach erodes the berm during storms. A beach with a seawall erodes at the base of the wall. (Finlayson 2006)

Pacific Ocean waves and swell have little influence on Puget Sound except near the entrance, so wave generation is directly linked to local wind conditions. Because of the relatively small bodies of water, waves are fetch-limited and rarely exceed significant heights of 3 to 6 feet, or periods of greater than 3 seconds during storms (Downing 1983; Finlayson 2006). The fetch-limited conditions do not just result in smaller waves, but lead to significant variability in the wave environment due to local differences in the orientation and length of fetch (Finlayson and Shipman 2003; National Research Council 2007). The

largest waves on Puget Sound are generated by winds from the south when it is channeled along the north-south water bodies (lighter colors in Figure 1-4 mean higher wave heights).

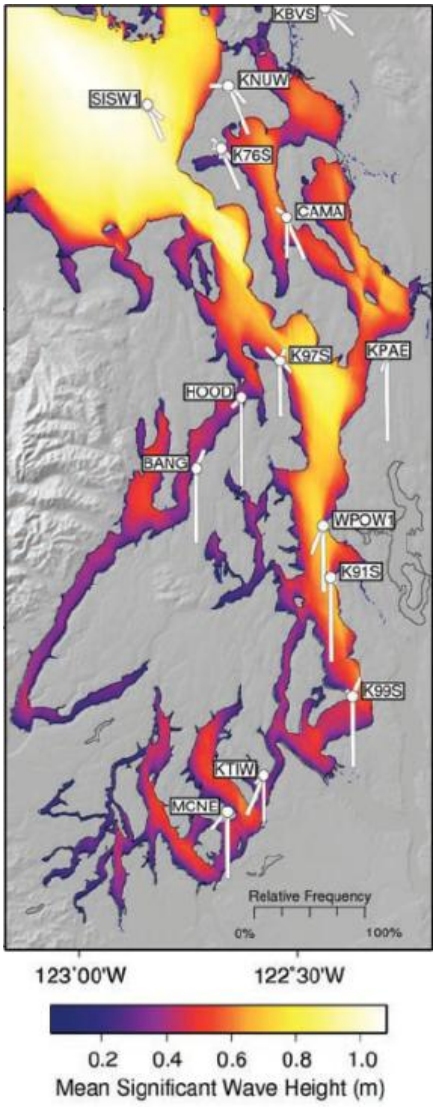

Figure 1-4. The height of waves for Puget Sound. Lighter colors indicate higher waves. Wind rose show how often and from which direction wind blew greater than 30 MPH between 1996 and 2004 (Finlayson 2006)

Where the coastline forms bays, or is oriented away from the south, wave energy is reduced and so is sediment transport and shoreline erosion (darker colors in Figure 1-4). This variability means that the shoreline erosion and risk to property are different depending on location and that different protection techniques may be used to suit the given the site conditions. On a process level, the irregular shore shape has created hundreds of discrete drift cells, each with its own sources and sinks of sediment (Schwartz et al. 1989).

When waves break at an angle to the shore, as they do in much of the north-south shoreline in Puget Sound, they create a strong force along the shore that transports the beach sediment forming the shapes we see on the shoreline, such as spits and barrier beaches (Finlayson and Shipman 2003). Sediment is delivered to our beaches by erosion of coastal bluffs and from rivers. These feeder bluffs are

the primary source of sediment. Rivers build large estuarine deltas at their mouths and smaller streams contribute to the gradual evolution of small estuaries (Figure 1-6). Of the Sound's 2,500 miles of coastline, about half consists of bluffs and small barriers, with the remainder comprising bedrock shores, several large river deltas, and hundreds of sheltered estuaries and barrier lagoons.

Puget Sound shores can be classified in various ways, but for the purposes of these guidelines the following list is used and discussed in detail in the sections that follow;

1. Beaches
2. Bluffs
3. Low energy shorelines, including salt marshes
4. Deltas
5. Artificial shores

Beaches

Beaches on the Sound differ in many respects from beaches on the open coast of Washington or beaches in other parts of the country, which is one reason why the *Marine Shoreline Design Guidelines* are necessary for responsible management. There are many guidelines and manuals for the design of protection techniques on high energy sand beaches, but few for the low energy, gravel dominated beaches found here, and none that attempt to minimize impacts to natural resources and nearshore processes.

Beaches are features consisting of loose sediment that has been shaped by the action of waves (Shipman 2008). In Puget Sound this sediment contains a wide mixture of sediment sizes, dominated by coarse sand and gravel, but often including cobble and occasionally larger sediment sizes. The composition can change rapidly alongshore, varying as the source of the sediment changes and the size and angle of the waves (Finlayson 2006). Beaches typically consist of a steep, coarse-grained beachface and gently-sloped, low tide terrace dominated by sand or cobble-boulder (Figure 1-5).

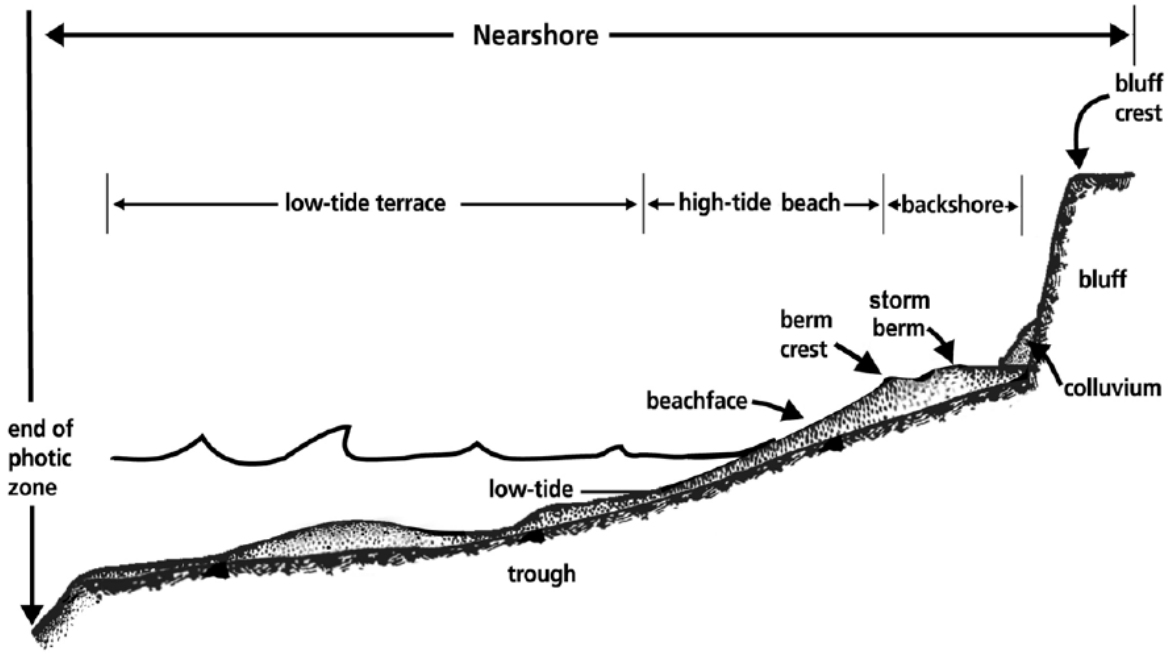

Figure 1-5. Cross section of typical beach on Puget Sound. (adapted from Komar 1976)

Low wave energy beaches are composed of poorly sorted sediment, with a relatively narrow backshore and intermittent intertidal vegetation. Higher wave energy beaches contain areas with well-sorted sediment over a broad intertidal and backshore area, usually devoid of fringing marsh vegetation. Coarse durable sediment is more likely to be retained on the upper beachface and provide natural bluff protection within a relatively narrow width (Johannessen and MacLennan 2007).

Eroding coastal bluffs are the primary source of beach sediment on most Puget Sound beaches (Johannessen and MacLennan 2007), although sediment abundance and size varies significantly, even over short reaches. Small streams may be a source of sediment on some shores where coastal drainages yield large amounts of sediment and where the configuration of the stream mouth allows transfer of sediment out of the estuary into the beach system. This is shown schematically in Figure 1-6 where the eroding bluff, often called a feeder bluff, in the lower part of the drawing is attacked by waves causing sediment to fall on to the beach. Waves then transport the sediment alongshore, depositing part of it at the barrier beach. Another feeder bluff supplies additional sediment, as does the stream delta, creating the sand flat and, ultimately, the spit at the top of the drawing.

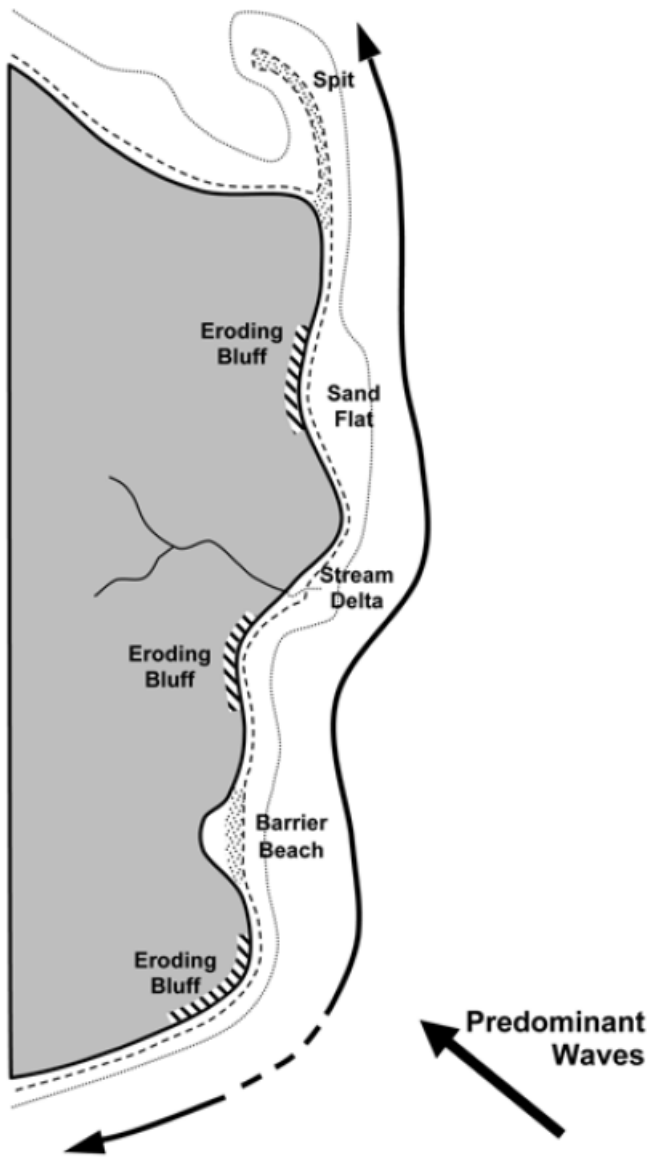

Figure 1-6. Sketch of a complex drift cell on Puget Sound. See text for explanation (Shipman 2008).

Bluffs

Coastal bluffs make up 60% of the Puget Sound shore length (Washington State Department of Natural Resources2001). They are the primary source of sediment for our beaches. Bluffs also provide expansive views of the Sound and surrounding mountains. It is these views that inspire people to build houses along the crest of the bluffs. Since coastal bluff recession is relatively slow, home owners are not fully aware of the risks to building too close to the bluff crest. When a landslide occurs, armoring the toe of the bluff is often the only alternative considered. Locating the house far enough back from the crest to provide a margin of safety would have been a good precaution, but many learn that too late. Other landslide triggers might involve natural geologic and hydrologic conditions or upland land-use practices. In these guidelines the reader will be guided through an assessment and alternatives analysis process to determine appropriate measures for owners of bluff property

During the last ice age various layers of sediment were deposited in the Puget lowlands creating a complex assortment of sediment sizes with different properties. Figure 1-7 shows a typical sequence of strata found in these bluffs. The layers, or geologic units, are different everywhere, as is the sequence of sediment type. As a result, the particular sediment unit exposed to wave action and erosion is going to vary at different sites – at some locations the hard, erosion-resistant glacial till will be exposed at the slope toe and result in a steep but relatively stable bluff face; elsewhere easily-eroded outwash gravel and sand will be exposed at the toe, making the bluff unstable. When a strata with high permeability overlies one with low permeability (sand and gravel over clay), groundwater flow is restricted from infiltrating below the contact and seeps out at the bluff face. This perched water can cause saturation of the overlying sediments which then become prone to land sliding. A number of factors contribute to bluff instability and erosion,

- Geology and sediment characteristics
- Groundwater – volume and nature of flow and discharge
- Surface water management – how runoff is collected and conveyed from an area or site (see Chapter 6 for best management practices)
- Wave energy environment – the length of fetch and orientation of the beach face to the prevailing wind direction
- Beach characteristics – the type of materials on the beach (sand vs. cobble), it's slope and the width of the backshore
- Sea level rise – higher water surface elevation during storms and high tides leads to increased erosion rates on bluffs

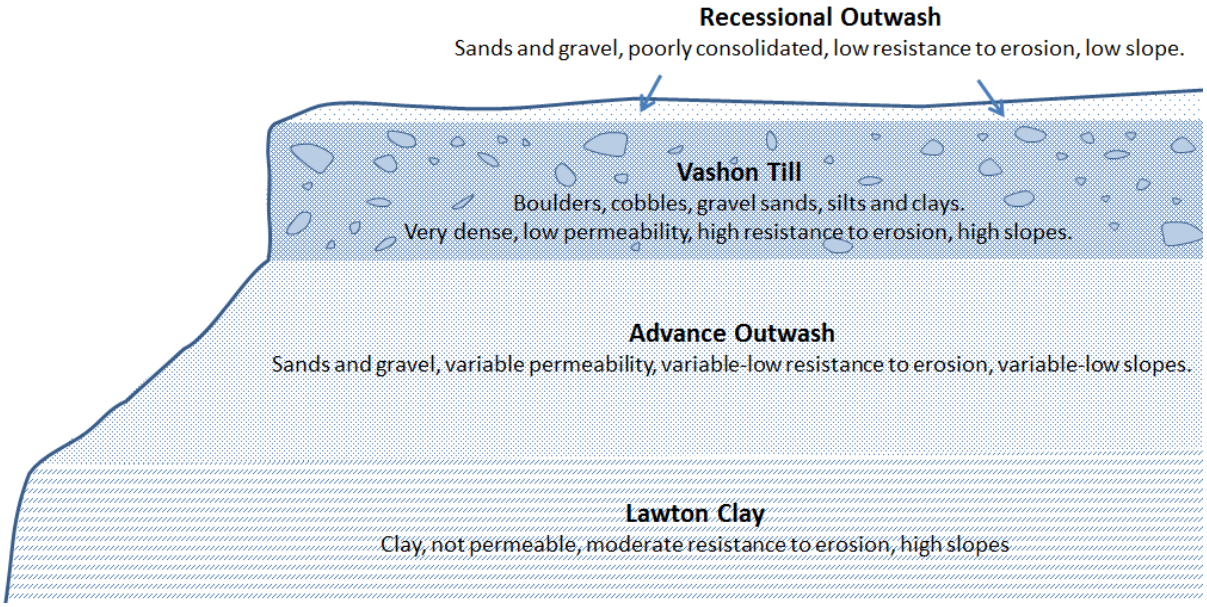

Figure 1-7. A sketch of a typical sediment sequence in Puget Sound coastal bluffs. Not all bluffs are underlain by this sequence or these strata, and thicknesses vary widely. Older strata from previous glaciers may also be present. Notes contain a brief description of the physical characteristics of the materials. (Savage et al. 2000).

Bluff soils can be saturated by natural groundwater, but the risk of failure is higher when the amount of groundwater is increased by directing runoff from roofs and roads directly into the ground or over the edge of the slope; by adding water from drainfields and irrigation; and by removing native vegetation,

particularly trees, from the ground. These factors are shown in Figure 1-8 and discussed further in Chapter 6.

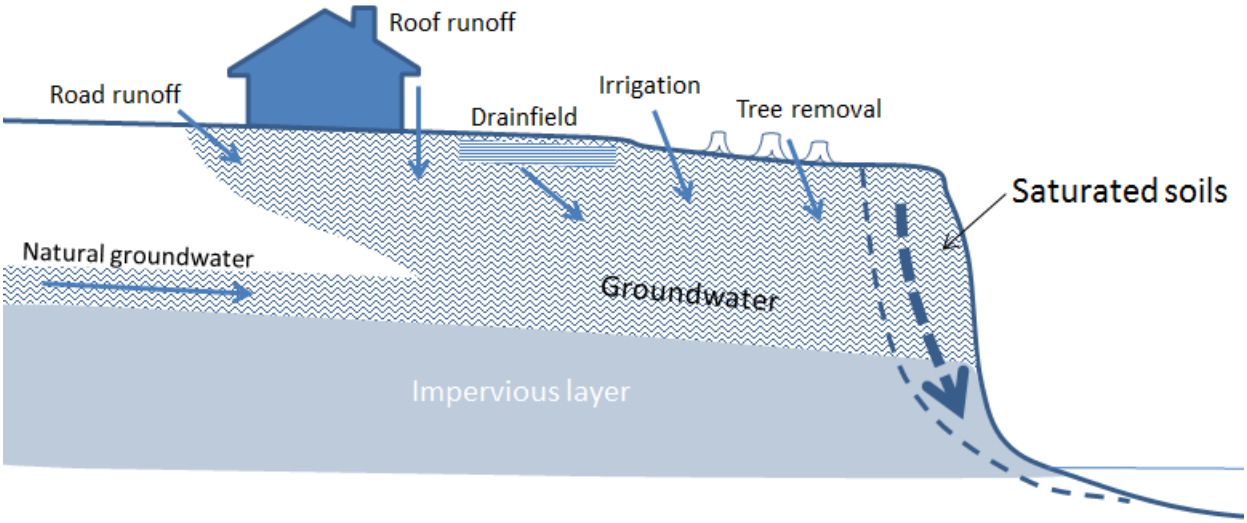

Figure 1-8. Sketch showing the how property owners can increase groundwater and saturate bluffs soils, increasing the likelihood of slope failure. (redrawn from Marsh 2005)

Low energy shorelines

There are places in Puget Sound where there is limited fetch, erosion rates are low and beach sediment is fine (Figure 1-9). Low energy shores are most common in southern Puget Sound where the inlets have limited fetch from the prevailing winds, but can occur anywhere a shore reach is protected. We single out this category of shore here to indicate that they can be treated differently than beaches, bluffs, and deltas because wave energy and net sediment transport are very low. Shoreline protection is not needed to prevent erosion in the conventional sense, but some measure may be considered to address slope stability.

Figure 1-9. Low energy shore, Case Inlet, southern Puget Sound.

Deltas

Deltas form where rivers and streams enter Puget Sound. They can vary from small gravel fans to huge, complex wetland systems such as the Nisqually or Skagit deltas. Deltas are ecologically valuable because they form the transition between freshwater river systems and the marine environment. This is where sediment from the mountains is deposited in the Sound forming marsh complexes and gravel beaches; where salmon transition between salt and fresh water and many species of fish feed; where waterfowl and shorebirds can be found by the thousands. But deltas are also a heavily modified shoreform and many have been diked and filled and no longer provide these natural functions (Shipman 2008). In this way many deltas have now become artificial shores, discussed in the next section. However, some deltas retain their natural functions and they deserve a careful approach to the design of shoreline protection projects.

The basic principle of delta formation is that sediment is continuously deposited at a single location. As it builds up in one area, say the left side of the bay or inlet, flow moves over to the right side and begins to deposit there. A balanced pattern of deposition forms a symmetrical fan, as can be seen at the mouths of some creeks, but more often deltas are ranging complex systems with multiple distributary channels and an irregular bay front. We can divide deltas into two forms, for shore protection purposes: coarse grained fans and marsh complexes.

Deltas, or fans, are composed of coarse gravel (Figure 1-10, left) and are essentially a beach composed of sediment from the river, rather than from glacial material. Mostly people have built on the edges of these deltas, less often in the middle. Roads and railroads often cross streams and force them to maintain a single location with a fan forming on the waterward side of the culvert or bridge.

Figure 1-10. Examples of Puget Sound delta shores. On the left is Stetson Ck. alluvial fan on Hood Canal (Dept. of Ecology Washington State Coastal Atlas). On the right is a salt marsh in Quilcene Bay.

On the other hand marshes and mud flats are composed of fine sediment - silt or clay. A marsh and mud flat shore is very different from gravel dominated shore (Figure 1-10, right). These broad flat surfaces tend to dissipate wave energy over a larger area than on steeper gravel beaches. Shortening or steepening these broad flat surfaces will cause greater erosion.

Artificial shorelines

Armoring and fill have created artificial shorelines in much of Puget Sound. Generally, these activities have steepened the intertidal area, reducing its width, biological value and resiliency (Simenstad et al. 2011b).

There are two major types or artificial shorelines with different potential outcomes; historical, long term development, and more recent, short term development. Historical development includes agricultural dikes, railroads, urban, or industrial development. These are larger scale uses that have transformed the shoreline in fundamental ways and support activities deeply entrenched in our culture and economy. Good examples are the railroad fill along the eastern shore of Puget Sound (Figure 1-11), or the Seattle waterfront. Some techniques can be used to increase their biological value (beach nourishment and large wood are examples, see Techniques 1 and 2) but, unless land use is changed, restoration of normal beach processes is impossible.

Figure 1-11. Railroad fill and seawall in Possession Sound (Dept. of Ecology Washington State Coastal Atlas).

On the other hand, shoreline protection in front of residences, parks, or other small developments can be treated in a less aggressive manner than the first category of artificial shorelines. Those in this category are the main audience for these guidelines since they can take advantage of the full range of techniques offered in Chapters 6 and 7.

Natural Processes in the Puget Sound Nearshore

So far this chapter has described types of shore features commonly seen in Puget Sound – beaches, bluffs, and deltas – and a little about their environment. But behind these types are a variety of natural processes that create and maintain them and the nearshore ecosystem. Knowing what these processes are can help the shore owner and project designer understand how impacts can be avoided or minimized when developing a project. Some of the more significant physiographic processes are listed here (Simenstad et al. 2011a):

Sediment Input: our beaches are made of sand, gravel, and cobble. Some of this material is lost to down-drift areas and some out across the beach to deeper water. Without a constant source of sediment, beaches lower and retreat.

Sediment Transport: sediments are transported by water and wind along and across the shore. These materials have to move along the beach to replace what has been lost and to respond to changing conditions. Interruptions in this flow starve downdrift beaches and diminish their biological, recreational and property value.

Erosion and Accretion of Sediments: this is the erosion (coastal retreat) of coastal bluffs and shorelines and deposition of sediment by water and wind. It also includes the settling of sediments and organic matter to form marshes and mud flats.

Tidal Flow: tides are one of the main elements of coastal processes. Many organisms live "between the tides." Tides spread the action of waves across a large area of the beach. Tidal flow carries marine organisms into bays and estuaries, up channels and into pockets all along the shore. Tides cause the circulation of nutrients, salinity and dissolved gasses. Dikes, levees or berms restrict tidal flow and cut off this important process.

The Formation and Migration of Distributary and Tidal Channels: these channels carry both fresh and salt water in and out of estuaries, along with the organisms that live in those waters. Cutting off a tidal channel, or diminishing the size of the marsh plain that supports it, eliminates the habitat essential to many species.

Freshwater Input: freshwater inflow from surface (stream flow) and groundwater (seepage). Freshwater creates the estuarine habitat so important to many species, some of which are uniquely dependent on it. Diverting flow away from established estuaries or fixing it in a set location has serious consequences for these species.

Detritus Import and Export: import and deposition of particulate organic matter (leaf litter, seeds) and large wood recruitment, disturbance and export. The marine riparian is an important connection between the terrestrial and marine environments. Preserving existing native vegetation and planting areas that have been disturbed will help maintain this nutrient pathway.

Physical Disturbance: much of the change that occurs in our natural environment happens as the result of disturbance events. Relatively little happens from day to day to change the shape and composition of the nearshore. Big river floods, windstorms, and rainstorms cause a lot of change in a short period. These changes – landslides, debris flows – carry huge amounts of sediment and wood to these habitats rejuvenating them and increasing complexity.

Puget Sound Habitats

The processes just described support the formation of nearshore habitat – the place where organisms live as part of an ecological community. When the landowner or designer looks down at the beach where they are proposing a protection project, they should be able to see habitat and recognize it as the place where species important to all Washingtonians either live or seasonally visit to feed or spawn. State or Federal law protects some of these species (Puget Sound Chinook salmon); others are sought after for as food (clams and mussels) or sport (chum salmon); still others are food themselves for these species (insects from riparian vegetation). Megan Dethier has identified six main types of Puget Sound nearshore habitat and they are described below (Dethier 2010) and pictured in Figures 12 and 13.

Mud and mixed fine sediments found in low energy, sheltered areas. Despite appearances, these are highly productive areas with rich benthic infauna (like worms and clams), algae, eelgrass. Some species found there include mud shrimp, clams, Olympia oysters. Feeding on these species are juvenile salmon, shorebirds and Great Blue Heron (Figure 1-12, left).

Sand; moderate energy, open beaches; eelgrass, sand dollars, clams, only a few primary producers: mobile sediments reduce density diversity. Shorebirds are seen feeding here and humans enjoying the beach (Figure 1-12, middle).

Mixed coarse; cobble beaches relatively stable, rich flora (most species of all shoretypes) and highest productivity, with critters attached to, living in-between the cobble, and in the sediments below. Crabs, snails, clams, oysters and many other species live here (Figure 1-12, right).

Bedrock; a relatively uncommon habitat in Puget Sound. Snales, rockweed, mussels, barnacles, seastars, and oyster catchers are found here, as well as humans searching tide pools (Figure 1-13, left)

High-shore; ecologically valuable area high on the beach and in the backshore. This is generally fine grained, relatively stable, and a repository of drift wood. Rich in amphipods and spawning site for forage fish (surf smelt and sand lance). Armoring often covers this area and eliminates functions (Figure 1-13, middle).

Marsh; vegetated fine sediment benches that can be found in narrow strips or as broad plains in deltas(Figure 1-13, right). This is an important source of detritus (plant parts, insects) and feeding area for many species of marine life.

Figure 1-12. Mud flat (left), sand beach (middle), mixed coarse beach (right).

Figure 1-13. Bedrock (left), high shore (middle), marsh (right).

Conclusion

Puget Sound is unique, different from the open ocean coast for which most of the design manuals for shore protection have been written. This chapter has described the shoretypes common here, the processes that create and maintain them, and the habitat that they form. The Marine Shores Design Guidelines are written to specifically address these unique characteristics and leads the designer through a selection process that identifies the most appropriate protection technique for their site.

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Chapter 2. STEWARDSHIP

Background

Bordered by approximately 2,500 miles of shoreline, Puget Sound supports a diverse array of marine habitats that provide important ecological functions for fish, shellfish, birds, marine mammals and other wildlife. In addition, it provides important services for the human population that inhabits the Puget Sound basin including recreation, commerce and residential properties. Increases in the human population in the Puget Sound area are expected to accrue an additional 1.5 million people by the year 2025, increasing the stressors on the ecosystem from increased use and development. In particular, shoreline development that includes the installation of armoring can impact ecosystem processes, structures and functions on Puget Sound beaches thereby adversely affecting shoreline habitats. For example, loss of sediment supply from eroding shorelines and feeder bluffs can impact formation and maintenance of forage fish spawning areas, lead to lowered beach profiles, and potentially affect eelgrass beds.

Approximately one-third of the Puget Sound shoreline is currently armored, with additional armoring being added each year. Based on data from the Hydraulic Project Approval (HPA) database maintained by the Washington Department of Fish and Wildlife (WDFW), an additional 7.43 miles of armoring was added to Puget Sound shorelines between 2005 and 2011. Restoration projects during this same period removed 0.79 miles of armoring resulting in a net accumulation of 6.63 miles of armoring. The amount of armoring removed each year has increased recently, but continues to be relatively small compared to the quantity of newly placed armoring. Data from 2005 through 2011also indicated that most of the removal projects occurred on public/government owned properties (68%), whereas most of the new armoring was being constructed on single-family residence properties (70%). Implementation of a program to address shoreline armoring and the use of alternatives will therefore need the support of individual shoreline property owners and their community organizations encouraging shoreline stewardship.

What is Stewardship?

At a basic level, stewardship means taking responsibility for our choices. Environmental stewardship is a responsibility shared by everyone whose actions affect the environment, including individuals, communities, companies, and government agencies. Environmental stewardship can assist with conserving natural resources and promoting sustainable outcomes for Puget Sound shorelines. To address the issues of adverse impacts to shoreline processes and habitat degradation, environmental stewardship solutions can provide a sound approach to address the root causes of these problems. Given the frequent decisions made by individuals that affect the environment, such as the installation of armoring on single-family residence properties, it is important to recognize that their collective actions can have profound benefits for the environment. While regulatory programs will continue to influence decisions, influencing individuals and communities to make environmentally responsible choices will be far more successful than government mandates.

Why should I care?

Preservation of the beauty and health of Puget Sound is reliant on all of us, as individuals and members of organizations we make everyday decisions that affect the quality of Puget Sound. If you live on the shoreline, you can have profound impacts on the shoreline's character and function through everyday actions and decisions regarding your property. For example, shoreline modifications such as armoring

that adversely impact the processes, structure and function of the beach often have alternative approaches that can be less impacting than traditional techniques. So, spending the time to explore alternative approaches to armoring on your property can provide benefits to the health of your beach.

In addition, individual actions on one property can affect other beaches and therefore the property of adjacent shoreline owners. This may occur because beaches are connected within a drift cell by the processes of erosion and wave-induced transport of sediment along the beach; sediment derived from one area is moved along the beach and deposited onto adjacent areas. This process is more or less continual throughout the year, depending on the weather and storms that generate waves in Puget Sound.

It is also important to note that several small independent actions can result in substantial impacts beyond the scope of the individual project (e.g., cumulative impacts). It is known that multiple actions can have impacts greater than the sum of the individual actions due to the interaction and combined effect of the activities. So, even though the action you take individually on your property is small, when combined with multiple other activities the overall impact can be substantial.

Many shoreline landowners on Puget Sound do a good job of protecting shoreline conditions at their respective properties. This type of stewardship reaps rewards beyond ecological functions and can play an important role by influencing friends and neighbors. While shoreline development will continue with increasing population in the Puget Sound region, the future trend of this development can include implementation of approaches that reduce ecosystem impacts while addressing the needs of shoreline homeowners.

Further, and maybe most importantly, whether or not you reside on the shoreline, your efforts to live sustainably and contribute to public support of environmental stewardship can be an important part of promoting a healthy shoreline. Our attitudes toward environmental stewardship can affect important decision-making as well as provide motivation for other individuals and organizations. If you enjoy visiting the shoreline of Puget Sound, remember that your actions affect the overall health of this picturesque environment.

Shoreline owners, regulators and designers are all critical to moving beyond standard approaches to shoreline erosion such as traditional hard armoring. Use of soft shore approaches such as those presented in this document needs the support of not only the homeowner, but also the contractors and designers who work with these shoreline owners. Further, given the proven success of soft shore techniques for addressing erosion concerns at many sites, the regulatory community needs to foster soft shore approaches and avoid regulatory complexities that discourage these alternative treatments.

Protecting Ecosystem Processes

Erosion is a natural process on Puget Sound beaches that occurs episodically, and in most locations at a relatively slow rate. The need to install shoreline armoring can often be instigated by the perception that an erosion problem exists at a site. This perception can be strongly influenced by friends, neighbors or contractors. In these circumstances, it is important to seek the advice of trained professionals to better understand the current condition, and the risks and options available to address the situation. Ideally, a trained professional can provide technical assistance through the county or local jurisdiction.

To become better informed as an individual, one can attend workshops or lectures, or find educational information on websites provided by local jurisdictions and state or federal agencies. Some local

jurisdictions provide workshops that include visits to local beaches for discussions of specific conditions and on site evaluations. There are also local groups that convene meetings with technical experts to explain the physical and biological processes that occur on Puget Sound beaches. An excellent example of this is the Beach Watchers program (see: http://www.beachwatchers.wsu.edu/regional/index.php).

Several voluntary programs exist to encourage stewardship of the Puget Sound shoreline. In some cases, grants are available to fund restoration actions, conservation easements or land acquisitions. In addition, new programs are being developed to support property tax reductions or provide low interest loans for those who exercise wise stewardship of their shoreline property. Further information on these programs can be obtained through your local city or county offices.

Regulatory Issues

Several regulatory programs exist that manage shoreline activities within Puget Sound. While it is beyond the scope of this document to provide detailed information on all of these regulatory entities and the pertinent rules, some basic background is worthwhile. For information on local regulations and permits contact your city or county offices.

- **United States Army Corps of Engineers** regulates construction activities on the beach below mean higher high water. Regulatory branch website: http://www.nws.usace.army.mil/Missions/CivilWorks/Regulatory.aspx
- **Washington Department of Fish and Wildlife** regulates shoreline activities that may impact fish life. Regulatory website: http://wdfw.wa.gov/conservation/habitat/permits_regs.html
- **Washington Department of Ecology** oversees compliance with the Shoreline Master Program that is implemented at the local level. Shoreline Management website: http://www.ecy.wa.gov/programs/sea/shorelines/index.html
- **Office of Regulatory Assistance** answers permitting questions and provides information on state regulations. Permitting website: http://www.ora.wa.gov/resources/permitting.asp

Chapter 3. SITE ASSESSMENT

Role and Purpose

The site assessment is the first step in the four-step process to identify an appropriate alternative for managing coastal erosion. Information from the site assessment is integrated with the broader coastal processes assessment (Chapter 4) to inform the alternatives analysis (Chapter 5), which recommends the erosion control technique(s) best suited to the site (Chapters 6 and 7). Figure 3-1 shows the progression through these steps.

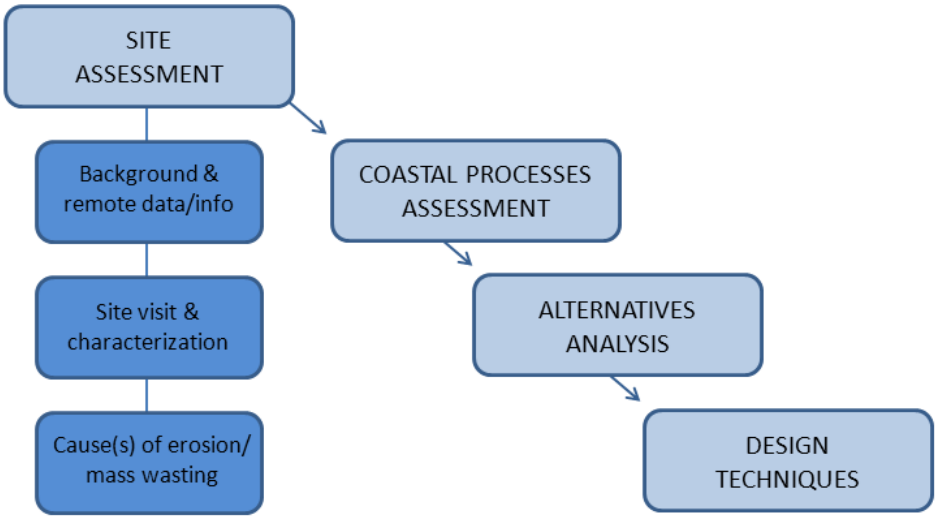

Figure 3-1. Components of a site assessment (dark blue) and subsequent steps applying the results (light blue).

A site assessment describes

- existing conditions and processes occurring at, and adjacent to, the site;
- human infrastructure at the site;
- associated risks to infrastructure, property, and the public;
- locations and potential causes of erosion and/or mass wasting.

The site assessment is one of several critical elements needed for determining if action is required, and if so, selecting and developing an erosion-control approach which will benefit the site while minimizing negative habitat impacts. As there may be multiple causes of erosion or mass wasting at Puget Sound coastal sites, a thorough examination of site features should be carried out. An initial analysis of causation can follow that examination, as discussed at the end of this chapter.

This chapter describes how to conduct a site assessment and develop a better understanding of the property and the coastal and upland processes affecting it. A formal site assessment should be completed by a qualified professional with proper training and experience, but a landowner can gather information as part of an informal site assessment when considering treatment options and for use in discussions with appropriate technical staff.

Necessary Level of Expertise

Conducting a site assessment to properly design a project may require input on a range of topics by several different specialists (geological, hydrological, biological, geotechnical, structural, etc.), or may

involve one primary issue that can be addressed by one specialist. It is important to find the appropriate professional or professionals to conduct the assessment and gather the necessary data from which to develop the project design. Any professional conducting a site assessment needs to understand the interaction of coastal, upland, and ecological processes; as well as the regulatory framework of shoreline management and the permitting process.

Different jurisdictions may require that practitioners carry licensing for specific tasks and reports being submitted to obtain project permits. These requirements will be specified in Shoreline Management Program documents. For example, a licensed engineer is often required for structure modifications, a licensed geologist is often required for a geologic assessment, a licensed engineering geologist or geotechnical engineer may be required for any earth-moving design work, and a licensed hydrogeologist may be required for conducting groundwater monitoring and assessing on-site drainage and infiltration effects.

The exact title of the professional being contracted is less important than ensuring they have the appropriate expertise, experience, and licensing if necessary. Potential consultants should be interviewed to find out what experience they have, particularly with the sorts of issues identified at the site; whether they have the necessary licensing; and whether they understand project goals, including the landowner objectives.

Conducting an Assessment

The scope, or level of detail, necessary for any particular site assessment is based on:

- project objectives;
- degree of erosion or slope instability;
- complexity of the site geology, coastal processes, and hydrology;
- risks posed to public safety and site infrastructure.

Clear project objectives guide the assessment and design process, and balance the needs of the landowner within the constraints of natural coastal and slope processes. The objectives describe the purpose of the project; the requirements of local, state, and federal permits; and any other goals, such as providing for sea level change. Some site assessments may begin with clearly defined objectives, but may expand to multiple or compounding objectives and issues that develop through the site investigation. These may require integrating several solutions.

Unstable, rapidly eroding sites will require a more detailed data collection and assessment procedure. This relates not only to the magnitude of the issues at the site, but also to the increased inherent risk associated with them. Obviously, sites subject to greater risk (see Chapter 5 for more on risk) require more detailed analysis because the consequences of coastal erosion and slope failure are more serious.

The more complex the situation at a site, and the more the various project objectives conflict with each other, the more important it is to collect detailed observations of conditions and processes affecting the site and immediately adjacent areas. Some of the steps involved in determining feasibility for a number of different types of shore enhancement and erosion mitigation treatments, and then for design development, are outlined in Clancy et al. (2009). Specific site-assessment approaches used for assessing drainage issues are included in Myers (1995). Assessment approaches regarding vegetation on Puget Sound bluffs are included in Menashe (1993).

The site assessment procedure recommended for marine shores is divided into four sections:

1. Background and remote information
2. Site characterization
   a. Site geology and geomorphology
   b. Site sectioning and measurements
   c. Upland surface water drainage
   d. Site vegetation, habitat, and species considerations
   e. Site development features and erosion control structures
3. Site-based causes of erosion
4. Risk/vulnerability of infrastructure

Conditions and processes need to be characterized and evaluated at each individual site, including risks present at that site. After the site assessment elements have been conducted, the findings should be integrated with the *Coastal Processes Assessment* (Chapter 4) to thoroughly consider a range of alternative solutions (Chapter 5) and mitigation design recommendations.

Background and Remote Information

Researching background information and compiling existing data is crucial to the success of a site assessment. Background information consists of site development history, existing reports, anecdotal information from local residents, and any remotely available data such as on-line photos, LiDAR, and coastal and geologic maps. Background information provides an initial perspective on site conditions and processes, a framework for site observations, insight into constraints for accessing the site, and an initial perspective for possible future treatment options.

Data resources available online include but are not limited to the following:

- The WDNR Geologic Information Portal provides limited data sets of subsurface boring data (http://www.dnr.wa.gov/researchscience/topics/geosciencesdata/pages/geology_portal.aspx).
- The Ecology Coastal Atlas includes oblique aerial photographs, slope stability, coastal habitats, and other information (https://fortress.wa.gov/ecy/coastalatlas/).
- The LiDAR data set includes DEM and hillshade components, which can be used to give approximations of elevations and larger “lay of the land” features that may affect the site (http://pugetsoundlidar.ess.washington.edu/).
- City and County geodata and GIS centers on Planning, Public Works, and Natural Resources Department websites are increasingly providing natural resources maps and data available for viewing or downloading.
- WDNR provides surficial geology data (http://www.dnr.wa.gov/ResearchScience/Topics/GeosciencesData/Pages/gis_data.aspx).
- Survey monument data and benchmarks can be found in the WSDOT Survey Monument Database (http://www.wsdot.wa.gov/monument/).
- WDFW Priority Habitats and Species (PHS) data are available on the WDFW website (http://wdfw.wa.gov/conservation/phs/).
- SMP and CAO requirements are regulations put into place by city and county jurisdictions to identify environmentally sensitive natural resources and protect and preserve the ecological

resources of our natural environment in the context of responsible development and growth management.

Site development history should include predevelopment conditions of the site if available, and any upslope changes in land use. Site development history can be obtained through review of county or city records and historical aerial photographs, as well as through interviews with the client/landowner, neighbors, or other members of the community.

Determining the history of shore changes at a site can be very informative for determining if an erosion control project is necessary and appropriate, and if so, which technique(s) would be appropriate. Beach or bluff erosion rates can often be determined by careful comparison of historical maps or aerial photographs with current data or site measurements. This work is typically carried out in a GIS framework or geospatial image processing package and requires systematic attention to proper image selection, orientation, and correction. These data can quantitatively determine whether the site is experiencing persistent erosion and recession, or if it is only experiencing intermittent wave damage. Recommended approaches for shore change work in Puget Sound are outlined in Johannessen (2009). That work recommended documenting erosion rates over a long enough time (ideally more than 50 years) to dampen the effect of short-term changes. Locally, either detailed maps or survey drawings can be very useful. More widely, one may start with the earliest detailed aerial photographs at 1:12,000 or 1:20,000 scale; these span from 40 to 65 years.

Current and historical land use may have implications as to what actions might be taken on the site and how those actions might be accomplished. Land designated for commercial use may have different regulatory restrictions regarding mitigation actions than single-family residential sites. A project proponent should become familiar with their local SMP.

Acquiring the landowner's objectives for the site is an important piece of background information for the site assessment. These will likely then be informed by and combined with regulatory or restoration goals, together shaping the solution. It is important to understand that the landowner is often unaware of some coastal and bluff processes which may significantly alter project objectives. Additionally, permit constraints can modify objectives.

Site Characterization

Characterizing a site involves describing physical aspects (conditions and processes) of the site and its adjacent areas, making observations, and collecting data that identify potential cause(s) of erosion and mass wasting (landslides). Characterization provides the foundation for determining what the best course of action is for a site. The site assessment checklist (Figure 3-2) is provided as a guide for the types of data to collect. Sketches and photographic documentation are important to show spatial relationships of key features and their possible interaction. Preparation of a site plan that shows data collected during a site assessment is typically required as a basis for detailed assessment findings and later design work. The assessment and discussion should delineate areas of existing fill or excavation, identify any drainage and septic systems that may be leaking or otherwise vulnerable, describe any buried contaminated debris, and identify historical wetlands (Clancy et al. 2009). Figure 3-3 shows an example site plan for a residential site.

Site Assessment Checklist	
Site geology and geomorphology ☑ geologic units, stratigraphy, unit descriptions, relevance to site issues ☑ past and current landslide evidence/ coastal erosion ☑ groundwater, relative permeability of geologic units ☑ shoretype or shoreform/ localized beach features ☑ relative wave energy environment/ beach scarps ☑ beach substrate and grain size ☑ backshore features: width, LWD, vegetation ☑ site section delineation and descriptions ☑ cross sections: elevations and slope of beach, bluff, subsurface data, backshore features, water line **Upland surface water drainage** ☑ general watershed conditions, streams, wetlands ☑ seeps and springs ☑ infrastructure water sources: storm water systems, impervious surfaces, discharge points	**Site development features** ☑ primary structures and locations: setbacks, potential to move landward ☑ secondary features: septic, sheds, garages, driveways, patios ☑ landscape features: irrigation, ponds, fountains ☑ presence of fill or excavated areas **Erosion control structures** ☑ type and material of structure ☑ condition of structure ☑ toe and crest elevation/ position on beach **Site vegetation, habitat, and species** ☑ vegetation communities, species ☑ existing vegetation condition and appropriateness ☑ juvenile salmon, forage fish habitat ☑ animal species present

Figure 3-2. Site assessment checklist to guide data collection at a site visit. Key list items are explained in the text, with key terms in italics.

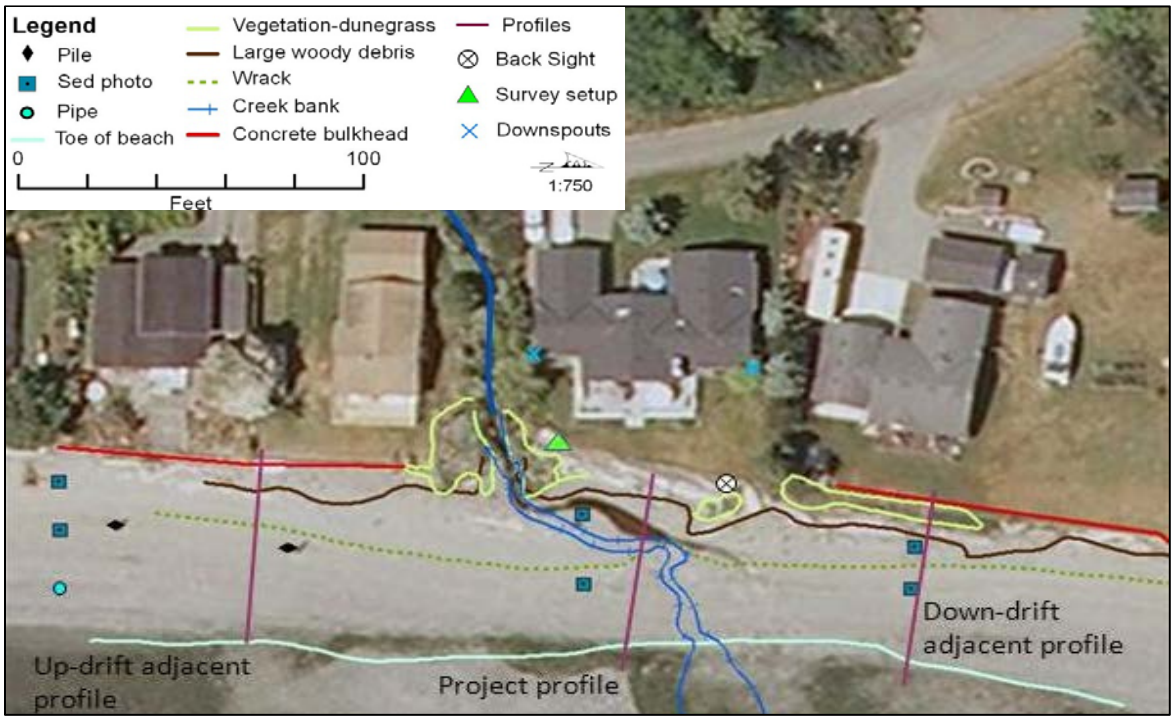

Figure 3-3. Example site plan created following a residential site assessment. The features on this map reflect items in the Site Assessment Checklist (above). Not all items in the checklist were necessary to collect or relevant to the objectives of this specific site assessment. Map based on Oak Bay site in Appendix A.

Site Geology and Geomorphology

Characterization of geologic and hydrologic conditions of a bluff or beach site should include descriptions of stratigraphy, relative sediment permeability, slope morphology and processes, surface and groundwater movement, potential effects of infrastructure and natural processes on erosion and slope stability, beach and backshore morphology, and any other physical conditions and processes that contribute to understanding site conditions and concerns.

Evidence of past *landslide activity* can include landslide deposits at the bluff/bank toe, bowl-shaped slope morphology, hummocky ground, leaning trees or bowed trunks, recently-exposed soil or sediment, or even-aged immature vegetation. Coastal erosion can also cause slope instability, however, eroding environments are not likely to preserve landslide deposits in the beach area for very long. Investigation into groundwater, bluff stratigraphy, and upland-related process may identify ways to minimize both shallow and deep-seated instability.

Groundwater ponding in the uplands, or seeping from a bluff face or from the slope toe, can indicate the presence of potentially destabilizing slope processes. (This topic is also discussed in Chapter 1 and Technique 3, Reslope/revegetation.) Subsurface data from geotechnical borings and water-well logs also provide useful information on potentially destabilizing slope processes. Relative differences in permeability between stratigraphic layers can affect groundwater flow, weaken certain layers, and trigger instability. For example, groundwater moves easily through sand and gravel strata, but tends to perch on underlying finer grained strata. The saturated overlying sediments are thereby weakened, and slope failure may occur. This is a typical stratigraphic sequence in Puget Sound bluffs (see Figures 3-4 and 1-7).

Hydrophilic (water-loving) vegetation at distinct locations in the bluff face should be noted, as they may also indicate groundwater seepage at the interface between strata, and indicate potential problem areas (Figure 3-4).

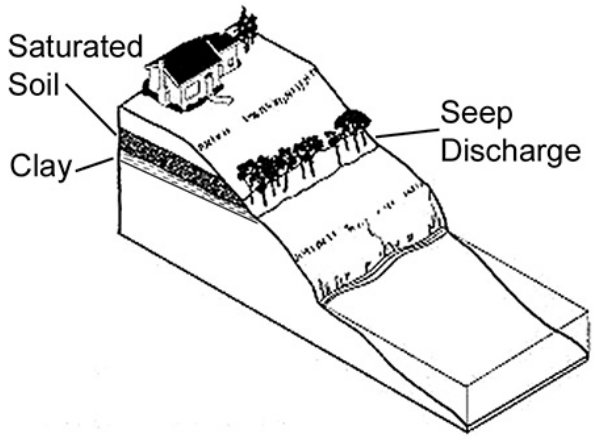

Figure 3-4. Water-loving vegetation as indication of groundwater seepage (Menashe 1993).

Observations should be noted on the *Geomorphology* of the beach based on shoretype, beach slopes, erosion scarps, the nature of the backshore, and whether the beach appears to be depositional or erosional. Apparent impacts to the beach from existing shore armor structures as well as other localized beach features which may be present such as berms, seeps, and scour should also be noted (see Figure 1-5 and Johannessen and MacLennan 2007).

Relative wave energy environment refers to the orientation of the site to the prevailing wind direction and exposure to wind-generated waves (fetch). This has a strong influence on the character of the beach and associated erosion potential. Describe any beach scarps; these are often an indicator of wave erosion and will be further explained below. Relative wave energy affecting a site can be researched beforehand and verified in the field. Additional coastal processes information, including larger scale and off-site influences and climate change, are addressed in the following chapter.

Beach substrate and grain size should be noted at different elevations on the beach, such as up slope of the beachface, on the upper intertidal beach, and in the backshore. This informs the determination of habitat conditions and also has relevance for potential future monitoring. Substrate can be documented during the site visit with a scaled grid (Figure 3-5). Natural seasonal variation of beach elevation and substrate may occur at the site and may require additional assessment during the alternate season.

Figure 3-5. Document beach sediment with scaled grid.

The *backshore* at the site, whether broad or narrow, should be described. Some sites may have no backshore if armor is burying it or if a bluff is present on a low-energy shore. Large woody debris (LWD) abundance and location can define backshore area and the landward extent of LWD can indicate areas of high water or past storm conditions. Backshore vegetation presence and community composition should also be noted.

Site Sectioning and Measurements

Sectioning the site appropriately along the shore can aid in describing the site. Sections, sometimes called reaches, can be delineated based on the initial site observations such as different shoretypes or areas with different erosion or accretion apparent, or can be based on areas with and without improvements. The delineated sections should include descriptions, photographs, GPS measurements, and sketches to highlight site features of interest. Sectioning can demonstrate spatial relationships and potential interactions of site features that may be causes of erosion on the site. Sectioning should be referenced both in cross section (perpendicular to shore) and alongshore (Figure 3-6).

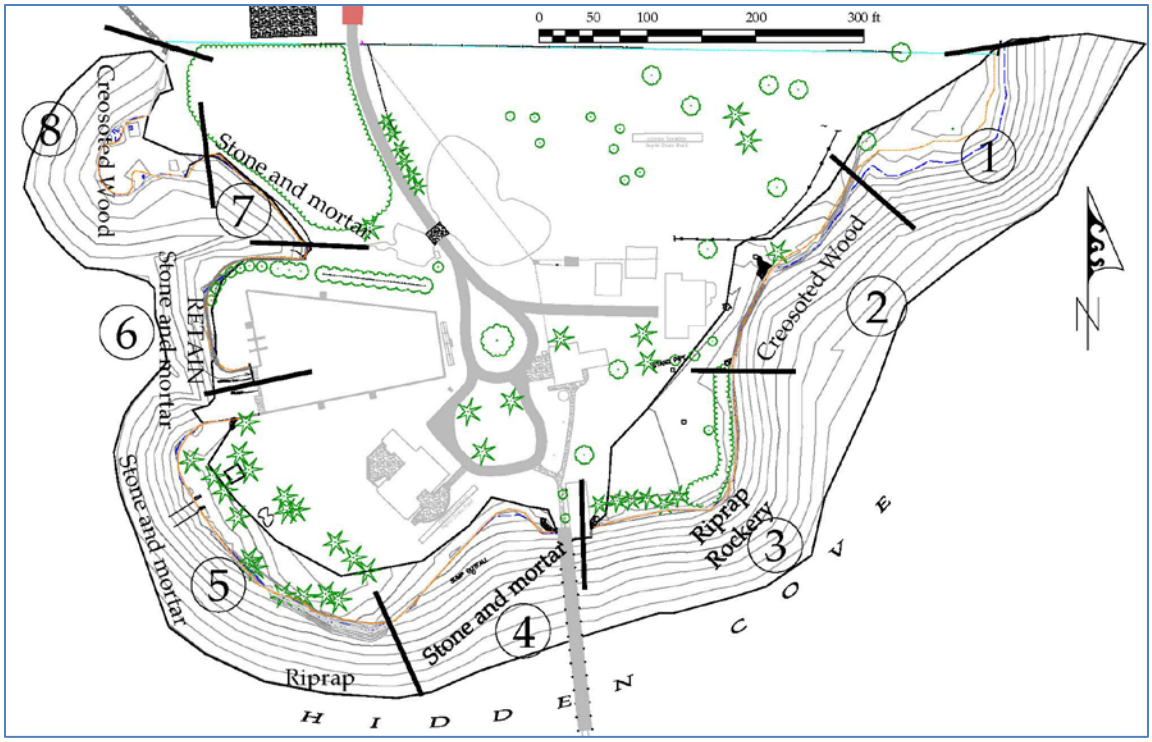

Figure 3-6. Example of site sectioning based on potential armor removal action shown in plan view (CGS 2011).

Cross sections represent measured beach, bluff, and development features to the extent possible perpendicular to the shore. Measurements should include the length, height, and elevations of key or defining features (Figures 1-5 and 1-8). Cross sections associated with elevations of beach features are also referred to as beach profiles (Downing 1983) or cross sections can include stratigraphy and hydrology as in a typical geologic cross section (Figure 3-7). Cross sections may include the following:

- beach toe or low-tide terrace
- beachface and storm berm
- MHHW and OHWM
- drift log line and backshore or salt marsh vegetation
- shore armor structure(s)
- bluff or bank toe, slope, riparian vegetation, and bluff crest
- groundwater seepage on bluff face
- upland development and drainage features
- setback distances for upland structures

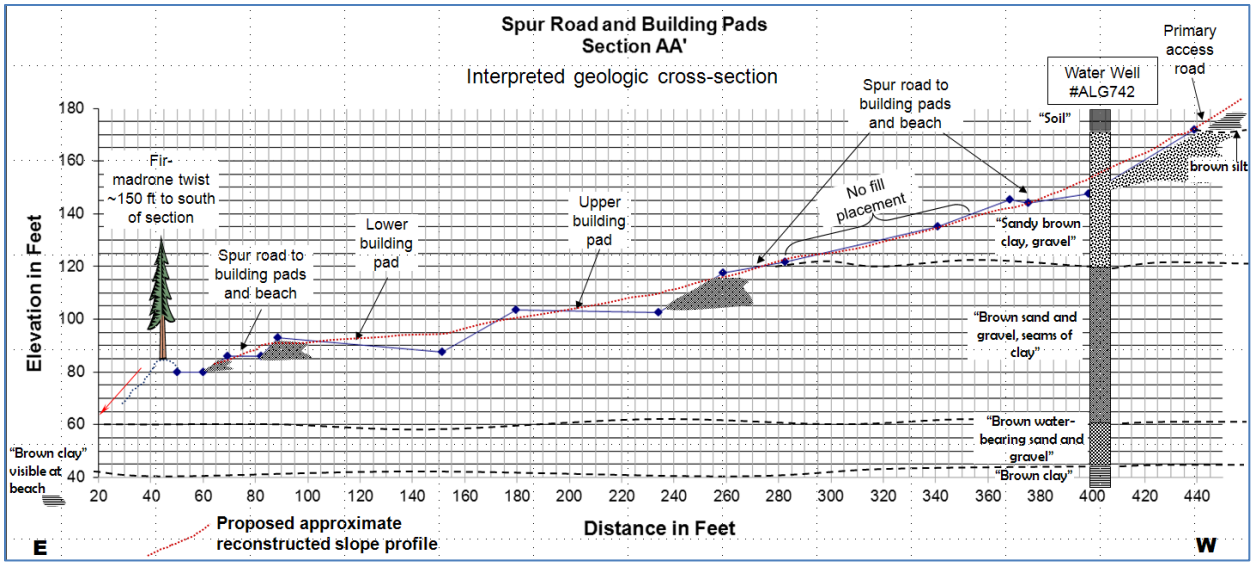

Figure 3-7. Interpreted geologic cross section for a regrading project (Johannessen et al. 2011, drawing by Gerstel).

The location and elevation of all of these features within the cross-section will guide the design process for potential erosion control or enhancement approaches for a site. For example, actions are typically not allowed to remove salt marsh vegetation. If considering a large wood project, the location and elevation of the natural drift log zone is a key piece of information to show on cross sections. Example cross sections drawn to the appropriate level of the project objective are available for each of the case study sites in Appendix A.

Upland Surface Water Drainage

Watershed conditions, stream or drainage contributions, and wetlands upslope of or adjacent to the site should be noted as this may influence drainage regimes at the site.

Seeps and springs apparent on the uplands, bluff, or beach should be noted. Features associated with the action of groundwater movement through the bluff face should be noted, including piping, wet layers within stratigraphy, and hydrophilic vegetation. Do seeps and springs appear to be causing erosion or mass wasting on the bluff or is the erosion in close proximity to the seeps or springs on the bluff?

Infrastructure water sources should be noted, whether natural or human constructed, and include stormwater systems, discharge points, and impervious surfaces. Figure 3-8 illustrates potential sources of surface water related to infrastructure (also see Figure 1-8).

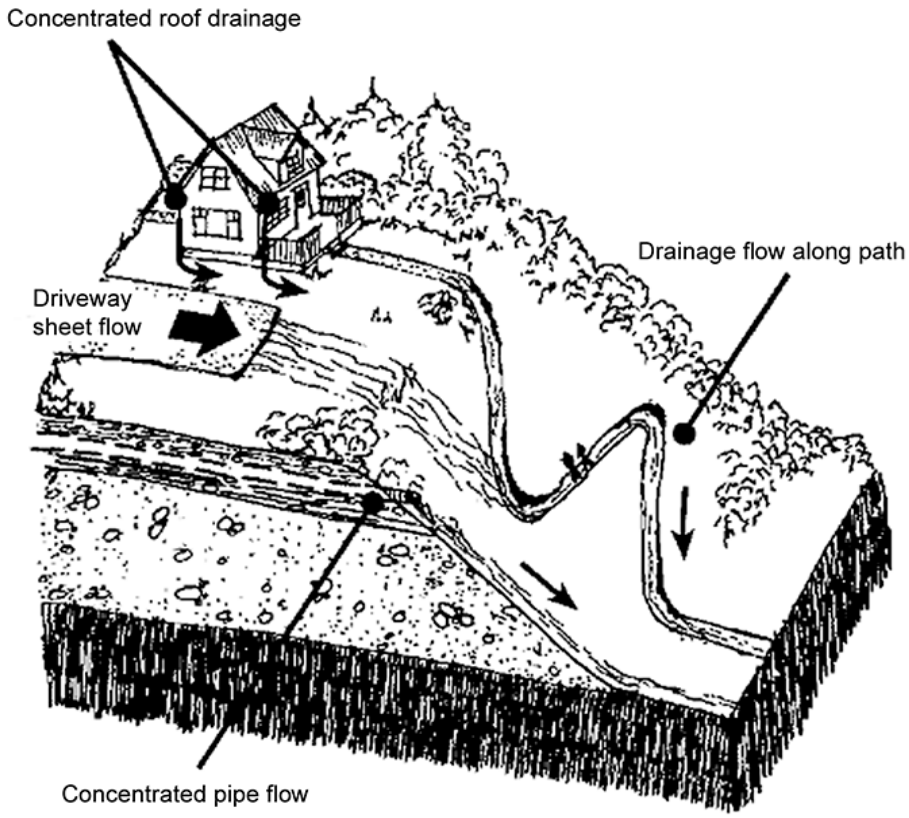

Figure 3-8. Illustration of potential on-site sources of surface water drainage to a coastal bluff (Myers 1995).

Site Vegetation, Habitat, and Species Considerations

Site vegetation, habitat, and species considerations are interrelated. The quality or degree of degradation of the habitat can be informed by condition of both the flora and the fauna found on the site. Key vegetation communities based on tidal elevation are listed below:

- Submerged aquatic vegetation, in particular eelgrass and bull kelp
- Potential forage fish spawning areas in the upper intertidal (rich in 1–7 mm sediment for surf smelt; rich in 0.5–3 mm sediment for sand lance)
- Backshore vegetation communities, including dunegrass
- Marine riparian vegetation, including overhanging the beach

Site vegetation can give important indicators of processes occurring at the site. For example, hydrophilic vegetation on a bluff face can indicate the presence of seeps (as noted above). Salt tolerant vegetation can indicate the extent of wave runup. Note the existing condition of vegetation at the site, the appropriateness of existing vegetation for the location (for example, salt tolerant plants closer to shore or native plant assemblages as opposed to lawn and ornamental species), and whether the conditions can be improved.

Animal species presence as observed or documented in background data may impact future project considerations and permitting. The habitat needs of juvenile salmonids include: a degree of complexity in the shoreline morphology, presence of marine riparian vegetation, and a percentage of overhanging vegetation alongshore for production of terrestrial macroinvertibrates (Brennan 2007). Forage fish

spawning habitat needs include beach sediment size between 0.5 mm and 7.0 mm at the upper beach and presence and a minimum percentage of overhanging marine riparian vegetation (Penttila 2007).

Overall, animal species found on the site should be noted if a positive identification can be made. Observations of marine invertebrates, shellfish, fish, sea birds, or other animals based on habits/tracks, remains, or actual sightings will provide valuable baseline documentation and implications for habitat conditions.

Site Development Features

Site and immediately-adjacent development features should be fully investigated and documented. The example in Figure 3-9 shows the development features to be measured and related to the beach and bluff locations.

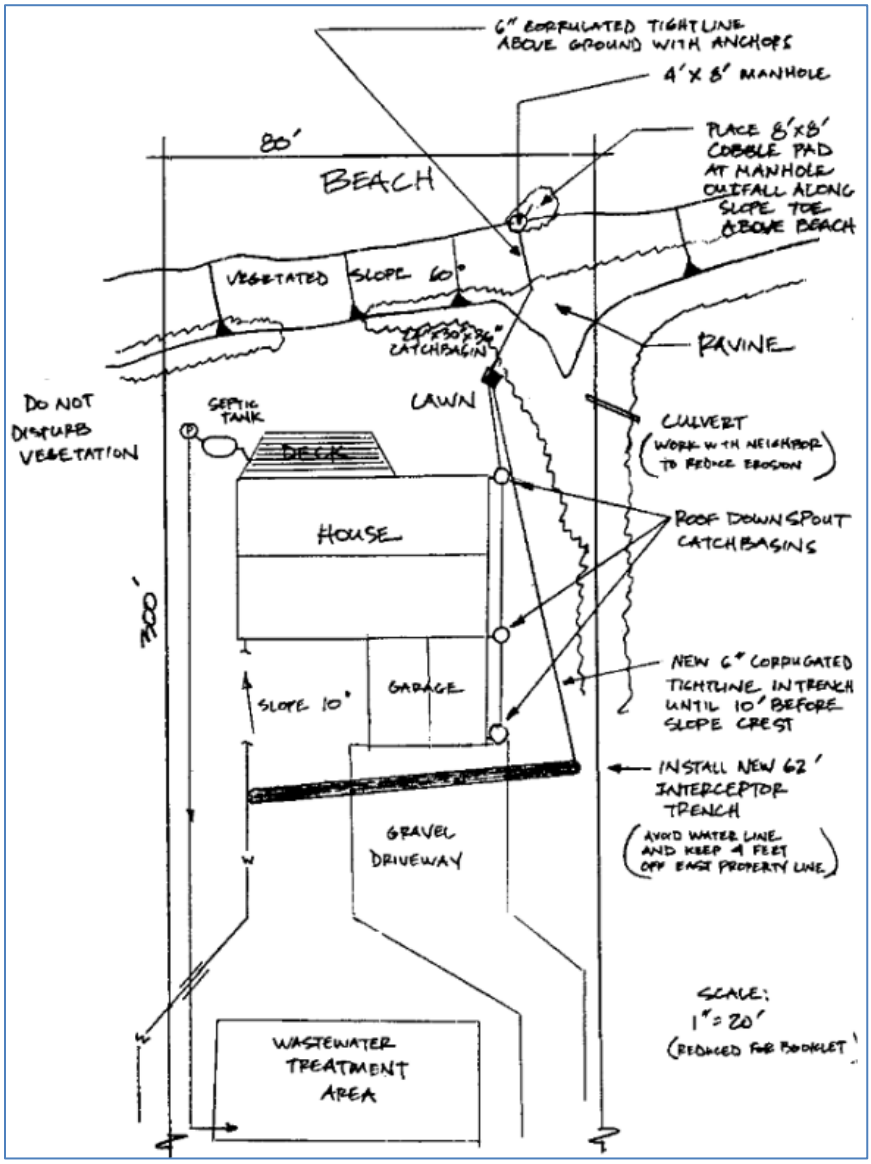

Figure 3-9. An example sketch of development features and measurements including location of structures and surface water drainage points, as well as their location relative or setback to the beach and bluff (Myers 1995).

Appropriate setbacks of *primary structures* from a potentially receding bluff crest should be considered based on site conditions already assessed. Does the setback seem adequate given the current conditions assessed, or do the structures appear to be at risk in the future? For instance, if a high bluff shows signs of past landslides a greater length of setback is needed than for a 12-ft-high bank composed of till. Also consider if there is space to move the structures landward or otherwise away or out of reach of the erosion.

Secondary structures and infrastructure, including septic systems, sheds, garages, driveways, or patios for instance should be measured as distance from bluff crest. These secondary structures are often movable thereby mitigating any threat of coastal erosion.

Existing erosion control structures should be described in detail. The type of structure, material used, dimensions, and condition of the existing structure should all be noted, as this will influence future actions taken at the site. The elevation of the toe and crest of the structure as compared to mean high water can indicate if habitats have been buried and the site has incurred a degree of habitat degradation. This could be especially important if the consideration involves rebuilding, repairing, or removing the structure. Erosion associated with the structure as observed, measured, or possibly caused by the structure should be documented.

Drainage control features associated with the infrastructure including gutter downspouts, trench drains, and drainage pipe size and material (such as “8 inch diameter HDPE tightline” or pipe) should be noted. Describe the relationship of the drainage infrastructure, and any potential damage or vulnerability to it. Note if drainage outlets coincide with erosion or landslide areas.

Site-Based Causes of Erosion

The site assessment needs to examine the types, locations, and processes of erosion occurring at the site. It is important to note that coastal erosion and mass wasting (landslides) can be influenced by different factors, but both contribute to bluff recession. Table 3-1 is meant to assist in differentiating between factors causing the two processes. Erosion or bank recession observed during the site assessment should undergo a series of inquiries related to the existing conditions and processes occurring that cause erosion or mass wasting at the site (Figure 3-10). Examination of historical information (see Chapter 4) is useful to augment the site assessment data.

Table 3-1. Types of erosion or mass wasting linked with key site measurements and potential causes.

Type of Erosion or Mass Wasting	Location	Key Site Measurements	Potential Causes
Beach/backshore erosion—entire site	At or below MHHW	Erosion scarps, erosion rate, sediment size	Storm wave attack, decreased sediment supply
Beach/ backshore erosion—specific area	Upper beach/backshore	Erosion scarps, extent and timing of erosion, sediment size, structure location, elevation and character	Wave refraction or wave energy concentration due to structures
Bluff toe erosion	Base of bluff	Evidence of beach erosion, extent of toe erosion, bluff composition and slope	Storm wave attack, decreased sediment supply, reduction in LWD/vegetation
Mass wasting/landslide	Lower to middle bluff face	Extent of mass wasting, bluff composition, groundwater, surface water	Storm wave attack, natural geologic instability, vegetation clearing
	Bluff crest to upper bluff	Extent of mass wasting, bluff composition, groundwater, surface water	Natural geologic instability, vegetation clearing and dumping
Rilling or gully formation	Discrete area of bluff	Extent of erosion, bluff composition, surface water and control	Uncontrolled or focused surface water drainage

Where on the site is erosion occurring?

Why is erosion occurring?

Potential causes:

- Natural coastal erosion of beach/backshore
- Beach gravel mining
- Historical fill only eroding
- Potentially reduced littoral sediment supply
- Adjacent coastal structures
- Altered surface/ground water regime
- Vegetation clearing
- Site excavation/other modifications

How fast is erosion occurring?

- On-site evidence
- Aerial photograph measurements

Is erosion short-term or cyclical?

- Temporary storm damage
- Seasonal accretion

What development or improvement is at risk?

- Substantial, such as house or landscaping
- Other unsubstantial improvements

Figure 3-10. Inquiries for a site to assist in qualifying causes of erosion and/or mass wasting (adapted from unpublished material by Hugh Shipman, WDOE).

The mechanism of failure is the physical process of erosion or mass wasting that is considered to be the primary "problem" at the site. Typically, stability problems along coastlines pertain to problems resulting from toe erosion, surficial instability, deep-seated instability, or some combination of these factors (MacDonald 1994). After carrying out the site assessment as outlined in this chapter, the site assessor should have sufficient data to reach preliminary conclusions as to the mechanism/cause of the instability. It is important to use site observations to support or substantiate the determination, and to be able to attribute to site management (surface runoff, drainage conveyance, fill placement, or other reason.) upland processes (road culverts, large-scale land-use practices, excessive irrigation, or other reason), geologic/hydrologic controls, or coastal processes.

Erosion or mass wasting at a site can be characterized by the location or area affected and how this may be related to potential causes. The location of erosion or mass wasting is influenced by impacts from upland processes, development, or cumulative issues affecting the observed condition. For example, upland processes from concentrated or redirected surface and groundwater flow may be driving erosion or mass wasting (Table 3-1). Note that storm wave attack is considered a natural forcing that can cause erosion with or without anthropogenic modifications, but can be exacerbated by modifications to the site or the drift cell.

A qualitative initial assessment of risk to infrastructure, taking into consideration all site observations and interpretations which the site assessor(s) was able to gather, is of value in addition to the quantitative risk measure described in the *Alternatives Analysis* (Chapter 5). Site-visit setback measurements from the OHWM or the top of the bluff to houses and major infrastructure are required for the quantitative assessment of risk. Integrating the preliminary erosion causation in the context of qualitative risk from the site assessment is one of the final steps of the site assessment. For example, a barrier beach site with clear and persistent erosion that threatens a house may be characterized as having high risk based on initial assessment. In other cases, high bluffs composed of loose, granular sediment, with a narrow beach and a minimal setback distance would be characterized as high risk based on the site assessment only.

Preliminary assessment of risk is also important because this risk is typically the means by which landowners initially seek an erosion-control structure. However, perceived risk may differ substantially from a careful examination of risk, and that is where discussions with the landowner become important for determination of the true driving processes and true risk for a site.

Other Considerations

Construction access should be evaluated while conducting the site assessment to allow planning for project implementation. Access routes to the site are a key constraint on many small properties; for instance, whether heavy equipment comes by land or by sea. Accommodations may be necessary in each case depending on whether there is an existing access road or installation needed, or a path may need to be temporarily cleared of large boulders in the intertidal for a barge landing. This information will be useful for the design stage.

When collecting field measurements it is often useful to initialize or reoccupy fixed points for potential future monitoring at the site. Beach profiling, simple beach elevation measurements related to key site

issues, or creating simple measurement stations to the crest of a receding bluff could be useful for better understanding the site-based and coastal processes acting upon a site. Obtaining this data while at the initial site visit could assist in shaping future project actions or treatments. Monitoring is discussed in greater detail in Chapter 8.

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Chapter 4. COASTAL PROCESSES ASSESSMENT

Role and Purpose

The information gathered from the site visit (Chapter 3) in the first step will inform this second step, the coastal processes assessment, and together these will provide the foundation for step three, the alternatives analysis (Chapter 5). The coastal processes assessment applies a landscape-scale lens to understanding the condition of the larger system in which the subject site is located. The "system" refers to the coastal process unit that encompasses the site. More specifically, the assessment should be focused on either the entire net shore-drift cell, or if the site is not located within a drift cell, then the full extent of the shoretype in which the subject site is found. The results of both the site assessment and coastal processes assessment should be used together to identify and design a feasible management technique with the least impact possible to nearshore processes, structure, and function.

The entire shore of Puget Sound has been delineated into distinct net shore-drift cells that function as alongshore sediment subsystems, each with its own sediment sources (feeder bluffs), transport zones, and sinks (depositional areas) (Johannessen 2010, CGS 2013). An example of net shore-drift cells is shown in Figure 4-1. Areas in which no substantial littoral drift occurs are mapped as "No Appreciable Drift" (NAD) areas. Bedrock shores are found within NAD areas, which commonly contain isolated pocket beaches. Neither bedrock shores nor embayments (such as those within a barrier lagoon or barrier estuary) should require erosion control measures. Bedrock shores have negligible erosion rates as embayed shores due to the protected, low wave energy environments in which they area definitively found. Delta shores are also commonly mapped as NAD areas, as they are dominated by large-scale fluvial systems. Delta shores should be assessed by combining the approaches discussed in this chapter with the reach assessment methods described in the Washington State Aquatic Habitat Guidelines Program's Integrated Streambank Protection Guidelines 2003 (Cramer et al. 2002).

The coastal processes assessment generally entails two distinct elements. The first element consists of evaluating specific characteristics of the drift cell or larger system to understand the natural range of physical conditions at the site and how those conditions compare across the region. For example, does the drift cell naturally have a low, moderate, or high volume of sediment in transport? How will the area respond to sea level rise (SLR)? The second element includes an assessment of how intact or degraded processes are in the system as compared to historic or pristine conditions. For example, is the sediment supply degraded at the site due to armored feeder bluffs up-drift of the site? The second element also entails identifying other confounding factors that alter nearshore physical conditions, with potential repercussions on subject site conditions.

Necessary Level of Expertise

A qualified professional in the field of coastal geology, coastal geomorphology, or coastal geography should perform the coastal processes assessment. The assessor should have a solid understanding of the range of conditions found in the Puget Sound region and be able to clearly identify sources of degradation to nearshore processes. The assessor should also be familiar with the key data sets and have the skills to use GIS.

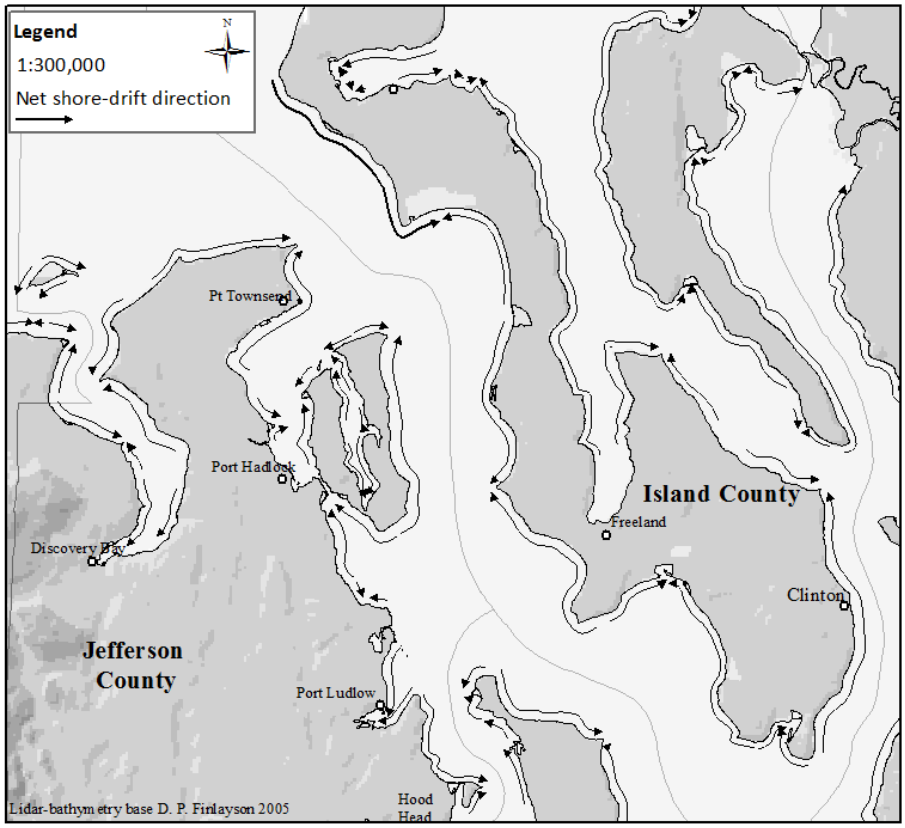

Figure 4-1. Variability of net shore-drift cell lengths in Island and Jefferson Counties, Washington (CGS 2013).

Conducting the Assessment

The first step in conducting a coastal processes assessment is to compile and review all relevant data. Relevant data would include, at a minimum, GIS data sets pertaining to physical processes for the area, historical and current aerial photographs, geology maps (ideally 7.5-minute quadrangles at the 1:24,000 scale), WDFW priority habitat species data, and LiDAR data. Required GIS data sets include Puget Sound feeder bluff mapping (MacLennan et al. 2013), the PSNERP Strategic Needs Assessment process evaluation framework (degradation) data (Schlenger et al. 2011), Puget Sound Change Analysis shoretypes (current and historical shoretypes) and stressor data sets (particularly armor and groins, both found in Simenstad et al. 2011), and net shore-drift data (as updated in MacLennan et al. 2013).

The net shore-drift data should be used to define the spatial extent of the assessment area. If the subject site is located within a net shore-drift cell, then the assessment area should include that entire drift cell. If the site is located within a NAD area, then the assessor should refer to shoretype mapping in Simenstad et al. (2011) to determine the full extent of the processes affecting the subject site. If it is a pocket beach, then the full extent of the pocket beach should be assessed in lieu of the drift cell for these sites.

Drift Cell Assessment

The overall intent of this portion of the assessment is to evaluate the current conditions of the larger system (drift cell; analogous to a coastal process unit in PSNERP terms) within which the subject site is located. Considerable variability exists within the length and shoretype composition of drift cells across

the Puget Sound region (Figure 4-2). The extent to which the drift cell is composed of active sediment sources (feeder bluffs) relative to other shoretypes and how it compares to other drift cells throughout the region can provide insight into the volume of sediment supply in transport in the drift cell. For example, longer drift cells with several miles of feeder bluffs are likely to have larger sediment budgets than shorter drift cells with fewer feeder bluffs. Similarly, some drift cells have only low-elevation bluffs while others have feeder bluffs that exceed 200 ft in height, which will affect baseline conditions within the adjacent shores. Understanding where the subject drift cell falls within the range of conditions provides context for the what one can expect from a site located within that system.

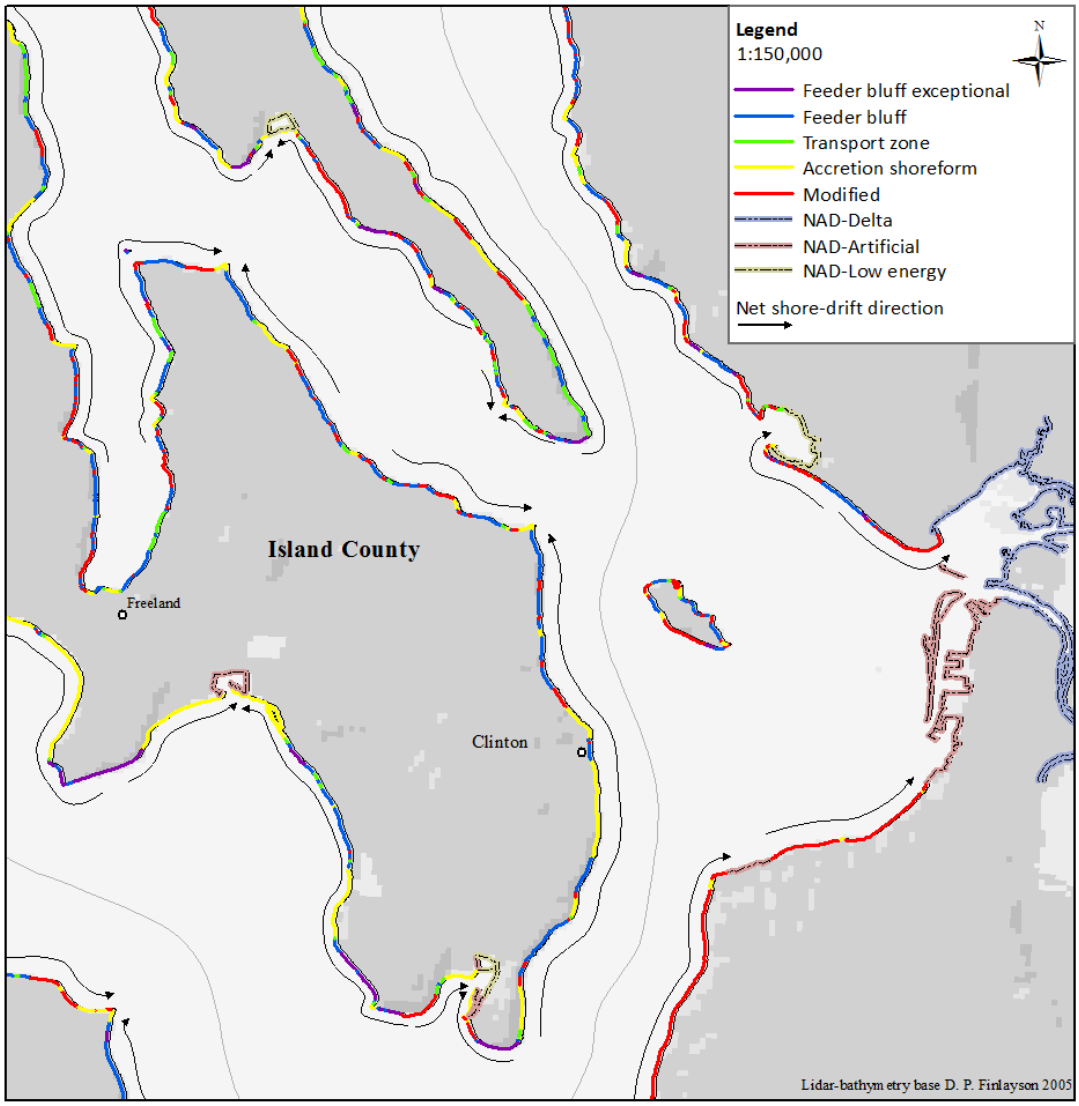

Figure 4-2. Variability of shoretype composition of drift cells in Central Puget Sound (CGS 2013).

The position of the site within the overall drift cell can also be informative. Sites located near the drift cell origin are typically more erosional as they are subjected to greater wave energy and have lower volumes of sediment on beaches, whereas those located near the cell terminus generally have lower wave energy, causing sediment deposition (Jacobson and Schwartz 1981). The distribution of shoretypes adjacent to the site of concern is also relevant to understanding baseline conditions. For example, if the

site is an accretion shoreform (broad beach or spit) located between two feeder bluffs, then it is unlikely that degraded sediment supply is driving the erosion issues at the site. Management technique designs should ensure there are no impacts to sediment transport under this scenario. The geology of the feeder bluffs in the drift cells has a direct influence on the sediment composition of down-drift beaches. Geologic units composed of finer material (fine sand to clay) will contribute less beach-building sediment than bluffs composed of coarser material (coarse sand to gravel).

Pocket beaches theoretically function as part of a closed system; therefore, the condition of adjacent beaches is less relevant to pocket beach dynamics. However the condition of the entire pocket beach should be assessed. Pocket beaches can range in length from a few tens of feet to thousands of feet. They are typically swash aligned, meaning they are oriented facing the predominant wave approach. In some cases, sediment is supplied from eroding banks landward of all or a part of a pocket beach. It is important to note any sediment input of this nature in a pocket beach. Other influences on the local wave climate, such as large glacial erratics and offshore bedrock promontories, should be assessed also.

Maximum fetch should be measured for both sites within drift cells and pocket beaches. Fetch from the predominant and prevailing wind directions should also be measured, as this provides a surrogate for the wave energy at the site. Habitats for priority species should be reviewed using WDFW Priority Habitat Species (PHS) data for the entire pocket beach and the shore down-drift of the subject property within a drift cell.

Aerial photographs of the site and adjacent shores should be compiled and reviewed to gain understanding of the baseline dynamics of the area. Explore the photographs to determine if and when considerable erosion has taken place at the site in recent history. Was the erosion associated with a particular event or perturbation, such as a 100-year storm? Are current beach characteristics, such as width of the beach and LWD presence, similar to historic conditions? What overarching trends (erosion, accretion, or relative stability) can be observed within the shoretype that encompasses the subject site? LiDAR data can also provide insight into processes affecting the drift cell or site, such as the extent of coastal or bluff features or if historic landslides have occurred. The site and surrounding shores should also be assessed for anomalous conditions that could result in exacerbated erosion or amplified wave energy, such as a tide channel, strong tidal currents, or changes in bathymetry.

Process Degradation Assessment

The second element of the coastal processes assessment entails evaluating the degree to which anthropogenic change has occurred within the greater system, with subsequent alterations to physical conditions and nearshore processes at the subject sites. Physical processes that should be evaluated include sediment supply, transport, and deposition; and wave regime. Process degradation data created for PSNERP (Schlenger et al. 2011) can inform this portion of the assessment together with aerial photography. A qualitative ranking of sediment supply, sediment transport, sediment accretion, and physical disturbance processes is included in version 3.0 of the PSNERP Change Analysis (Simenstad et al. 2011). Results are categorized as low, moderate, high, none, and not applicable in the database for the process condition throughout the process unit (Figure 4-3). The level of degradation within a given unit for each nearshore process was measured by evaluating the co-location of specific stressors in shoretypes that are known to degrade nearshore processes. For example, the presence of groins within a barrier beach or bluff-backed beach in which sediment is actively transported would be a source of

degraded sediment transport. These data can be found in the Strategic Needs Assessment process evaluation framework GIS data (SNAR_ProcessEvaluationFramework, Schlenger et al. 2011).

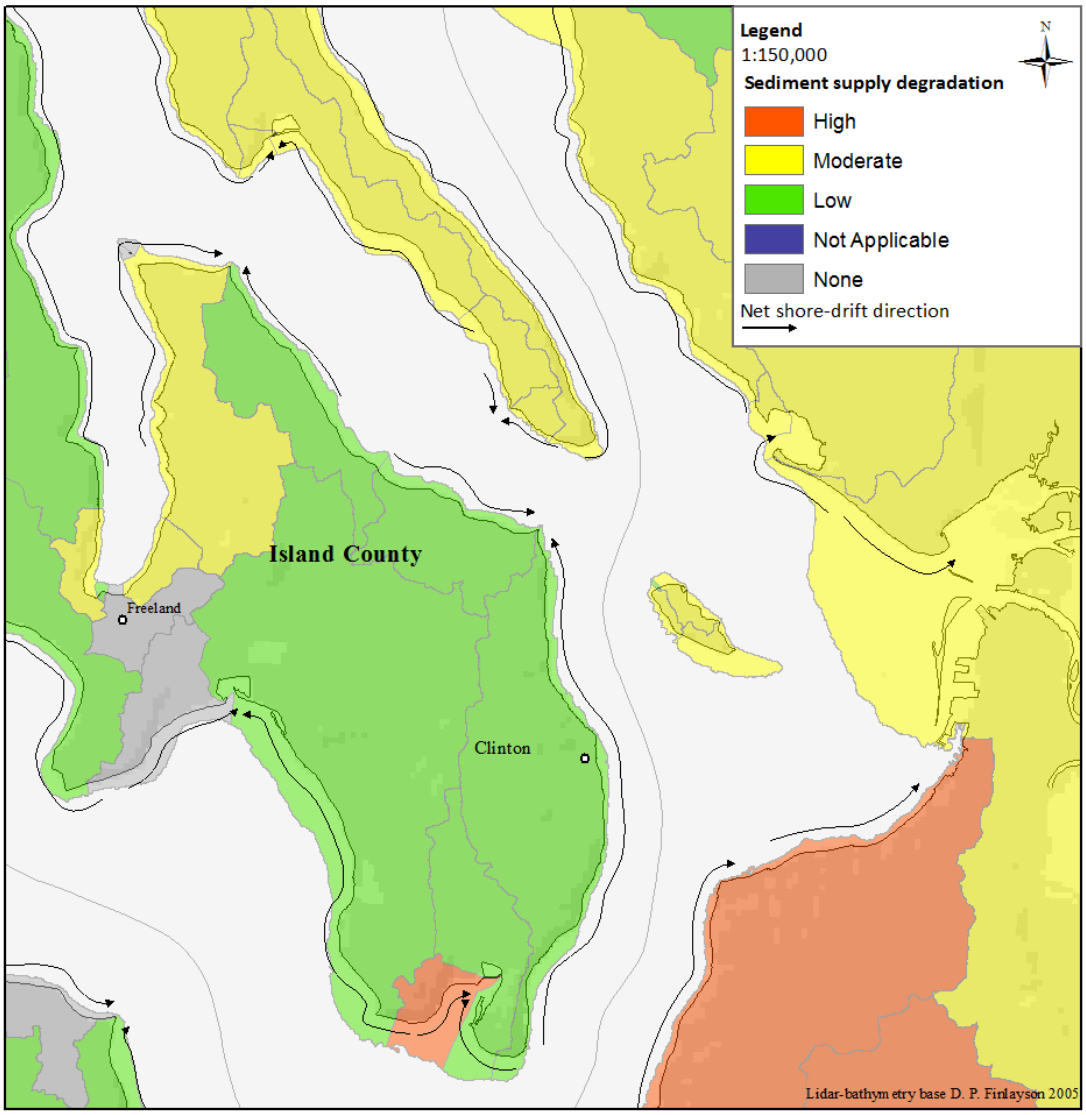

Figure 4-3. Sediment supply degradation from PSNERP Strategic Needs Assessment process evaluation framework (Schlenger et al. 2011, Simenstad et al. 2011).

Investigation beyond the PSNERP data into drift cell conditions and alterations to coastal processes is typically required, as the PSNERP data is fairly coarse scale in most areas of Puget Sound. Further investigation will provide more spatially explicit information on the condition of physical processes within the drift cell. Puget Sound feeder bluff mapping data can be used to inform the degree to which sediment supply up-drift of the site has been altered by armoring. Modified shores that were historically feeder bluffs can be identified by reviewing the historic feeder bluff attribute in the geodatabase. All armored shores are attributed to describe if the segment was a feeder bluff prior to being armored. If a considerable length or portion of the feeder bluffs in the drift cell are armored feeder bluffs or if the drift cell has highly degraded sediment supply based on SNAR data, then some of the erosion occurring

at the subject site may be due to lost sediment supply. Similarly, if sediment transport has been altered up-drift of the site, then the volume of sediment delivered to the site may be unnaturally low.

Additional review of the stressor data sets or shoretype-alteration data sets in the PSNERP Change Analysis (version 3.0) can aid understanding of anthropogenic change at the landscape scale. Data sets that could be most informative to this work include those for shore armor, breakwaters and jetties, marinas, nearshore fill, railways (abandoned and active), and tidal barriers. Degraded sediment transport can occur as the result of an impediment to littoral drift such as a breakwater, groin field, or navigation channel (associated with a marina). Deep-water channels dredged for navigation often create a sediment sink that traps sediment in transport and precludes it from reaching the down-drift shore. An altered wave regime resulting from a breakwater or jetty often reduces or eliminates the continuity of littoral transport resulting in impacts to the down-drift shore. The adjacent shores should also be assessed for other sources of wave regime alteration, such as large boat wakes associated with major shipping routes, ferries, or other boating facilities.

Climate Changes and Sea Level Rise

Implications of climate change, including SLR, should also be evaluated for the subject site and adjacent shores. Evaluating relative sea level rise for the area is of critical importance and will provide a foundation from which additional analysis can be applied. Relative sea level rise integrates local vertical land movement (uplift or subsidence) with global (eustatic) SLR projections. Because SLR projections are constantly being updated with the advancement of global climate models, only the most recent projections recommended for the State of Washington should be used (National Academy of Sciences 2012). Projections are commonly reported using a range of scenarios (low to high or very high). To be conservative, the higher magnitude (or the upper extent of the range of) projections should be considered.

Once local SLR is calculated, the types of threats that are likely to occur at the site (coastal flooding versus erosion hazards), and the likely management responses (adaptation versus protection) should be explored. Several nearshore processes are likely to be altered as a result of climate change and SLR (Table 4-1).

Table 4-1. Potential impacts of sea level rise and climate change on nearshore processes (from Clancy et al. 2009)

Process	Anticipated Impacts
Sediment supply and transport	Increased sediment supply from bluff erosion and streams, increased littoral drift rates, likely loss of sediment sources because of new shore protection.
Beach erosion and accretion	Exacerbated erosion along erosional and generally stable shores, and likely shifted areas of accretion. Overall landward shift (transgression) of coastal features and associated habitats.
Distributary channel migration	Channels may accrete with rising sea levels and have greater tendency for migration in response to altered freshwater input.
Tidal channel formation and maintenance	Tidal channel may accrete and processes may become less predictable in response to altered freshwater input.
Freshwater input	Freshwater input predicted to become more variable, with more flooding (winter-spring) and drought conditions (summer-fall).
Tidal hydrology	Greater inundation and tidal flows into semi-enclosed systems, increased saltwater incursion.
Detritus recruitment and retention	Likely greater detritus recruitment due to overall greater wave energy reaching marine riparian zone. Likely increased storminess and storm surges (including more frequent and intense El Nino storms) and from rivers due to increased peak flows.
Exchange of aquatic organisms	Reduced productivity of threatened salmon stocks due to increased winter flooding, decreased summer and fall stream flows, and elevated warm season and estuary temperatures. Loss of biological diversity/localized extinctions of marine and freshwater species if habitat shifts outpace ability of species to migrate or adapt to changing conditions.
Solar radiation	Altered solar patterns due to hotter summers, colder winters.
Wind and waves	Overall greater wave erosion and potential accretion due to SLR

Identifying how impacts to nearshore processes will affect the subject site is important to understanding the long-term dynamics of the site. Data from the site assessment can be used to understand the likely future position of the shoreline. This information should guide which management options are most sustainable.

There is a wide range of adaptive capacity across shoretypes and larger reaches of shore. Several variables contribute to the resilience of a given reach of shore, each of which should be assessed to gain a broader understanding of the future of the site. These variables include

- shoretype
- wave climate (fetch, aspect)
- bathymetry
- tidal range
- intact sediment supply
- upland topography
- upland/landward geology
- presence of armor or other shore modifications that could preclude profile transgression

Results of the coastal processes assessment should be used together with results of the site assessment (described in Chapter 3) to perform an alternatives analysis of appropriate management solutions for a given site. A detailed alternatives assessment approach is provided in Chapter 5 that synthesizes these results to screen feasible design techniques and inform site-specific design elements. Incorporating design elements from several different techniques often enables the achievement of multiple objectives while limiting adverse impacts to the greatest extent possible.

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Chapter 5. ALTERNATIVES ANALYSIS

Objectives

In this chapter guidance will be provided on how to evaluate and select an appropriate erosion control technique for a specific site. Techniques are not "one-size fits all", and with each approach comes variable benefits, enhancements, impacts and costs. Ideally the alternatives analysis will result in the selection of a design technique that sufficiently addresses the (perceived) needs of the property owner while minimizing impacts to physical and ecological processes to the greatest extent possible. In this chapter, the range of approaches will be outlined, methods for measuring cumulative risk will be described, and the relative performance of each design technique will be summarized across different variables of influence to project performance. In addition, costs and benefits, critical design considerations, mitigation and monitoring requirements associated each technique will be described.

Data collected during both the site and coastal processes assessments will be used to inform the alternatives analysis and forthcoming design process. The alternatives analysis is reliant upon several earlier steps that nested within the larger MSDG process (Figure 5-1), the first of which entails identifying project objectives and defining the problem. Next the site assessment data provides key site characteristics and specifications, identifies the predominant drivers of erosion, constraints, and cumulative risk measures (Chapter 3).Data resulting from the coastal processes assessment provides critical spatial and temporal context that should be integrated in to design. Data collected in Chapter 3 and 4 are used together with tools in this chapter to identify appropriate approaches for the subject site. Benefits and impacts associated with the different alternatives should then be compared and reconciled. The alternative with the greatest benefits and least impacts is recommended for selection. Additional assessment data should be integrated into the selected design. Mitigation options would then be considered, and a monitoring and maintenance approach developed.

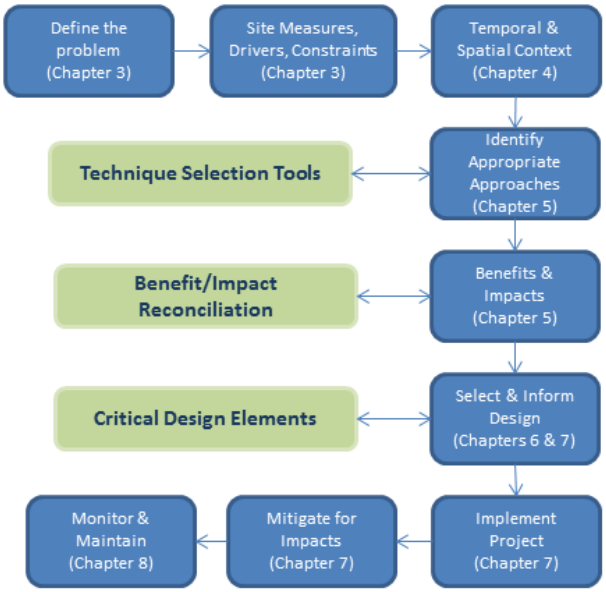


Figure 5-1. Components of the MSDG process for implementing shore protection in the Puget Sound region.

Range of Design Techniques

A broad spectrum of shoreline management approaches exist, ranging from passive management approaches that require minimal engineering to soft and hard shore armor. No Action alternatives are characteristically more passive approaches that preserve natural processes and have few to no negative impacts on nearshore ecosystem functions, goods, and services. Soft shore protection approaches preserve the natural beach and typically rely only on natural materials (at least above grade). Soft shore approaches include projects in which gravel and sand are added to the beach (beach nourishment), large wood is installed to curb erosion in the backshore, or the bank is regraded and revegetated to reduce bank erosion. Because soft shore protection projects commonly include beach nourishment they can benefit areas (drift cells and shoreforms) with decreased sediment supply, such as drift cells with large lengths of armored feeder bluffs. Hard armor represents rock revetments and vertical bulkheads, which are designed to preclude shoreline migration and bank erosion. Each type of approach has varying degrees of impact with the no action alternatives resulting in the least impact and hard armor having the greatest impact (Table 5-1).

Table 5-1. Range of approaches, associated design techniques, elements and impacts.

TYPE OF APPROACH	DESIGN TECHNIQUES	KEY ELEMENTS	IMPACTS
No Action	▪ Best management practices ▪ Managed Retreat	▪ Non-engineered management practices ▪ Preserves/enhances natural processes ▪ Move structures at risk	None
Soft Shore Protection	▪ Large Wood ▪ Beach Nourishment ▪ Reslope/ Revegetate	▪ Preserves shoreline dynamics ▪ Use of natural materials ▪ Slows rather than eliminates erosion	Low
Hard Armor	▪ Revetments ▪ Vertical Bulkhead	▪ Static shoreline ▪ Lost beach substrate ▪ Slows rather than eliminates erosion	Mod- High

Table 5-2 includes more detailed descriptions of each of the design techniques. Each of the design techniques can be used alone or in combination, depending on site characteristics and project objectives. For example bulkhead removal can be used purely for restoration, or it can be used when replacing old armor that is perhaps at the end of its design lifetime with an alternative measure. Large wood projects often also include a small volume of beach nourishment. Bulkhead removal can also be applied to a limited (spatial) extent of the project, such where there are no structures potentially at risk (Figure 5-2). Revetments can also be used in combination with other techniques, such as beach nourishment. For example a limited extent of revetment may be used to protect a structure in close proximity to the shore, within a larger beach nourishment project area.

Figure 5-2. Before (2004) and after construction (2007) at Marine Park in Bellingham, Washington as an example of multiple techniques employed at one site: bulkhead removal, with beach nourishment and rock drift sill to contain sediment, and adjacent revetment maintained to protect railway (in foreground).

Table 5-2. Basic description of each approach.

DESIGN TECHNIQUE	DESCRIPTION
Bulkhead removal (BR)	This is typically a beach restoration design technique applied along shores where erosion is not substantial or where armor serves more of a landscape feature and the beach may be restored, while infrastructure remains unaffected.
Bank re-slope and revegetation (RE)	Re-sloping is lowering the slope of the bank to increase stability. Revegetation is planting a bank with native riparian vegetation to create a root network (and ultimately, shrub or tree canopy) that reduces erosion. It can be applied to the existing bank or one which has been re-sloped.
Large wood (LW)	Large woody debris (LWD) is used to retain beach materials and dissipate wave energy (may contain some rock to provide ballast but not in excess of 20% areal density).
Beach nourishment (BN)	Beach nourishment is the addition of sand and gravel to build the beach to mitigate coastal erosion.
Rock revetment (RV)	Placement of stationary sloping rock, e.g., “riprap”.
Vertical bulkhead (VB)	Vertical face structure constructed of concrete, sheet pile, rock, or wood.

Informed Design Assessment

The development of the MSDG began with a case study analysis (Appendix A) that was conducted to compare site characteristics, design specifications, and various measures of success of the more commonly implemented design techniques on Puget Sound shorelines. Originally six techniques were explored however two techniques vertical concrete bulkheads and rock revetments were later combined in to a single technique referred to as hard armor. To support this effort a performance evaluation criteria was developed to measure how well suited the selected design technique is for site conditions, and what design specifications contributed to project success of failure. A successful shoreline design project would integrate the following key elements:

- Appropriate design technique for site conditions at the landscape (coastal process unit) scale and site specific (parcel) scale.
- Adherence to general design standards.
- Maximize benefits and minimized negative impacts

In total, twenty-five sites were assessed across the Puget Sound region. Limitations associated with attaining permission to access properties and identifying appropriate design techniques that had been installed over 3-years was a challenge and precluded efforts to have equal sampling across the different design techniques. Low sample numbers limit the user's ability to make broad inferences or generalizations about trends in the data, however, some patterns are still evident.

Simple patterns easily discernible from the case study assessments, results of the evaluation criteria, and the relative benefits and impacts associated with the different design techniques will be summarized in the following section.

How to Measure Cumulative Risk

A cumulative risk model was developed that integrates risk associated with natural conditions with infrastructure (Table 5-3). The model was calibrated and refined using data from the 25 case study sites, along with some additional site data from Shipman et al. (unpub.) and the CGS files. The first step of the risk model entails quantifying the erosion potential of the site by evaluating the shoretype and maximum fetch at the site. Shoretype mapping (sometimes call feeder bluff mapping) was recently completed for WDOE (MacLennan et al. 2013). The highest risk sites would be high bluffs that are characteristically receding and contributing large volumes of sediment to the nearshore (feeder bluff exception and feeder bluff, in order) with considerable wave exposure. Shoretypes which typically have minimal erosion (transport zones) receive a lower score under erosion potential, while accretion shoreforms, pocket beaches, and shores outside of drift zones get the lower score. Sites with greater fetch have a greater erosion potential, hence the classes with greater fetch received a higher score than this category (Table 5-3). The shoretype score is then added to the fetch score to give the resultant erosion potential score.

Because the natural process of erosion and mass wasting does not pose a risk unless infrastructure is threatened, the type and proximity of infrastructure are critical to qualifying risk at a site. Minimal risk is assumed for shores in which structures are adequately setback from the shore, regardless of value or erosion potential. The magnitude of the risk directly corresponds to the setback distance, type of infrastructure, its value, and whether or not it can be relocated. Landscaping features are assumed to be mobile are not considered at risk and are therefore are only a perceived risk. The proximity of the

infrastructure or setback distance from either the bluff crest or OHWM for sites without a bluff or bank to the infrastructure provides an additional indicator of the magnitude of cumulative risk. The smaller the setback the higher the setback score risk number (Table 5-3). The highest potential score for infrastructure type is for major infrastructure such as primary commercial or industrial buildings, or public roads. These two variables (setback and structure type) are then multiplied together with the erosion potential at the site to determine the infrastructure threat. Finally, the erosion potential is multiplied by the infrastructure threat to give the cumulative risk score, which represents the magnitude of risk. With this model, the highest possible cumulative risk score is 128, although the highest cumulative risk scores for the 25 case study sites was 80 (Appendix A).

The North Orcas Island project serves as a good example of how the cumulative risk score was calculated. The project was located on an accretion shoreform, so the shoretype score was 1. The fetch was measured at 101 miles, so the fetch score was 4. The setback of 43 ft to a house gives a setback score of 2 and infrastructure score of 3. The cumulative risk score is then calculated as

$$(1 + 4) * 2 * 3 = 30$$

To give a total cumulative risk score for the project of 30, a moderate level of risk.

Table 5-3. Cumulative Risk Model. **Fetch** = Whichever is greater: maximum fetch from southern quadrant or half of maximum from other aspects. **Setback distance** = Measured distance from bluff crest (or OHWM for no-bank) to most waterward infrastructure.

CUMULATIVE RISK MODEL			
EROSION POTENTIAL			
Shoretype	**Score**	**Fetch**	**Score**
Accretion shoreform, No-Appreciable Drift, Pocket Beach	1	0-1 mile	1
Transport zone	2	1-5 miles	2
Feeder bluff	3	5-15 miles	3
Feeder bluff exceptional	4	15+ miles	4
Erosion Potential Score (sum)	**Shoretype + Fetch**		
INFRASTRUCTURE THREAT			
Setback	**Score**	**Infrastructure Type**	**Score**
>60 ft	1	Property without structures	1
40-60 ft	2	Septic drainfield or non-living, unattached residential infrastructure	2
20-40 ft	3	Home or residential building	3
0-20 ft	4	Major infrastructure	4
Infrastructure Threat Score (product)	**Setback x Type**		
CUMULATIVE RISK TOTAL (product)	**Erosion Potential x Infrastructure Threat**		

Examination of the cumulative risk model results (Figure 5-5 and Appendix A) allowed for determination of different risk classes (e.g. low, medium, high) as follows:

- Low risk scores between 0-20
- Moderate risk scores between 21-40
- High risk scores greater than 40

The cumulative risk model score should help to distinguish the perceived and actual need for erosion control at the subject site. The risk model score along with other site characteristics will help define what design techniques are appropriate for the subject site.

Case study results (Appendix A) showed that revetments were more commonly applied on sites with higher cumulative risk scores. Reslope/revegetation sites also typically had moderately high risk scores (although only 2 sites were evaluated for this technique); which was equivalent to vertical bulkhead risk scores. However, beach nourishment, large wood and bulkhead removal sites were associated with sites with lower cumulative risk (Figure 5-3). Bulkhead removal, unless used in combination with managed retreat, is not an appropriate technique for sites with moderate or high cumulative risk. In addition to cumulative risk (scores), other sources of data, such as data derived from site and coastal processes assessments, are recommended for guiding technique selection and design criteria, several of which will be described in the forthcoming sections of this chapter.

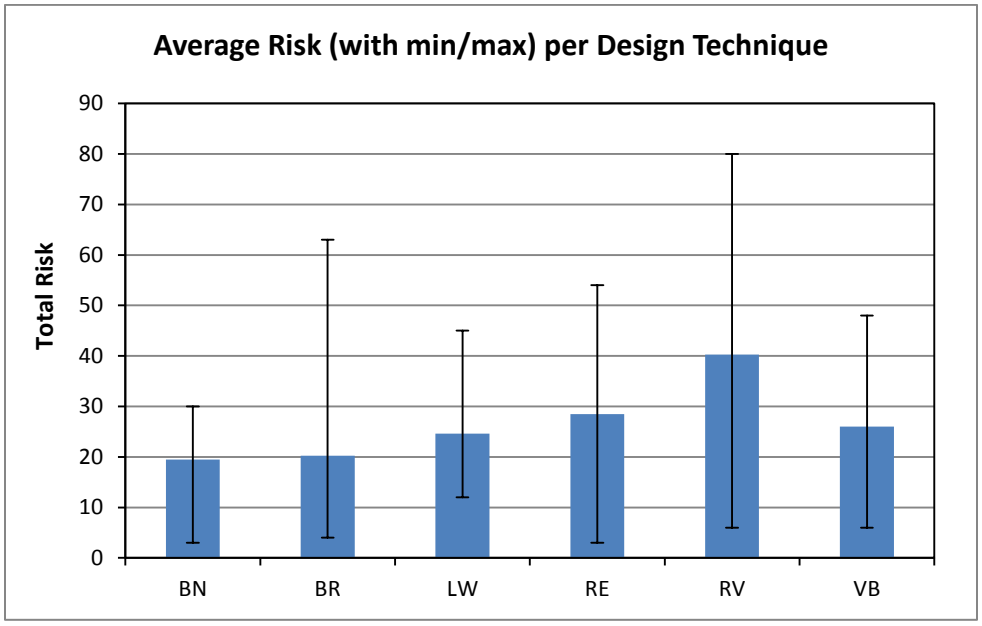


Figure 5-3. Average risk and range of from the 25 case study sites grouped by design technique.

Effectively Slowing Erosion

Project success was measured using the evaluation criteria developed for the case study assessment by measuring the relative measure of benefits and impacts associated with the application of each design technique. Benefits associated with a project included the following criteria:

- Effectively stopped or slowed landward erosion or protected infrastructure,
- Sediment volume augmented,

- Input/exchange of LWD, detritus,
- Backshore vegetation enhanced,
- Marine riparian vegetation enhanced, and
- Low cost, simple installation of the project.

One of the most critical criteria contributing to the selection of a design technique is the relative effectiveness of that technique at curbing erosion across variables influential to project success, most notably the effectiveness of the technique at slowing erosion. The predominant driver of erosion along marine shorelines is wave energy, which is commonly measured using the maximum fetch at a given site. Case study data were analyzed to explore the relative efficacy of each design technique across different fetch categories (low – very high, Figures 5-4 – 5-10). Bulkhead removal projects were not included in this analysis as curbing erosion is not a key objective of the application of that design technique.

Case study results showed a general decline in the effectiveness of slowing erosion rates with increasing fetch for both beach nourishment and large wood projects (Figures 5-4 and 5-5). Moderate success was still achievable at sites with high and very high fetch for beach nourishment projects, if site conditions were permissible and appropriately designed for those conditions.

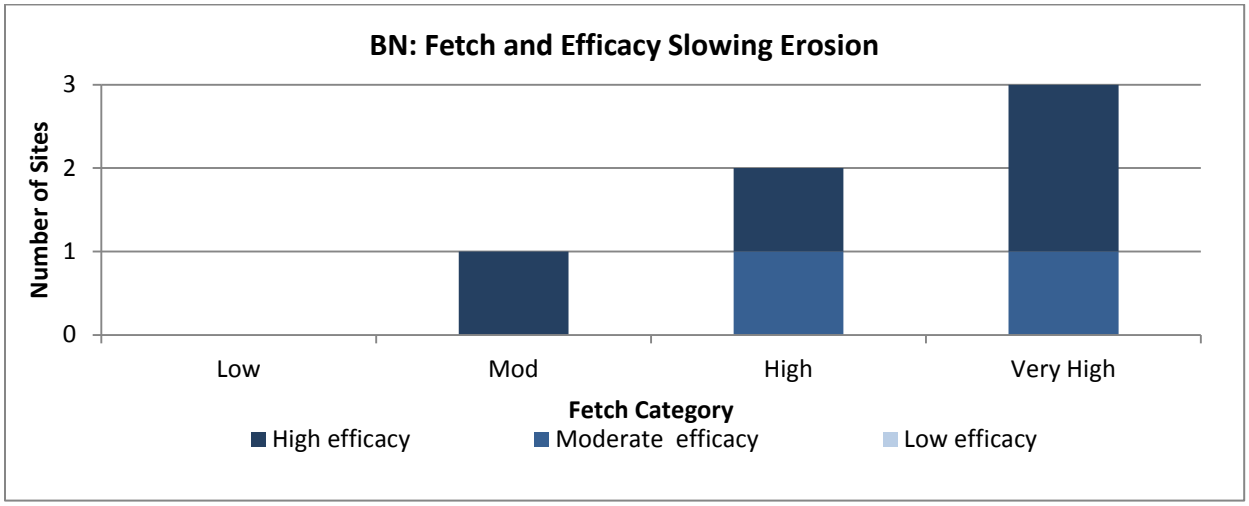


Figure 5-4. Fetch categories and effectiveness at slowing erosion, Beach Nourishment case study sites

Similar to beach nourishment case study sites, large wood projects showed a decline in effectiveness slowing erosion with increasing fetch, with only a low level of success slowing erosion at the site with very high fetch. Erosion can however be effectively slowed using large wood if site characteristics are amenable and designed appropriately for site conditions.

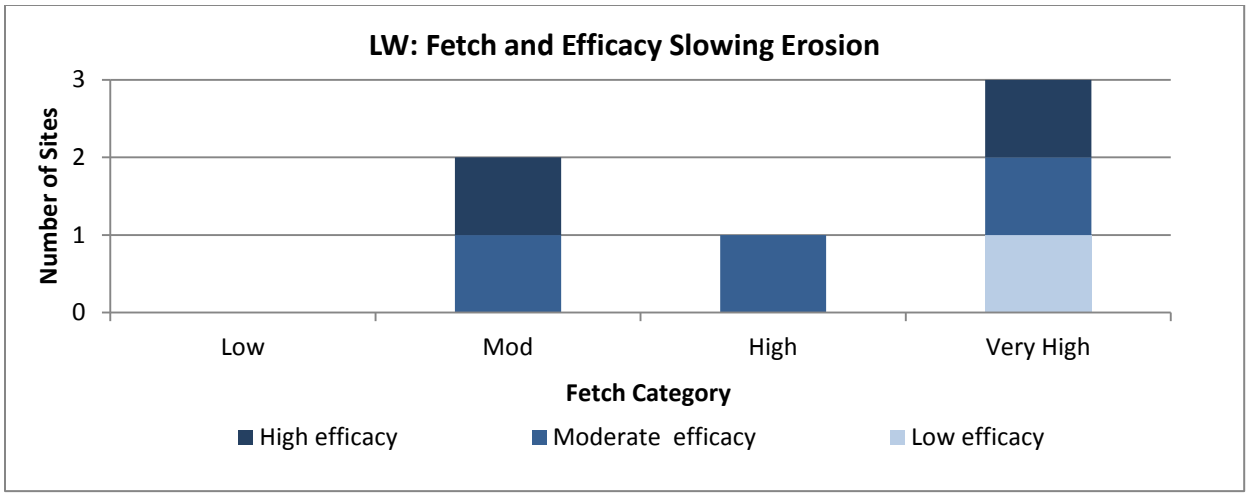


Figure 5-5. Fetch categories and effectiveness at slowing erosion, LWD case study sites.

Very few (two) reslope and revegetation projects with direct exposure to the marine environment were accessible for site visits. As a result, few patterns could be identified on the variables that contribute to the effectiveness of a given project. The limited case study data showed that erosion could be effectively slowed to a moderate degree at site with very high fetch (Figure 5-6). The site with low level of effectiveness slowing erosion also had low fetch, suggesting that design or construction were likely a contributing factor to project short-comings.

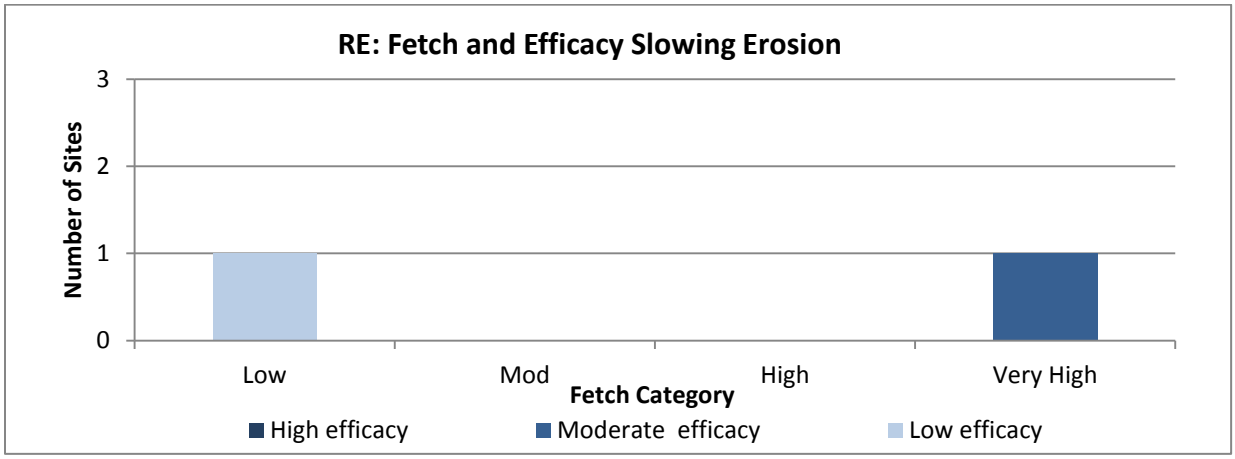


Figure 5-6. Fetch categories and effectiveness at slowing erosion, reslope/reveg case study sites.

Case study data showed that hard armor approaches, such as revetments (RV) and vertical bulkheads (VB), are not effective at slowing erosion across all fetch categories (Figures 5-7, 5-8). For example, revetment case study sites were exclusively located on shores with a moderate degree of fetch, however erosion was not always precluded or adequately slowed at those sites. A low level of effectiveness was documented at one revetment site (with moderate fetch), which was likely due to poor design and construction practices. In contrast to revetment case studies, vertical bulkhead case study sites were distributed across sites with variable levels of fetch. Vertical bulkheads were effective at slowing erosion at all sites, excluding the case study location with very high fetch. The case study location with very high fetch was located along the northwest shore of Whidbey Island, where fetch is at

the upper range of conditions seen across the Puget Sound region. At this location, the most appropriate shoreline management technique is likely realignment or relocating structures further landward from the shore, rather than attempting to preclude shoreline migration in such a dynamic, high energy environment. Design and construction issues may also have contributed to the failed effectiveness of that design technique in such a high wave energy environment.

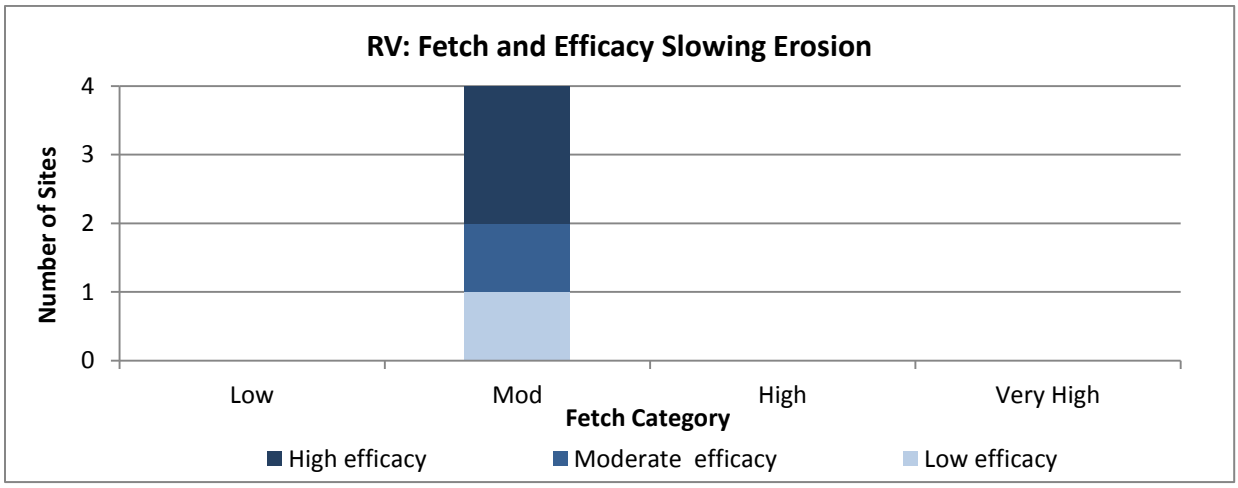


Figure 5-7. Fetch categories and effectiveness at slowing erosion, revetment case study sites.

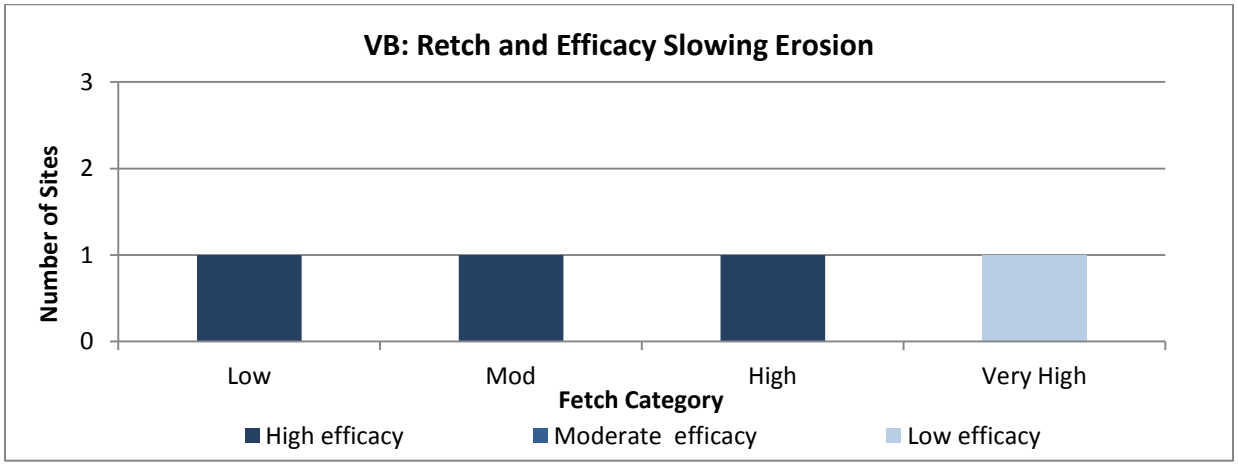


Figure 5-8. Fetch categories and effectiveness at slowing erosion, vertical bulkhead case study sites.

Greater under of the range of conditions that a given design technique will function in is integral to the design selection process. Additional variables identified as influential to the design technique selection process will be discussed below in the section entitled "*Selecting an Appropriate Approach*".

Design Technique Benefits and Impacts

The relative benefits and impacts associated with the different design techniques displayed the general pattern outlined in the previous section of: softer solutions providing fewer impacts and more benefits as compared with hard armor (Figure 5-9), while still proving effective at slowing erosion.

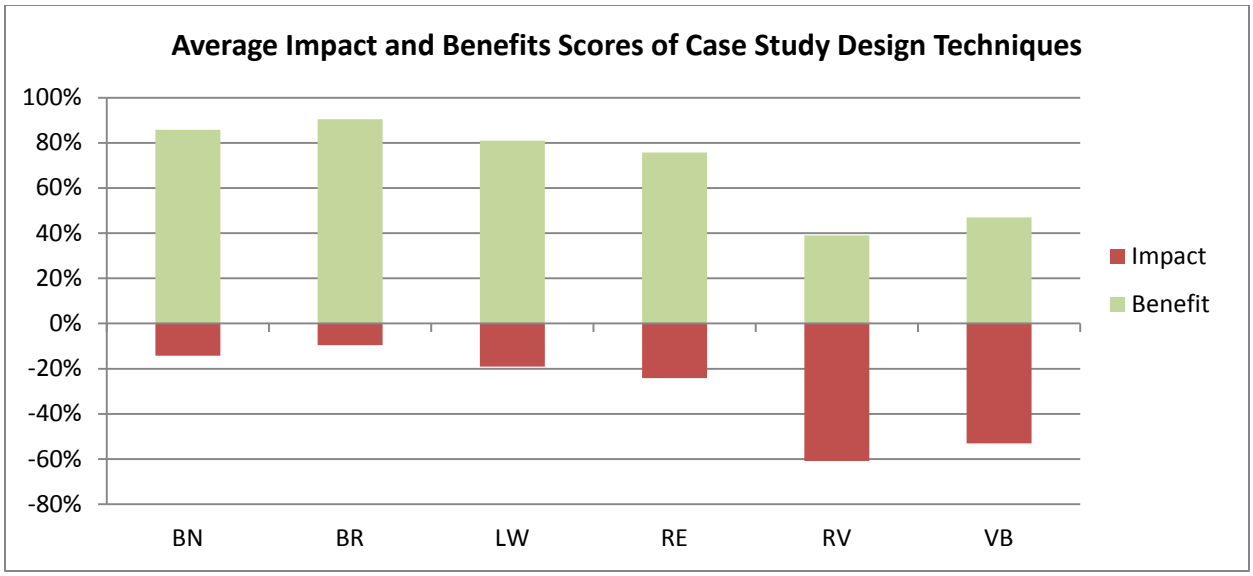


Figure 5-9. Average cumulative impact and benefit scores from case study data for each design technique.

Case study results highlight the additional benefits associated with softer solutions (Figure 5-9, left side), and particularly bulkhead removal, which has the fewest impacts among design techniques. The greatest impacts were seen at revetment sites. Slightly fewer impacts were documented along vertical bulkhead sites (compared to revetments), which may have been due to subtle design differences or the smaller footprint of vertical bulkheads. Cumulatively revetments also had the least benefits, again slightly fewer than vertical bulkheads, as compared to hard armor approaches. Bulkhead removal case study sites on average had the most cumulative benefits. Among the soft shore approaches, reslope and revegetation case study sites on average had less benefits than large wood and beach nourishment sites.

Among the individual benefit scores from case study assessments, considerable variability was displayed among the benefit categories of the different design techniques (Figure 5-10). Beach nourishment had the highest average scores across each benefit category. All of the design techniques were at least moderately effective at curbing erosion. Because the objective of bulkhead removal is not to curb erosion but restore nearshore processes, scoring was adjusted for this specific benefit category. Instead, bulkhead removal sites were assessed based on their effectiveness at restoring nearshore processes. Case study results showed that the design technique was effective at achieving this objective. Bulkhead removal sites also typically increased LWD input and storage, were cost effective, and increased nearshore sediment volume. Increased LWD recruitment was also a benefit associated with beach nourishment, LWD placement and reslope and revegetation sites. Beach nourishment and large wood placement projects were shown to be most beneficial at benefiting backshore vegetation. Costs associated with the case study sites were generally comparable, with the most cost effective solution being reslope and revegetation projects.

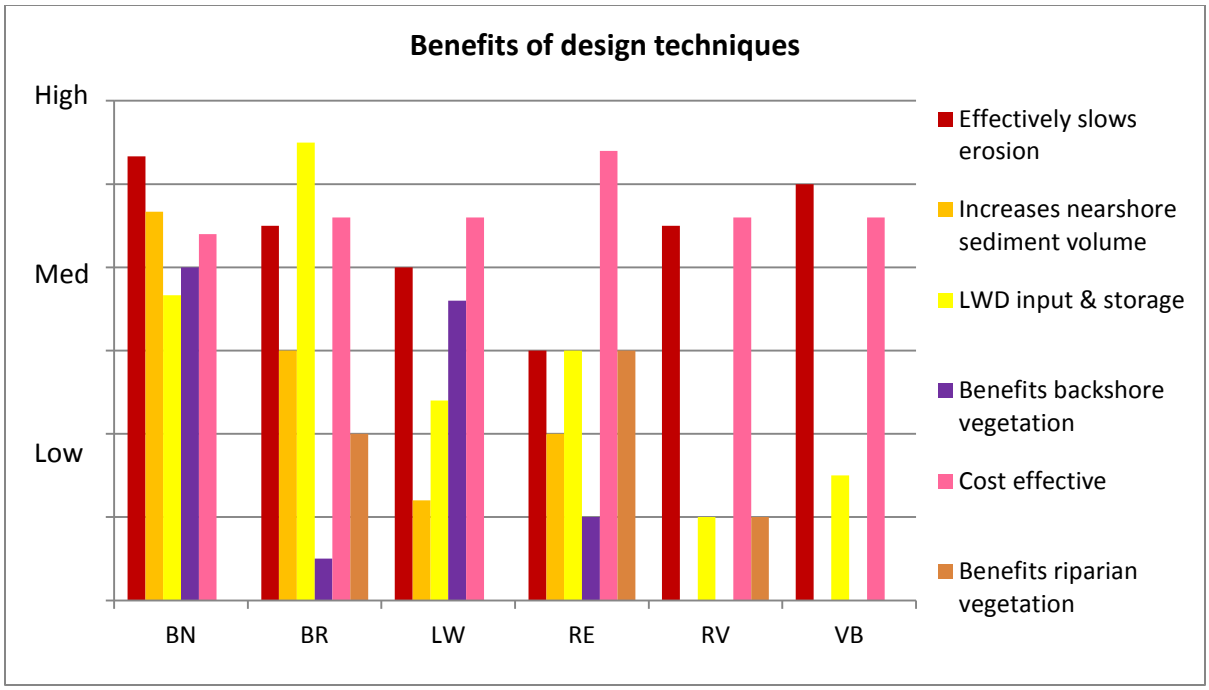


Figure 5-10. Benefits of different design techniques using average of scores of generally 4-6 case study sites per technique.

The impacts associated with each design technique were also highly variable. As shown in Figure 5-11, cumulatively and across each individual impact scoring criteria, more impacts were observed at hard armor sites than softer solutions and bulkhead removal. On average, beach nourishment impacts were between none and low. Minor impacts were the development of a steeper beach profile and the frequency of maintenance typically required at beach nourishment sites (both of which were low). Large wood had a similar low range of potential impacts, with the greatest impact being the burial of upper beach area beneath the large wood structure, although large wood is often associated with beneficial micro-climate conditions. The maintenance required for reslope/revegetation projects was the greatest impact associated with that design technique.

The greatest impacts associated with revetments projects were reduced LWD recruitment and buried upper beach area. Similarly vertical bulkhead also had considerable impact due to buried upper beach, with additional impacts due to end effects with erosion at the adjacent shore(s) caused by wave refraction. Sediment impoundment and coarser, steeper beaches were also high scoring impacts of hard armor case study site applications.

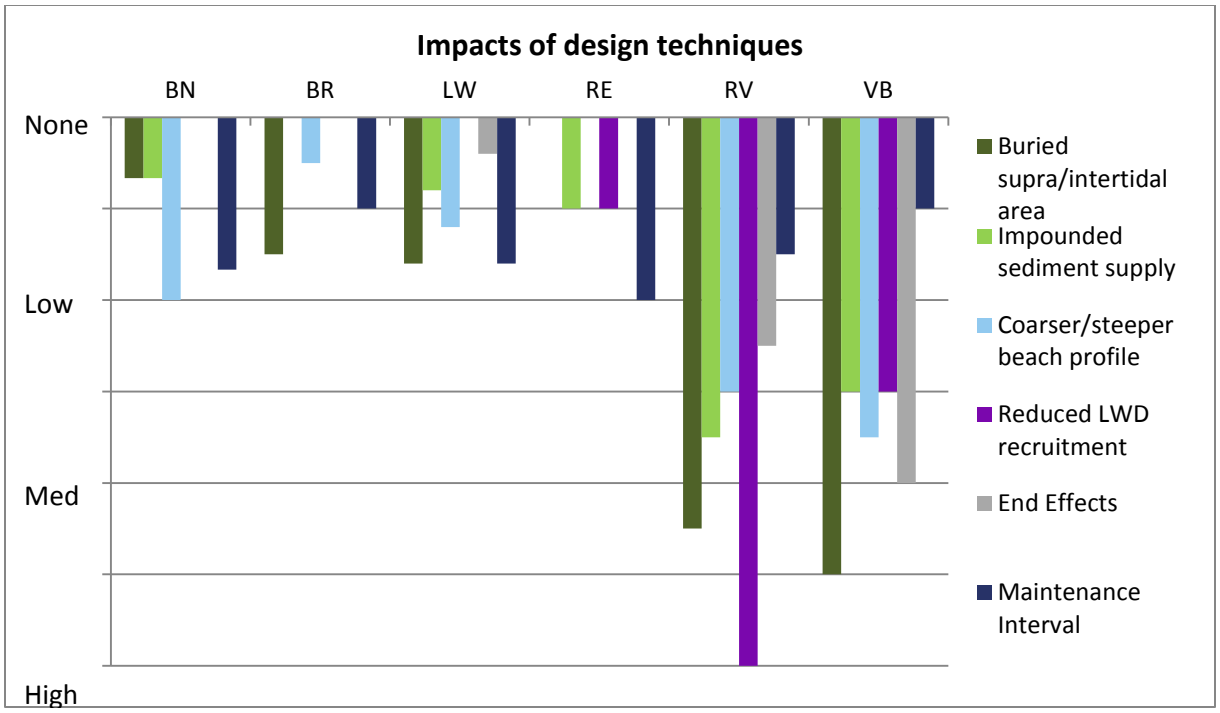


Figure 5-11. Average impacts of different design techniques based on case study data.

The collective lessons learned from these case study assessments can guide the design technique selection process and ideally enhance the likelihood of project success.

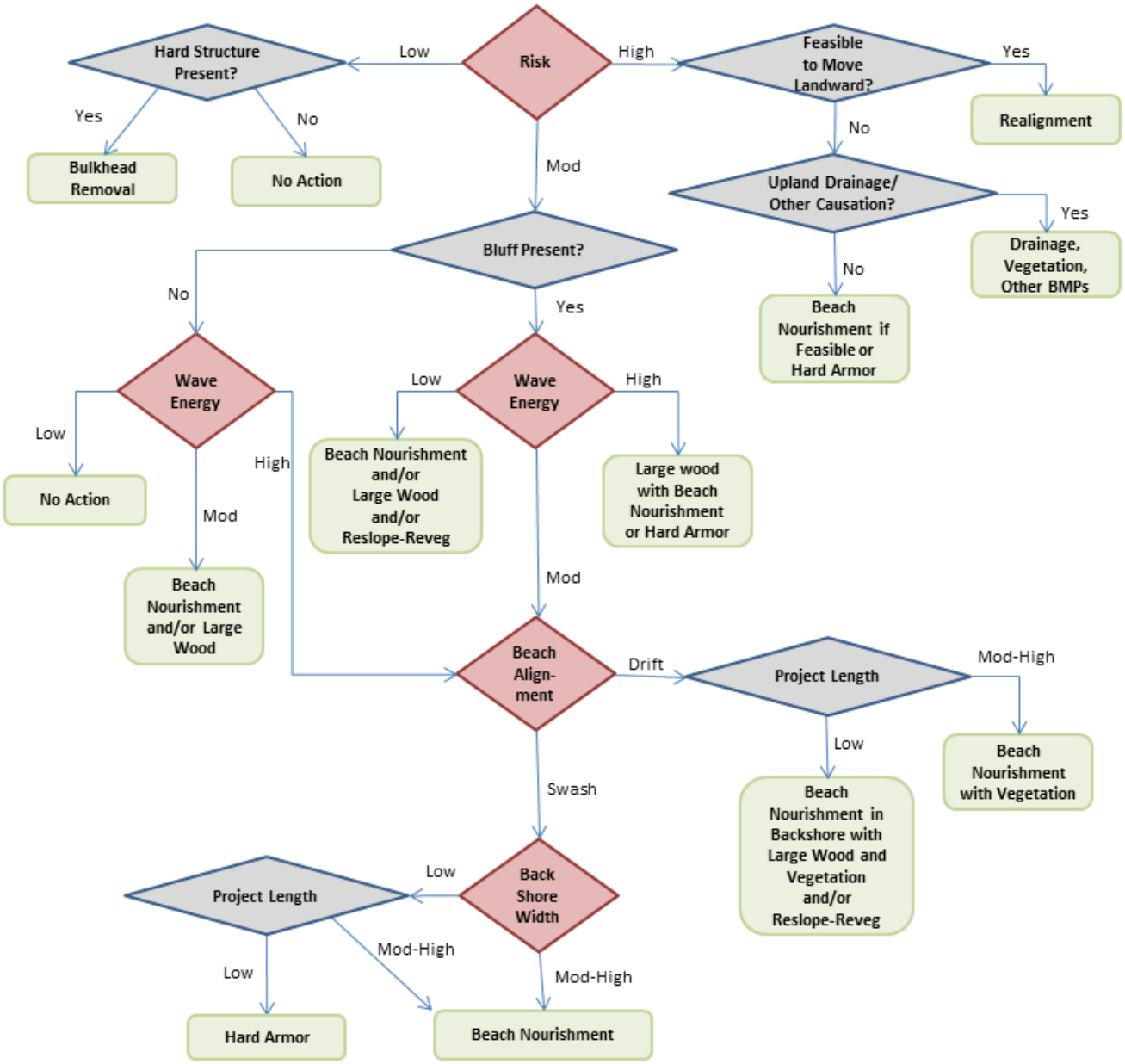
Selecting an Appropriate Design Technique

Fundamental site characteristics will drive what design technique or other approach best suits each site and what will effectively address the perceived need for intervention. Detailed site specifications from the professional that conducted the site and coastal processes assessments will inform what design techniques and additional management solutions are appropriate for the subject site. The appropriate approach for a site will largely be determined by the current condition of the site, the cumulative risk, wave energy, alignment, shoretype, and available backshore width.

Figure 5-14 presents a decision tree that can be used together with site assessment data to identify the appropriate design techniques for a given site. Similar decision tools produced by Cox et al. (1994) and Herrera Environ were referenced in the development of this new tool. Cox et al (1994) was more focused on hard armor alternatives (rather than soft shore alternatives) and was developed relying on little data from the Puget Sound. Recommendations for reducing impacts from shore armoring produced by EnviroVision et al (2010) cited the (draft) Whatcom County SMP language for regulating the development of shoreline stabilization structures (Section 23.100.13, Whatcom SMP) that encouraged the use of surface water management techniques, followed by soft shore protection, and only permitting hard armor if demonstrated to be necessary to protect and existing primary structure that is in danger or loss or substantial damage, and where mitigation of impacts would not cause a net loss of shoreline ecological functions and processes (EnviroVision, Herrera and AHG 2010).

The first variable of influence to identifying appropriate techniques is the Risk at the site. The cumulative risk at the site should be calculated and classified using the approach presented in the previous section.

If it is a high risk site, then realignment should be explored to determine if it would be feasible to move the structure landward out of harm's way. Retreat, although costly, is the lowest impact and most effective long-term solution to a threatened structure. Next, the degree to which erosion may be exacerbated by poor surface water and vegetation management practices should be explored. If erosion could be slowed by applying better management practices then actions should be identified to address these causes of erosion. If it is not feasible to move the structure landward, and there are not necessary improvements to surface and vegetation management at the site, then beach nourishment, hard armor, or some combination of the two options should be explored. For example, beach nourishment may be a viable option at the site, particularly if the site is not a feeder bluff and is swash aligned. Or hard armor could be applied only waterward of the structure, with beach nourishment used elsewhere at the subject site.



Note: Beach nourishment with vegetation refers to gravel beach nourishment with robust backshore vegetation installation on elevated storm berm.

Figure 5-12. Decision tree in support of identifying appropriate design techniques for a given site.

If the site is rated moderate risk, then the shoretype and wave energy must next be evaluated. If the site is not a bluff site and has low wave energy, then no action may be required and threat of erosion and necessity of erosion control may only be a perceived need. If there is moderate wave energy at the site (and it is not a bluff), then it is likely well suited for beach nourishment or large wood. Non-bluff sites with higher wave energy are good candidates for beach nourishment or reslope /revegetation (small projects), if drift aligned. If swash aligned and backshore width is large enough, then beach nourishment is viable, if not then hard armor may be required.

For moderate risk bluff sites, the wave energy at the site is the largest determinant of eligible design techniques. Lower energy sites are appropriately suited for beach nourishment, large wood, and reslope-revegetation. Sites with high energy are eligible for large wood with beach nourishment or hard armor. Sites of this nature (moderate risk, bluff sites) with moderate wave energy are generally good sites for beach nourishment, but large wood may be required to maintain nourishment material along drift-aligned sites. Vegetation plantings should accompany nourishment along sites that are larger in size. Where backshore width is low, armor may be required.

After appropriate design techniques are identified, the benefits and impacts should be weighed, before selecting a design technique. After evaluating the options, benefits, and impacts associated with each option, site assessment data should be revisited to explore if multiple approaches could be applied to reduce the potential impacts associated with the chosen approach. Conditions, and particularly risk, are often variable within parcel-boundaries, particularly on large properties. The suitable design technique for the area waterward of the home may not be appropriate or necessary for the entire site. For example, if the risk at the site is high due to a low setback distance, whether that is the case for the entire property or just for a portion of the property, should be explored. If portions of the property are amenable to other approaches then the spatial extent of the armor should be limited to the greatest extent possible to limit potential impacts and mitigation requirements.

Key variables of influence for design technique selection are displayed in Figure 5-4. Typically more than a single approach is appropriate for site conditions and this additional analysis should be conducted to determine which design technique to select for implementation.

Table 5-4. Key variables of influence to selecting the appropriate design technique.

RISK	WAVE ENERGY	SHORETYPE	BACKSHORE WIDTH	APPROPRIATE TECHNIQUE
Low	Low – High	All	Low – High	**BULKHEAD REMOVAL***
Low – Moderate	Low – Moderate	All	Moderate – High	**LARGE WOOD**
Low – Moderate	Low – Moderate (drift aligned)	All*	Low –High	**BEACH NOURISHMENT**
	High (swash aligned)		Mod-High	
Low – Moderate	Low – Moderate	Bluff	Low – High	**RESLOPE AND REVEG**
Moderate - High	High	All	Moderate – High	**HARD ARMOR SLOPING**
Moderate - High	Moderate	All	Low	**HARD ARMOR VERTICAL**

*If not armored then NO ACTION.

**Beach nourishment is only appropriately applied on bluffs when integrated with other measures, including backshore vegetation OR on shores with low wave energy.

Linking Design with the Cause of Erosion

Specific design elements should be linked with the identified causes of erosion and site characteristics, using data from the site and coastal processes assessment. Detailed design guidance for each technique is provided in Chapter 7 of this document. However the professional that conducts the assessments for the site should also provide synthesis on the key elements specific to the site relevant to the design process as well as the appropriate design alternatives. One of the final steps from the *Site Assessment* (Chapter 3) was to attempt to determine the causes of erosion. These data should be revisited in the alternatives analysis.

An example of a site-based cause of erosion is a large bulkhead located immediately adjacent to the subject property that infringes on the intertidal beach and has fill landward of the bulkhead. The armor is causing end-effects and the subsequent erosion occurring along the adjacent shore is occurring at a moderate rate. This particular driver of erosion may point to a specific treatment, such as expanding the bulkhead to the adjacent (subject) shore where the erosion is focused. However because the erosion is largely driven by end-effects from the adjacent shore, then the treatment area can be limited (spatially) to that area. The process described above for determining which techniques are appropriate still applies, with the additional knowledge of *where* actions should occur, and also making sure that *appropriate* techniques are chosen which will address this site-based cause of erosion. In the bulkhead example, as long as other characteristics indicate suitability, options include anchored log design which could be augmented with beach nourishment and installation of backshore vegetation.

In some cases, results of the coastal processes assessment will indicate that widespread impacts of development such as extensive shore armor up-drift of the property, are contributing to erosion at the subject site. While this is clearly an impact of development, it cannot be as directly addressed as the site-based cause of erosion presented above. Reduced sediment input should immediately lead to the consideration of beach nourishment design. The relative benefits of nourishment design should be evaluated and include comparison of bolstering sediment supply on-site, or up-drift of the site. Analysis of site conditions (alignment and sediment transport rates) should address if the nourishment material will be maintained adequately or if drift sills will be required. Again, the results of these sites and coastal processes analysis would have to be integrated into the design process outlined in Chapter 7 for beach nourishment in this case.

There are many causes of erosion or mass wasting that are not caused by development, such as passive erosion. Passive erosion occurs over time due to wave attack during large storms. The process of selecting the appropriate technique and the development of the associated design should address each of these types of erosion, and integrate all of the measurements and knowledge gained about the subject site.

Impacts and Costs

The ideal design technique for a given site will effectively achieve the objectives of the project, while resulting in the least possible impacts and the greatest benefits. Each design technique is associated with impacts that range in duration, magnitude and variety. Certain impacts associated with a given design technique should be prevented if another alternative is available. For example, if forage fish spawning is likely to occur at the site, then a design alternative should be selected that DOES NOT impact or bury upper intertidal spawning habitat. This course of action is recommended in all cases. Table 5-5 can be referenced to identify the range of impacts associated with each design alternative.

Table 5-5. Impacts and duration of impact associated with each design technique.

Design Technique	Impacts	Duration of Impact
Beach nourishment (BN)	▪ Beach disruption from equipment access, materials staging and placement ▪ Burial of current substrate (smothers meso/meiofauna) ▪ Commonly coarser and some times more angular substrate is applied ▪ Sills can temporarily impair sediment transport ▪ Sills bury intertidal beach	▪ Temporary ▪ Intermediate ▪ Permanent
Large wood (LW)	▪ Subgrade excavation disturbance to beach substrate ▪ Anchoring system commonly comprised of non-native materials ▪ Beach disruption from equipment access, materials staging and placement	▪ Temporary ▪ Permanent
Bank re-slope and revegetation (RE)	▪ Disturbance and upland habitat loss associated with regrading bank ▪ Sedimentation associated with vegetation clearing ▪ Beach disruption from equipment access, materials staging and placement ▪ Changes in upland surface water flow	▪ Temporary
Bulkhead removal (BR)	▪ Sedimentation/turbidity associated with removal ▪ Disturbance of beach substrate during subgrade excavation ▪ Disturbance associated with access	▪ Temporary
Hard Armor: Rock revetment (RV)	▪ Increased turbidity ▪ Beach disruption from equipment access, materials staging and placement ▪ Precludes sediment input ▪ Buries upper intertidal spawning habitat ▪ Degrades salmonid migratory habitat ▪ Coarsened sediment composition ▪ Can steepen beach profile ▪ Precludes LWD input and deposition ▪ Aquatic vegetation alteration ▪ Riparian vegetation alteration ▪ Altered wave energy, sediment transport, and littoral drift	▪ Temporary ▪ Intermediate ▪ Permanent
Hard Armor: Vertical bulkhead (VB)	▪ Increased turbidity ▪ Beach disruption from equipment access, materials staging and placement ▪ Precludes sediment input ▪ Buries upper intertidal spawning habitat ▪ Degrades salmonid migratory habitat ▪ Coarsened sediment composition ▪ Can steepen beach profile ▪ Precludes LWD input and deposition ▪ Aquatic vegetation alteration ▪ Riparian vegetation alteration ▪ Altered wave energy, sediment transport, and littoral drift	▪ Temporary ▪ Intermediate ▪ Permanent

In addition to the adverse impacts associated with each design techniques, several other elements are relevant to design technique selection that may not be initially apparent. For example, some approaches have greater natural adaptive capacity and are likely to sustain sea level rise with little alteration, while other approaches are more likely to fail or further impact the beach as shorelines migrate inland (Table 5-6). As shown in the case study assessments, techniques vary in the benefits to nearshore processes as well as maintenance costs and intervals. Typically techniques with a high maintenance interval may not cost as much to both implement and maintain. While those that appear to require little maintenance,

may have a shorter design lifetime and require a full re-build rather than gradual maintenance (such as a vertical bulkheads).

Table 5-6. Typical costs and benefits associated with different design techniques. L = Low, M = Moderate, H = High.

Design Technique	COST	SLOWS EROSION	BENEFITS PROCESSES	ADAPTIVE CAPACITY	MAINTENANCE COST	MAINTENANCE INTERVAL
Beach nourishment (BN)	M	H	M-H	H	L-M	L-M
Large wood (LW)	L-M	M-H	M	L-M	L	M
Bank re-slope and revegetation (RE)	M	M	M	M-H	L	H
Bulkhead removal (BR)	♦ L	na	H	H	None	None
Hard Armor: Rock revetment (RV)	M-H	H	None	None	M	L
Hard Armor: Vertical bulkhead (VB)	M-H	H	None	None	H	L

Mitigating Impacts

The ultimate goal in selecting the appropriate alternative is to find balance between the project objectives and other factors such that the project avoids or minimizes impacts and maximizes benefits to the greatest extent possible. However, in some cases, the selected design technique does result in impacts of considerable magnitude and duration, such that mitigation is required to prevent a net loss. Additional guidance is available on mitigating strategies for habitat loss due to shoreline armor in EnviroVision et al. 2010.

Where impacts associated with the selected design alternative cannot be avoided, compensatory mitigation efforts should be identified and integrated into the design. Mitigation should emphasize on-site and in-kind rehabilitation or replacement of degraded processes, habitat, and ecological function to the greatest extent possible. Many impacts can be avoided or minimized with proper planning and design, however some impacts are unavoidable and are difficult to adequately mitigate. When mitigating for hard armor it is important to be mindful that extensive data show that hard armor can produce measureable impacts on the shoreline that extend for many times the length of the structure (Coyle and Dethier 2010). The distance at which these impacts occur was related to the length of the armor with longer stretches of armor resulting in more wide-ranging alongshore effects (Coyle and Dethier 2010). Therefore mitigation requirements for shore armor should reflect this association and larger armor projects should require additional mitigation to compensate for the less direct wider reaching impact of the larger project.

Off-site mitigation for can be effective if applied within the same drift cell as the subject site. For example, armor removal at another location within the same drift cell could be adequate compensatory mitigation for installing armor at another site within the drift cell (assuming that both sites are the same shoretype and do not encompass forage fish spawning areas). Beach nourishment can be effective at partially mitigating for armor, however it must occur up-drift of the subject site and cannot effectively mitigate for lost forage fish spawn area due to direct loss via burial. However the duration that the mitigation would be required (e.g. every 5 years, indefinitely) could result in considerable cost to the project proponent.

Table 5-7. Potential mitigation options associated with each design technique.

Design Technique	Potential Mitigation
Bulkhead removal (BR)	Not Applicable. Revegetation if disturbance to vegetation occurs as part of accessing the shoreline to remove structures.
Bank re-slope and revegetation (RE)	Not Applicable. Revegetation if disturbance to vegetation occurs as part of accessing the shoreline to remove structures.
Drift and anchored logs (LW)	Backshore vegetation enhancement. Additional volume of forage fish spawn sediment size material used to nourish the upper beach and mitigate burial beneath anchored LWD. Monitor maintenance of forage fish spawn material.
Beach nourishment (BN)	If beachface sediment composition is coarser than natural substrate, forage fish spawning substrate sediment composition should be applied to the upper reaches of the beach profile. Monitor maintenance of forage fish spawn material.
Hard Armor: Rock revetment (RV) and Vertical bulkhead (VB)	Structure placement as far landward and high on beach profile as possible. Avoid clearing to greatest degree possible of marine riparian and backshore vegetation plantings; replant any disturbed areas. Nourish upper beach if necessary to preclude beach lowering, coarsening. Augment sediment supply if bluff site.

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Chapter 6. PASSIVE TECHNIQUES

Passive Techniques are management practices that help the shoreline owner deal with erosion without using the engineered approaches featured in Chapter 7. These techniques have, on the whole, fewer impacts to beach processes and habitat, and are less expensive than professionally designed and engineered shoreline protection techniques. All shoreline owners should consider these techniques as best management practices when considering alternatives for managing erosion on their property. The passive techniques include:

- managing surface and groundwater
- vegetation management
- managed retreat

Managing Surface and Groundwater

In the undeveloped, forested condition, rainwater is intercepted by the canopy, where it accumulates on the foliage and is transpired or evaporated. Very little reaches the ground, and what does is absorbed by the thick layer of leaf litter and humus. When the property is developed and the forest cleared, rainwater is collected on roofs, roads and over imperious surfaces and is often piped over the bluff crest or directly into the ground. Figure 1-1 schematically shows these changes to groundwater. Runoff from a site acts in two ways to exacerbate erosion of coastal bluffs;

1. Surface water from developed property collects and flows over the soil carrying away particles, forming rills and then gullies. The gullies can undermine portions of the bluff and cause them to shear off or otherwise interfere with a landowner's use of the property.
2. Water that is allowed to seep into the ground near the crest of the bluff helps saturate the soil, increasing pore water pressure and decreasing the strength of the soil structure. This saturated soil can then fail catastrophically in a landslide or slump.

Managing runoff around homes and other structures at the top of bluffs is an important technique to reduce erosion. Best management practices for drainage are clearly explained in Department of Ecology's **Managing Drainage on Coastal Bluffs**, which can be found at: http://www.ecy.wa.gov/programs/sea/pubs/95-107/drainsys01.html (last accessed 6/20/13).

Vegetation management for bluffs

Appropriate management of existing vegetation on steep slopes can help reduce the risk of failure. Vegetation intercepts a portion of rain water, preventing it from reaching the ground and eroding the surface. The roots of this vegetation act to bind the soil particles together, increasing its strength and stabilizing the slope. Maintaining the existing vegetation, or planting new native species, preserves these functions.

Vegetation management is discussed in Technique 3, Reslope-Revegetation, although the focus of the technique is on slope recontouring. The Department of Ecology has a guide for this technique, **Vegetation Management: A Guide for Puget Sound Bluff Property Owners** http://www.ecy.wa.gov/programs/sea/pubs/93-31/intro.html (last accessed 6/20/13). This is an older document that has not been updated, although the information remains useful. The central conclusion is that when site-appropriate vegetation management is incorporated into the initial development plan,

it can reduce erosion risk and maintain slope stability. It should be understood that not all risk can be eliminated; deep-seated slope instability may not respond to vegetation management.

An additional resource is Management Measure 17: Revegetation in,

Clancy, M., I. Logan, J. Lowe and J. Johannessen, et al. 2009. Management Measures for Protecting the Puget Sound Nearshore, Report No. 2009-01. Olympia, Washington, Puget Sound Nearshore Estuary Restoration Project. http://www.pugetsoundnearshore.org/technical_papers/mangement_measure.pdf (last accessed 6/21/13)

Managed retreat

Managed retreat is moving coastal infrastructure inland to allow natural shoreline erosion – moving a house or a road back from an eroding bluff rather than trying to stabilize it using one of the Techniques in Chapter 7. This approach is also referred to managed realignment. An owner could choose managed retreat simply for economic reasons since it is typically less expensive than armoring. Managed retreat may be the only reasonable alternative as a consequence of sea level rise. But there are other reasons to retreat, and they are at the very heart of these guidelines: managed retreat will have fewer impacts to nearshore ecology and processes than renewed armoring. This is particularly true on feeder bluffs, where eliminating a sediment source has far ranging effects. But it also can allow for the formation of a backshore, let tidal water flood back into a former marsh, or as a realistic response to continued sea level rise.

Managed retreat has been used frequently for coastal roads. A good example is Scenic Heights Road on Penn Cove, Whidbey Island, shown in Figure 6-1. Coastal erosion has increased the risk of failure at this site to unacceptable levels. The alternatives for this situation are to either build a massive bulkhead and retaining wall to control the unstable slope, or to abandon or move the road away from the crest of the bluff. Island County has chosen to reroute this road rather than stabilize the eroding bluff.

Similar scenarios are common around Puget Sound and can involve houses or other infrastructure. The decision to choose managed retreat is outlined in Chapter 5, Alternative Analysis. The environmental benefits of this technique are clear; it allows the natural processes that create and maintain nearshore habitats to continue. In the end, the owner must weigh the costs over time of an engineered solution to manage the erosion process against the cost of moving the threatened structure, considering the long term maintenance costs and the continued effects of sea level rise.

The design of projects for managed retreat covers a range of disciplines, most of which are outside the scope of these guidelines, such as the civil engineering and contracting challenges associated with moving a house, a road or a sewer pipeline. The aspect most clearly associated with shore protection techniques is bulkhead removal, Technique 4 in Chapter 7, which could occur in association with the managed retreat.

Figure 6-1. Scenic Heights Road, Penn Cove, Whidbey Island. (Dept. of Ecology Digital Coastal Atlas)

Resources for the landowner or designer include:

Clancy, M., I. Logan, J. Lowe and J. Johannessen,et. Al. 2009. Management Measures for Protecting the Puget Sound Nearshore, Report No. 2009-01. Olympia, Washington, Puget Sound Nearshore Estuary Restoration Project. http://www.pugetsoundnearshore.org/technical_papers/mangement_measure.pdf (last accessed 6/21/13).

Techniques outlined in Management Measures cover some aspects of managed retreat such as

- MM 1: Armor Removal or Modification
- MM 3: Berm or Dike Removal or Modification
- MM 21: Topography Restoration

The NOAA Ocean and Coastal Management website on managed retreat strategies: http://coastalmanagement.noaa.gov/initiatives/shoreline_ppr_retreat.html (last accessed 6/21/13). Managed retreat has become more popular in the San Francisco Bay and Europe, where there are many case studies available.

Chapter 7. TECHNIQUE 1
BEACH NOURISHMENT

Description

Beach nourishment, also referred to as beach replenishment or beach feeding, is defined as "the natural or artificial supply of sand or gravel to a beach" (Bird 2005). Finkl and Walker (2005) discussed it as:

> "the artificial (mechanical) placement of sand along an eroded stretch of coast …Efforts to artificially maintain beaches that are deprived of natural sediment thus attempt to proxy nature and (re)nourish the beach by mechanical placement of sand. The beach sediment is thus replenished by artificial means."

In the Pacific Northwest gravel beach nourishment has been referred to as "constructing a protective berm" by early practitioner Wolf Bauer, who designed the first gravel nourishment projects in Puget Sound in the 1970s (Bauer and Hyde 2010). Beach *re*nourishment typically refers to the resupplying of nourishment material at a previously nourished beach where the placed sediment has eroded.

Beach nourishment projects are usually designed to emulate a natural shore, although many times the resiliency of the beach is enhanced through the use of sediment larger than native sediment or other measures that extend the function of the nourished beach. Nourished beaches are intended to adjust in response to wave action such that the beach geometry often changes both spatially and temporally, appearing to erode and accrete (grow) in different areas over time. The degree of protection to infrastructure is not constant for a deformable shore as it usually is with hard armor (revetment or bulkhead, Cox et al. 1994). Despite this fact, beach nourishment has become a popular method of erosion control in the Puget Sound region (Shipman 2002) and has been applied on coasts throughout the country and across the globe (Finkl and Walker 2005).

It is important to note what is not covered by these guidelines for beach nourishment. Several projects referred to as beach nourishment projects, are also soft shore protection projects. However for many of these projects the "soft" portions of the project design have been outweighed by the "hard" engineering approaches (Johannessen 2000). For example, rock revetments covered with sand and gravel have at times been submitted for permitting as beach nourishment projects. All of those involved in project implementation must be able to critically examine scaled design drawings (plan view sheets and cross sections). The discussion herein focuses on projects that are dominated by gravel or gravel and sand nourishment, which may or may not have smaller project components in limited portions of the overall project area.

Application

Beach nourishment is a common technique used for shore protection in many parts of the world. The application of beach nourishment has increased in recent decades as hard armor had become less desirable due to habitat impacts, down-drift sediment reduction, and increasing costs (Finkl and Walker 2005). Additionally, the economic and ecologic benefits of beaches have become better understood in recent decades. In the Puget Sound region, gravel beach nourishment was pioneered by Wolf Bauer (Shipman unpub., Bauer and Hyde 2010). Early Bauer nourishment projects have served as models for landowners and designers since his first public project in Puget Sound in 1972 (Tolmie State Park,

described in Appendix A), although some designs have been criticized for using sediment that was considerably more coarse than pre-project.

Beach nourishment can satisfy a variety of objectives, scales of application, and different configurations. The beaches of Puget Sound are unique both nationally and across the globe, in both the fetch-limited fjordal estuarine environment and mixed sand and gravel sediment composition. The majority of the beach nourishment literature concerns placing sand on open coast beaches exposed to large, long-period waves. Puget Sound region beaches are dominated by gravel-sized sediment due to repeated glacial ice sheet advances and subsequent deposits (Booth 1994). Gravel is used almost exclusively as the dominant nourishment sediment. It is more resistant to erosion and transport than finer sediment. The Puget Sound region has a crenulated (complex) shoreline with a great variety of geomorphic and geologic controls. These controls directly affect the type of application that is feasible for a given site, and also underscore the need for site-specific designs.

Beach nourishment has most often been used in the Puget Sound region to reestablish broad beach profiles that act as buffers against wave attack, and to mitigate erosion of the upper beach and backshore areas. Many beach nourishment projects have focused on creating, or recreating, a relatively high-elevation backshore storm berm to limit the effects of storm waves in this area. The simple augmentation of beach sediment volume, whether in the intertidal or in the backshore alone, provides a wider and/or higher buffer to incident storm waves. The energy of gravel beaches can dissipate up to 90% of the incident wave energy (Diserens and Coates 1993).

Sites appropriate for applying beach nourishment include those that have naturally eroded, putting buildings or other development at risk. Nourishment projects have been initiated at other sites where the impacts of shore modifications such as bulkheads have caused erosion and increased risk. For example, at North Samish Island (Johannessen 2002) the cumulative negative impacts of extensive bulkheading along feeder bluffs and the installation of groins led to substantial loss in beach width and elevation (Canning and Shipman 1995). Gravel beach nourishment was initiated at North Samish Island in 1998 to offset these impacts, and so far has been successful.

Beach gravel mining has been carried out throughout human history, and was widespread in Puget Sound through the mid-20th century (Johannessen and MacLennan 2007). Gravel mining depleted many local beaches, although documentation is sparse. Beach nourishment is applicable at many of these locations.

Effects

Gravel beach nourishment absorbs a large amount of incident wave energy on the beach. As explained below, sediment that is slightly coarser than native beach sediment is often used in nourishment designs and this can help form a high berm for storm protection (often called a storm berm). This berm dissipates storm wave energy by reducing swash run-up through increased friction. Backwash water volume and velocity are also dissipated as the water percolates through the coarse gravel (Komar et al. 2003). Another benefit of gravel nourishment is the typically steepened beach slope which can provide additional erosion control in the form of wave reflection. Waves reflect off the beach and collide with incoming waves, which then enhances their breaking and energy loss (Komar et al. 2003).

The use of coarse sediment for nourishment tends to alter the beach habitat somewhat, at least in the initial years after placement. The use of coarser sediment is normally limited in documented forage fish

spawning areas. Most of the beaches that have been nourished with coarser sediment, with the exception of some sites in low-wave-energy locations (such as Place Eighteen in Zelo et al. 2000), have naturalized with beach surface sediment closely resembling native sediment conditions within 3 to 5 years after placement (such as the Marine Park and North Beach Orcas Island case study sites in Appendix A). Photos of the range of beach nourishment projects sites surveyed for preparation of these guidelines are shown in Figure 7.1-1 as examples of Puget Sound nourishment projects.

Beach nourishment projects can provide sediment to down-drift beaches at higher rates than in preproject conditions by augmenting the littoral transport that has often been degraded due to development. Beach nourishment projects selected for the case study assessment (Appendix A) were distributed over the full extent of the Puget Sound region (the American portion of the Salish Sea). Projects were located between the Nisqually Reach, the Strait of Juan de Fuca, and Whatcom County. Sites assessed for the study covered a wide range of conditions and design approaches, and were installed between 1972 and 2005, with the majority installed between 2002 and 2005. As there were more beach nourishment projects than projects using other design techniques, we were able to select most project case studies with 7 to 10 years in-place to allow for assessment of medium-term performance. Table 7.1-1 summarizes conditions at the six case study sites.

Table 7.1-1. Case study project summary data for beach nourishment technique. VH=very high, H=high, M=moderate, L=low.

SITE MEASUREMENTS	PROJECT NAME					
	East Dungeness	Tolmie State Park	Snakelum Point	Marine Park Bellingham	North Beach Orcas Is.	East Lummi Is.
Total Risk (0-128)	30	3	16	8	30	30
Wave Energy	VH	M	H	H	VH	VH
Length (ft)	1500	900	50	300	510	181
Volume (CY)	1740	6000	38	2759	2500	440
Density (CY/FT)	1.2	6.7	0.8	9.2	4.9	2.4
Toe Elevation (ft MLLW)	6.5	9.5	13	2-4	2	9.25
MHHW (ft MLLW)	7.36	13.89	11.4	8.51	8.68	8.77
Berm Elevation (ft MLLW)	12.74	14.5	15.6	13.0	11.0	14.5
Crest Height (Berm/MHHW)	1.73	1.04	1.37	1.53	1.27	1.65
Sediment d50 (in)	0.3	1.75	3	1.25	1.25	2.5
Sediment Range(in)	0.1-2.0	-	2-5	0.1-5	0.5-2.5	1.5-4
Year Install	2006	1973	2002	2004	1992	2004
Maintenance (Y/N)	Y	N	N	Y	N	N

Note: East Dungeness berm elevation was dune elevation in reality.

Along with the intensity of large windstorms, the relative wave energy (wave climate) is a critical factor in determining the amount of erosion at a site. Larger waves usually equate to larger littoral drift rates, and can lead to loss of nourishment sediment. Conditions varied considerably at the six nourishment sites assessed for this study, from low to very high wave energy (Table 7.1-1) and with dominant wave fetch ranging from 6 to 101 miles. Fetch exposures also varied, with three generally southern-aspect sites, two generally northern-aspect sites, and one site exposed to very long fetch from the northeast (East Dungeness). The wide range of erosion processes in play made the sites difficult to compare. For example, the Marine Park site was located in a highly modified reach of shore (termed “artificial” in PSNERP mapping) with a moderately high rate of background erosion in the absence of shore protection. Although it was not possible to determine background erosion rates at most of the Appendix A sites, it is clear that erosion rates were far lower at the more protected sites such as Snakelum Point or Tolmie State Park.

The beach nourishment sites also covered a wide range of project beach lengths, from 50 ft at Snakelum Point to 1,500 ft at the East Dungeness site. Four of the projects were in residential areas, with two at single-family properties and two encompassing adjacent properties. The remaining two projects were at public park shores. Sites at two of the longer project reaches, Marine Park and East Dungeness, allowed for nourishment to extend across most of the intertidal. The single-family nourishment projects were limited to placement above MHHW.

a) East Dungeness, Clallam County.

b) East Lummi Island, Whatcom County.

c) Marine Park, Bellingham.

d) North Beach Orcas Island.

e) Snakelum Point, Whidbey Island.

f) Tolmie State Park, Thurston County.

Figure 7.1-1. Examples of beach nourishment projects surveyed for this study (Appendix A).

Design

The Puget Sound region shores are characterized as complex with a high degree of variability and therefore site-specific design is always required. The region has a wide range of wave fetch distances, variable drift cell lengths, and littoral transport rates so that these and other factors must be considered in the development of a final design. The design sequence would include these elements:

- establish project goals
- determine risk to structures
- determine general scope and size of project area
- evaluate design parameters and development details

The beach nourishment design approach should be largely controlled by the scale or shore length of each site, the magnitude of wave energy the site is exposed to, and whether the beach at the site is swash aligned or not. These and other parameters are shown in the generalized design model for beach nourishment presented in Figure 7.1-2. The design model is not intended to produce design dimensions; instead it is intended to highlight key factors contributing to site feasibility determination (upper portion) and outline key design elements to be evaluated in the design process (lower portion). Risk is discussed in Chapter 4. The dominant wave approach angle (Figure 7.1-2) is explained in the *Site Geometry* section below. Determining the shoretype as mapped by PSNERP and wave energy are in outlined in Chapter 4. Project length is discussed in the next section of the same name. Failing to evaluate all of these parameters when developing a beach nourishment design can result in a design that either does not achieve project objectives or one that requires excessive maintenance. These design parameters are discussed in terms of design development in the following section.

The *Design* section is organized to assist the designer to assess and evaluate key design parameters in an effort to balance project elements to achieve a functioning and resilient beach, without unnecessary changes or impacts to coastal processes or on- or off-site habitats. This section is organized as follows:

- project length and placement approach
- wave energy and volume density
- site geometry
- sediment size selection
- beach habitat considerations
- site grading

As a general overview to this design section, beach nourishment projects can be suitable for barrier beach or other sites with adequate backshore width, or those with sufficiently long project length (greater than 300 ft long). Sites which are most favorable are swash-aligned beaches, where the beach faces directly into the predominant wave approach. Other favorable characterizes are a site where gravel mining occurred in the past, which was fairly common. Beach nourishment is generally not suitable for rapidly eroding sites.

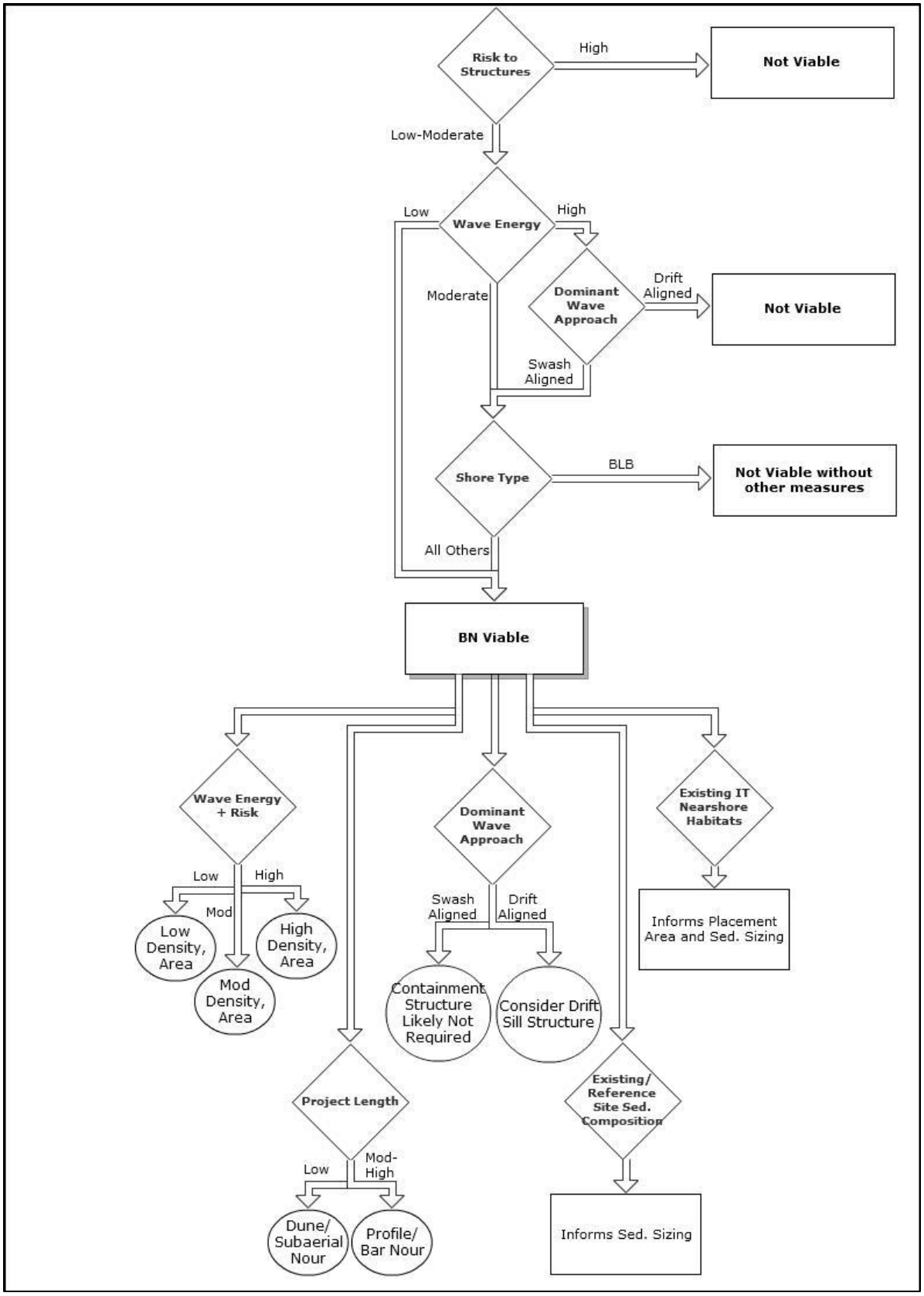

Figure 7.1-2. Design model for beach nourishment.

Project Length and Placement Approach

Beach nourishment sediment can be placed over the entire beach profile from the backshore area down to the subtidal, or only on a portion of the beach profile. Placement options consist of the following (Figure 7.1-3), in general order from the broadest cross-shore coverage to the least:

- entire beach (profile nourishment)
- mid-intertidal to backshore
- upper intertidal to backshore
- bar
- backshore
- dune

Extensive profile nourishment allows for nourishing the entire beach down to the depth of closure (the greatest depth where wave energy reaches), which is termed profile nourishment. The depth of closure is not defined for Puget Sound and is also quite variable depending on the wave climate, but is normally in the range of -8 to -15 ft (MLLW). Profile nourishment is rare in Puget Sound due to negative impacts to the subtidal biota. With the clear break in slope on most Puget Sound beaches in the vicinity of MLLW (Figure 1-5), profile placement typically means nourishment of the entire intertidal and backshore profile, and not extending to the depth of closure (Figure 7.1-3). Bar nourishment refers to only placing nourishment sediment on the shallow subtidal or the lower intertidal, with the expectation that sediment will be transported onshore to protect the beach. Bar nourishment is seldom carried out in the Pacific Northwest.

Other placement approaches include nourishing the mid-intertidal up to the backshore, or just focusing on the upper intertidal to the backshore (Figure 7.1-3). These are fairly common approaches in the Puget Sound region. The nourishment footprint may also be confined to above MHHW and sometimes 1 to 2 vertical feet above MHHW. These approaches are backshore placement and dune placement. Dune placement may be mostly aimed at increasing the elevation of a small dune and be separated by some distance from the active beach. The choice of which placement approach to use is related to the project area length, wave energy and approach angle, and biological considerations, all of which are outlined below. Examples of most of these approaches are presented in Appendix A.

The term “equilibrium profile” refers to the generally accepted understanding that a beach with an unchanged sediment size will have a dynamically stable beach profile (Bruun 1988). Following this reasoning, if sediment of the same grain size as the native sediment is placed ungraded on only on a portion of the beach profile, waves will distribute this sediment and adjust the beach back to its original slope. However, the use of coarser sediment will result in steeper profiles, and the creation of a higher berm will also change profile responses. These factors need to be evaluated together for the selection of the project length and placement elevation.

The elements of nourishment placement type, placement elevation, and project length are dependent on each other. Examination of the project length and nourishment volume from Appendix A sites along with other sites from Shipman (unpub.) and CGS files shows that there is a weak relationship between total project length and the total volume, as expected (Figure 7.1-4).

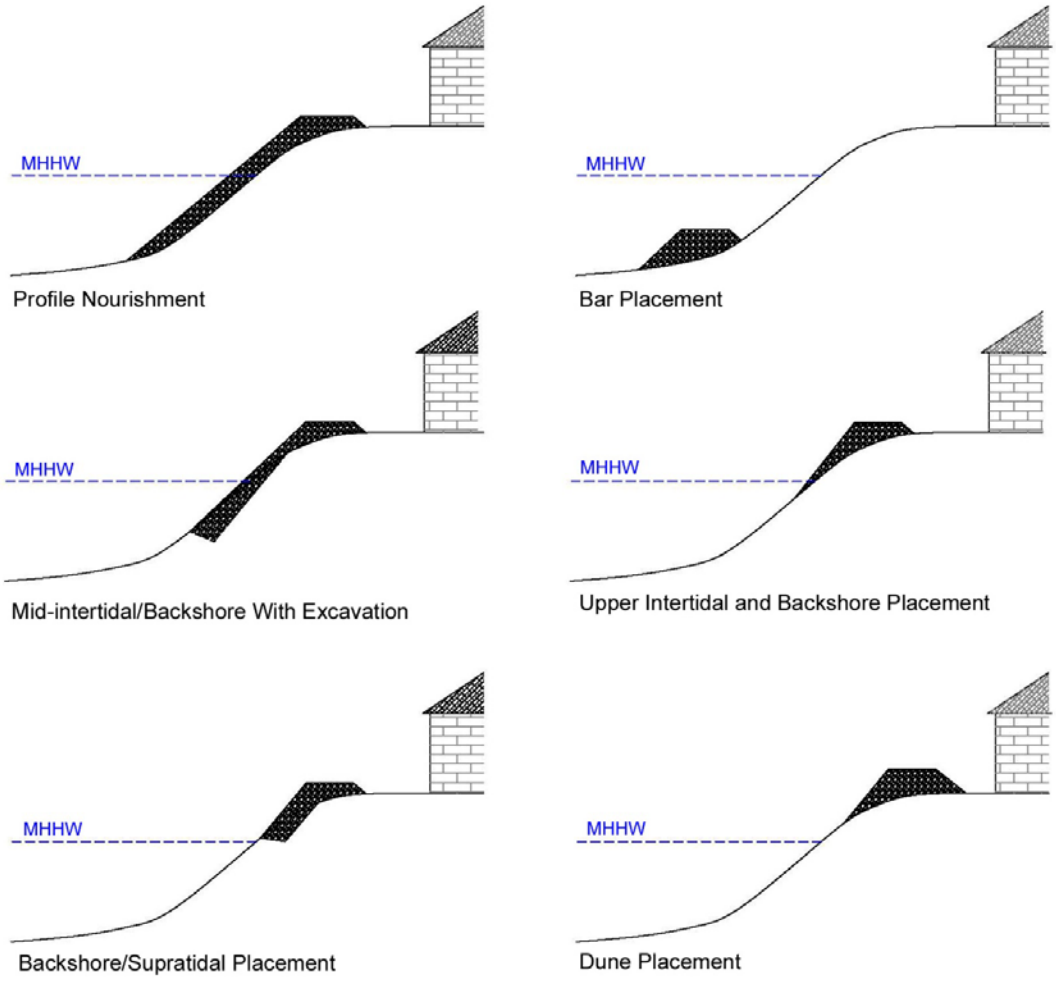

Figure 7.1-3. Beach nourishment placement approaches for Puget Sound application.

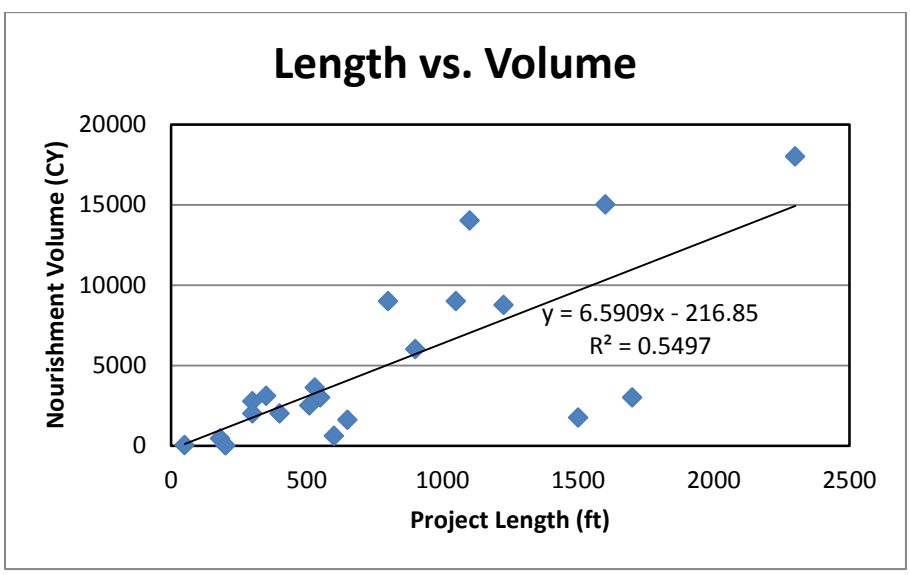

Figure 7.1-4. Plot of beach nourishment volume with project length.

The scale of beach nourishment projects in Puget Sound typically ranges from several thousand feet for larger projects to less than 100 feet for small residential parcels. In terms of the overall alongshore extent of a nourishment project, project length is highly relevant. Shorter nourishment projects, particularly ones that extend into the intertidal, will tend to have relatively greater sediment loss than longer projects due to the dominance of both ends of the nourished beach (Dean 2002). Nourishment sediment placed low on the beach in a short project would make the beach out of equilibrium and unstable, potentially requiring more maintenance (renourishment) than is generally acceptable.

Long beach nourishment projects appear to experience greater longevity in retaining nourishment material (Leonard et al. 1990). An example is North Beach Orcas Island (Figure 7.1-1 frame d, and in Appendix A), which had nourishment placed above +4.0 ft MLLW along four properties for a total length of 510 ft. This very-high-wave-energy project (Table 7.1-1) has not needed maintenance since installation in 1992, and appears to not require maintenance in the foreseeable future.

The nourished beach berm should be set at an elevation that will make the beach slightly higher than preproject conditions for a more robust berm. Berm elevations should be cautiously designed, as elevations that are too low or too high can undermine project success. The berm elevation should be set low enough that waves and cross-shore sediment transport result in a scarp (steep erosion feature) preset at the reach of storm waves with a constructed berm above the reach of waves. The berm elevation should also be set such that it is inundated every few years or more frequently, to keep a scarp from being cut into a berm that extends too high, and to help minimize the spread of invasive species in the backshore (such as has occurred at Lincoln Park in Seattle in the past; MacDonald et al. 1994). Figure 7.1-5 illustrates that as risk to infrastructure goes up, the elevation of the constructed berm crest (relative to MHHW) was also higher at the Appendix A and several other projects with available data (Shipman uppub.), although only with a weak relationship.

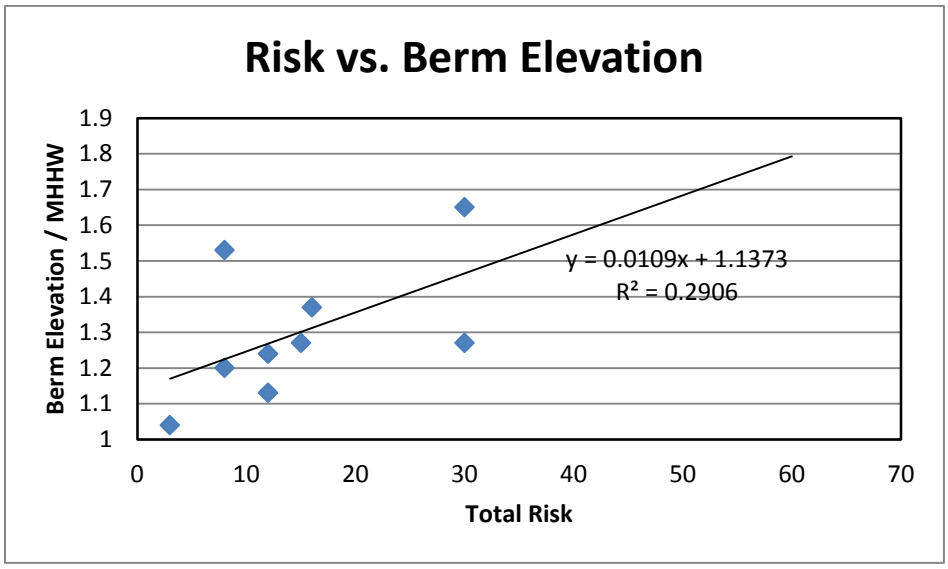

Figure 7.1-5. Plot of cumulative infrastructure risk with relative berm crest elevation.

Wolf Bauer's rule of thumb was to start with a berm elevation of 2 feet vertically above local MHHW and then adjust according to the site conditions (such as was done at North Orcas Island, Table 7.1-1, Appendix A). Conditions such as high wave energy (greater than 5 miles fetch from the southerly

quadrant or for predominant waves, e.g., from the west in the Strait of Juan de Fuca; or 10 miles from other quadrants) or greater potential for storm surge would suggest a need for a slightly higher berm elevation, while very low wave energy would suggest a slightly lower berm elevation. Note that this principle applies to the active beach berm, and not to an elevated storm berm in the backshore which may be separated spatially from the active berm (such as at Snakelum Point or East Lummi Island, where the storm berm was set 4–5 ft higher than local MHHW ;Table 7.1-1). Also, it is important to understand that a nourished beach with a berm set lower than a natural robust storm berm will experience onshore gravel transport to create a higher berm.

With current projections of sea level rise (NAS 2012), using berm elevations that are higher than what has been done in the past is appropriate. Planning for a minimum of 1 ft of sea level rise with a 1 ft from higher berm is a minimum design adaptation. For major projects with a longer planning horizon, such as 50 years or more, the inclusion of a 1.5–2.0 ft higher berm is appropriate.

Wave Energy and Volume Density

The relative wave energy (wave climate) experienced at a site is a critical factor in determining the amount of sediment mobilization that may occur. Larger waves usually equate to larger net shore-drift rates (the net, long-term effect of littoral drift). Wave energy relates directly to determining the ideal sediment placement approach, sediment volume density, and grain size. Beach nourishment is typically feasible at low- and moderate-wave-energy sites (defined as less than 1 mile fetch, and 1–5 miles of fetch, respectively; Cox et al. 1994). High-wave-energy sites can also be suitable in combination with other parameters such as longer project length and swash alignment (Figure 7.1-2). Therefore, consideration of wave climate must be paired with site geometry and alignment, which is discussed in the following section. Background or “passive” erosion refers to historical coastal erosion that occurred at a site prior to project installation. This is noticeably different from “active” or “structural” erosion, which is caused by engineered structures. Beach nourishment is usually initiated at sites where background erosion has persisted (Dean 2002). The magnitude of background erosion must be quantified and considered in the beach nourishment design process. It is assumed that background erosion rates will be superimposed on a nourished beach (Dean 2002). In other words, postproject erosion rates will be greater than background erosion rates since the beach profile is pushed waterward (Verhagen 1996). Persistent significant background erosion can jeopardize the success of any beach nourishment project (Clancy et al. 2009). However, the use of coarser gravel or other methods to bolster the stability of a nourished beach can offset this process.

The total erosion rate at a site is the sum of background erosion and active erosion. It is not critical and often not possible to separately quantify these two components of the total erosion rate. However, it is critical to have an understanding of the magnitude of the total erosion rate at a site prior to developing a beach nourishment design. Ideally an erosion rate should be determined over a period of 30 or more years. This is best done through the use of survey or other accurate site measurements that can be compared over time. Historical aerial photographs spanning back to the 1960s or earlier are also a very good way to quantify the erosion rate at a site. Delineating one or several beach features such as the vegetation line, waterward extent of drift logs, bluff toe, or other features from multiple years allows for comparison. Aerial photographs need to be very carefully rectified and georeferenced to remove as much distortion as possible in the photographs prior to comparison (Morton 1991). Erosion rates are best expressed in terms of inches per year (in/yr), with the initial and current data points as far apart in

time as possible. However, for sites or shore reaches which have incurred significant modification, it is most useful to compare the end point erosion rate with the erosion rate for the period following the shore modifications.

Sites with relatively high erosion rates (e.g., greater than 3 in/yr) should include more robust beach nourishment design, typically involving a high sediment volume density. Sites with even higher rates will need renourishment over time, and possibly a significantly coarser sediment size (further discussed below).

The density, sediment per unit of shore length (cubic yards per foot - CY/FT), is an important design consideration that is determined by balancing budget with durability. Nourished beaches often have erosion "hotspots" where one or several areas suffer greater losses than adjacent areas (Dean 2002). If volume density is low, such areas can suffer unacceptable sediment losses such that renourishment is required after a short interval or the public perception of the project success is reduced. Volume density must account for loss of fines if the nourishment sediment is finer than native beach composition. An overfill factor is used to counteract this, in order to inflate the needed volume to account for the likely loss of fines in the short term (Terich et al. 1994).

Determining an appropriate volume density depends primarily on the wave climate and erosion rates, although other factors affect the decision process to a lesser extent. High-wave-energy sites that are not swash aligned generally require high beach nourishment volumes to be successful, and renourishment may be required at some of these sites. Volume densities for the six projects described in Appendix A ranged from 0.8 to 9.2 CY/FT, with the small dune nourishment at Snakelum Point on the low end and Marine Park in Bellingham on the high end (Figure 7.1-1). Other documented Puget Sound projects have ranged from 2.5 to 9.0 CY/FT, with (typically shorter) backshore/dune projects on the low end and (longer) profile nourishment projects on the high end.

Site Geometry

Site geometry refers to the configuration of the shore surrounding the potential nourishment site. This ranges from linear shores to complex headlands, and pocket beaches. Shoreline configuration and the geometry of the subject site play a critical role in determining the location and degree of future erosion. Charlier and DeMeyer (1995) examined numerous beach nourishment projects and summarized physical parameters that should be considered in the design of any beach nourishment project. Nourishment is most successful at beaches located between headlands (such as pocket beaches), because sediment loss can only take place in a cross-shore direction. Many Washington State nourishment projects were designed using headlands or rock structures to partially mimic pocket beach conditions (Shipman 2002, Shipman in unpub.). Shorelines near tidal inlets tend to be more dynamic and unstable than those along straight coastlines. Similarly, nourishment sites near dynamic spits and river channels would also be expected to be dynamic and potentially unstable.

A "swash-aligned" beach is oriented facing the predominant waves at the site, such that the larger wave fronts tend to reach the beach (after the waves are refracted by the bathymetry of the adjacent bay bottom) parallel to the beachface (Bird 2005). This is typically the case at a pocket beach, and is not uncommonly the case at some accretion shoreforms. However, most spits and bluff-backed beaches in the Puget Sound region are not swash-aligned, and are conversely "drift-aligned" (Figure 7.1-3). Along drift-aligned shores the dominant waves break at an oblique angle, which generates littoral drift parallel

to the shore. Many beaches are intermediate between the two conditions, such that in practical application beaches that are oriented close to the direction of drift generally are considered drift-aligned, and those aligned closely with the dominant wave approach swash-aligned.

Figure 7.1-6. Examples of swash-aligned (left) and drift-aligned beaches (right) from the Livingston Bay area of northeast Camano Island. Arrows indicate prevailing wave direction.

Beach nourishment projects are more likely to succeed at swash-aligned beaches because the losses of sediment due to littoral drift are often negligible. These beaches have a greater number of options in terms of specific design elements and often beach nourishment can be successful even where wave energy is high. Examples of this are North Beach on Orcas Island (Appendix A) and nourished pocket beaches. Similarly, beaches which are very close in orientation to swash aligned are favorable for nourishment. Drift-aligned beaches can be good sites for beach nourishment as long as transport of nourishment sediment off-site is analyzed and included in design work. Drift-aligned beaches and areas of moderate wave energy may require the construction of a drift sill, which is a low-elevation rock groin constructed at, or minimally above, the nourished beach profile. These sills generally do not extend below the lower intertidal; however at highly modified, urban sites, they may need to extend down to several feet below MLLW. Examples of drift-aligned sites that required drift sills include Seacrest Park in West Seattle, Seahurst Park North in Burien (not yet constructed), North Samish Island (Johannessen 2002), and Marine Park in Bellingham (Figure 7.1-4 and Appendix A). The Marine Park and North Samish Island sites are examples of drift-aligned beaches coupled with greatly reduced sediment supply from up-drift armored bluffs. This resulted in the need for a drift sill at the down-drift end of both nourished beaches.

Beaches where the refracted waves reach the beachface at a 45-degree angle tend to have the highest littoral transport rates and design development needs to be quite conservative; these drift-aligned beaches are not generally suitable for nourishment where moderately high wave energy is present.

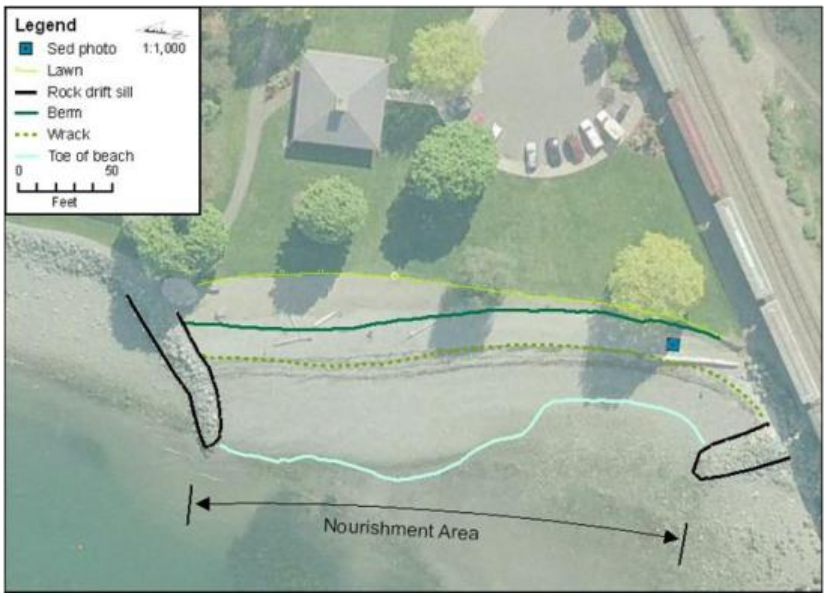

Figure 7.1-7. Marine Park, Bellingham, WA. The nourished beach is confined between drift sills in this highly altered, urban shore outlined in black.

Sediment Size Selection

Beach nourishment using gravel has been far more common in Puget Sound than sand nourishment. Natural beaches with abundant gravel, such as those in the Puget Sound–Strait of Georgia area and in the United Kingdom, have proven to be a practical form of coastal protection (MAFF 1993). Beach nourishment in the Puget Sound and Georgia Strait typically consists of the placement of select size(s) of rounded gravel on the upper beach. The intent is to slow, not necessarily to halt, beach erosion (Shipman 2002, Johannessen 2002). The general goal of beach nourishment in our region has been to build up (or rebuild) a high-elevation, protective gravel berm to limit storm damage and recreate a wider beach at high tide (Johannessen 2000, Johannessen 2002). Beach nourishment projects that use gravel often nourish from the mid-intertidal beach up to and including the backshore area (Shipman 2002). This type of gravel beach nourishment has proven to be much cheaper than the use of sand (the most common type of nourishment globally) because it uses smaller fill volumes and requires much less frequent renourishment.

Sand nourishment projects that only nourish the dune area or the upper foreshore tend to experience relatively rapid erosion following placement (Bruun 1988). Sand nourishment sediment placed in the intertidal should be expected to lose substantial volumes from the upper intertidal, which is often transported down to the lower foreshore and subaqueous portions of the profile, and potentially alongshore (Bruun 1988, Finkl and Walker 2005). An example of a project with very short sediment longevity was Wolf Bauer's first beach nourishment project on a pocket beach on northwest San Juan Island in the 1960s. Sand was placed in the upper intertidal and backshore, and only lasted several years before the majority of the sediment was displaced to much lower elevations (Bauer pers. com. 1998). This trend appears to apply to the majority of the Puget Sound region such that intertidal sand nourishment should only be performed where sandy beaches exist and there is adequate cross-shore room for a lower slope beach. Otherwise, where very low cost sandy substrate is available (e.g., through beneficial reuse or dredged sand), this sediment can be placed for beach enhancement, as it was at Jetty

Island near Everett. Nourished sandy beaches of this type will likely erode faster than natural beaches. Sandy sediment can also be used for short-term augmentation of a coarse-grained beach for habitat reasons (such as at Lummi Shore Road near Bellingham, discussed below).

Gravel tends to remain high on the intertidal and supratidal beach profile, minimizing loss to the adjacent subtidal area (Houghton et al. 1999), and tends to form a relatively steep beach profile, with slopes of 5:1 to 10:1 (horizontal:vertical) (Van-Hijum 1974) or steeper. Therefore, the equilibrium profile of a gravel beach is considerably steeper than that of a sand beach. Up to a certain size, gravel is normally transported onshore, minimizing loss to the adjacent subtidal area. Indeed, nourishment projects monitored in Appendix A and prior work (Johannessen 2002, Shipman 2002, Houghton et al. 1999) have shown virtually no loss of gravel offshore.

Most Puget Sound beach nourishment projects have relied primarily on rounded gravel greater than 0.75-inch diameter or larger. This was true for five of the six projects surveyed (Appendix A). Nourishment sediment at one project was primarily coarse sand, with pebble to coarse gravel (cobble) used at the remainder of the projects. The East Dungeness project had a mix of coarse sand with medium pebble, atypical for most nourishment projects in the region. One project (Marine Park) used mostly 0.5- to 2-inch sediment, but also contained a much wider mix of sediment sizes, mainly to aid in recruiting additional fine gravel and coarse sand for habitat improvement and recreational benefits. Cobble-sized sediment was included in the Marine Park nourishment sediment mix to allow for a portion of the cobble to augment the toe of the beachface in this erosional area.

Gravel should be washed clean of fines, which is typically completed at the gravel pit. This is to minimize turbidity which can occur during high tides soon after nourishment. However, often “oversize” gravel (greater than 2 inches in diameter) is not available washed. For projects above MHHW, it is acceptable to used nonwashed gravel as this sediment will very infrequently be in contact with marine water, and contact will typically occur during storms when ambient turbidity is high.

Gravel used for nourishment must be rounded to both resemble natural beach gravel and to allow for good drainage. Gravel particle shape has been shown to be important for sediment transport and sorting (Houghton et al. 1999). Generally, discs tend to be transported onshore and spherical clasts are more easily entrained and roll down the beachface. Puget Sound gravel pits do not typically have the percentages of flat and elongated particles that some other regions have; however, gravel with over 10% of elongated or fractured particles should be avoided. The only reasonable exception to this is in areas with bedrock where natural beach gravel contains a substantial percentage of angular particles.

It is important to understand that the force of the waves moving a given gravel size up the beach must exceed the forces of gravity and backwash moving it down the beachface. These conditions are different for each site and the specified nourishment sediment must be tailored to a given situation. Gravel particles that are too large typically end up at the toe of the high-tide beach. A good example of this occurred in Birch Bay in Whatcom County, where renourishment of oversize cobble in the 3- to 8-inch range resulted in the larger clasts moving downslope to the toe of the high tide beach (Figure 7.1-5). This sediment was not the size specified in the earlier design by Bauer. Bauer had warned against up-sizing nourishment sediment based on the false assumption that larger substrate makes for a more successful project in terms of gravel stability. His reasons included instability on the upper beach where wave energy is greatest and infringement on the low-tide terrace with nonnative sediment.

Figure 7.1-8. Large cobble (3–8 in) added to the upper beachface and sorted by waves to the toe of the high-tide beach and over the low-tide terrace, making wading difficult at this popular recreational beach on central Birch Bay Drive, Birch Bay, Whatcom County, 2002 (photo by J. Johannessen).

The term "sediment compatibility" refers to the degree to which the nourishment sediment would perform compared to native sediment (Dean 2002). The use of finer sediment sizes for intertidal habitat enhancement has been incorporated into gravel beach nourishment design in the Puget Sound area (Shipman 2002, Johannessen 2002); however, this is typically not feasible at moderately erosional sites with more than low wave energy. Several examples of sand nourishment used high in the backshore are found in Appendix A, with only one site studied consisting primarily of sand nourishment (East Dungeness). That project consisted of augmenting a dune where the primarily sandy beach had a very low slope and broad profile.

Coarser nourishment sediment usually erodes more slowly than finer sediment. Sediment selected for beach nourishment must be at least as texturally coarse as the original beach material (Dean 2002). Sediment that is too fine leads to erosion of nourishment sediment and offshore deposition (Finkl and Walker 2005). Some practitioners have recommended a mean grain diameter of at least 1.5 times that of the original sediment in quantities sufficient to establish the ultimate slope compatible with the wave climate. Terich et al. (1994), advising on Puget Sound nourishment design, stated "As a general rule, the replacement sediment should be slightly coarser than the original beach sediment. This should be accomplished within the aesthetics of the replacement sediment and the availability of a source of supply."

Weighing all of the processes and issues discussed in this section it is possible to provide general guidance on appropriate gravel sizes for nourishment of generally erosional beaches. This applies to most of the sites which have received beach nourishment in Puget Sound, but is not appropriate for nourishment design for habitat enhancement only, or for truly restoring natural processes, which should instead be based on recreating historic substrate size (and other parameters). Examination of Table 7.1-1 and other project data (Shipman unpub., CGS unpub.) reveals that the majority of intertidal nourishment projects contained rounded gravel with the general range of 0.5–2.5 inches or similar. Backshore-only nourishment (above MHHW) typically utilizes a slightly coarser sediment mix than

intertidal and backshore nourishment designs. Refer to Table 7.1-2 for guidance on appropriate gravel nourishment sediment sizes, with the caveat that all nourishment design elements are site-specific and site conditions and individual project objectives must be incorporated.

Table 7.1-2. General ranges of appropriate gravel sizes for beach nourishment for erosion control in Puget Sound. Note sediment size selection is controlled by many interrelated processes and issues and each site requires design analysis.

Wave Energy Class (Fetch)	Intertidal Nourishment (median diameter in inches)	Nourishment Above MHHW Only (median diameter in inches)
Low (<1 mi)	0.25–0.9	0.25–1.0
Moderate (1–5 mi)	0.25–1.5	0.5–2.0
High (5–15 mi)	0.5–2.0	1.5–4.0
Very High (>15 mi)	1.0–3.0	2.0–5.0

Beach Habitat Considerations

Habitats such as surf smelt spawning substrate have been successfully recreated in beach nourishment projects through the use of fine gravel (Johannessen 2002). Where intertidal habitat includes forage fish spawning, or the desire to recreate this habitat, the use of multiple layers of beach nourishment has been carried out. Examples include the beach at North Samish Island (discussed in Zelo et al. 2000 and Gerstel and Brown 2006; design developed by Bauer and Johannessen) and Seahurst Park South (Hummel et al. 2005). The general approach has been to place a coarse gravel lower layer in the mid-intertidal up to the backshore, provided for additional resistance to erosion when needed, with a fine gravel layer above. At Samish Island, potential forage fish spawning habitat was recreated after several years of natural onshore transport of sand from the broad, sandy low-tide terrace. This also occurred at Seahurst Park South but to a more limited extent.

A limited number of nourishment projects have been carried out with the goal of habitat enhancement, not for erosion control. One large project was designed for mitigation of the impacts of a new rock revetment constructed along approximately 1.5 miles of the north shore of Bellingham Bay for defense of the rebuilt Lummi Shore Road. The road was set back from the unstable and eroded bluff shore in some areas to a limited extent, and the US Army Corps of Engineers designed and built a substantial rock revetment, which extended from +8 to +18 ft MLLW. In order to offset the loss of feeder bluff function and partial burial of the upper beach, a beach nourishment program was designed to routinely replenish the beach with sediment (Figure 7.1-6). There was more suitable surf smelt spawning habitat and surf smelt spawning than before the project. However, nourishment was not continued beyond the first five years, and in subsequent years the amount of potential spawning habitat appeared to have been significantly reduced.

Figure 7.1-9. Before (top, 1998) and after (bottom, 2000) revetment installation and beach nourishment for mitigation at the same location in the central reach of Lummi Shore Road, Lummi Reservation on the north shore of Bellingham Bay, WA (photo by J. Johannessen).

Another large habitat enhancement project completed was the Mount Baker Terminal beach project just east of the Town of Mukilteo in 2005–2006 (Pentec 2011). This was a 1,100-foot-long reach of beach created through a multilayered beach nourishment design waterward of the BNSF railway and revetment (Figure 7.1-7). This beach project was completed as mitigation for an adjacent development, with the goal of habitat enhancement in an area of limited beaches. The western, up-drift end of the beach was found to have lowered and coarsened, with deposition in the eastern, down-drift end of the beach five years after the project (Pentec 2011). This enhancement project is an example of the large volume of sediment required to create a broad beach in front of the 120-year-old railway revetment. The Mount Baker Terminal beach had the highest known volume density of documented projects in the Sound, at 12.7 CY/FT.

Figure 7.1-10. Before (top, pre-2005) and after (bottom, late 2005) beach nourishment for mitigation at approximately same location, Mukilteo, WA (Port of Everett photos).

Site Grading

Excavation prior to beach nourishment is appropriate at some limited-size properties. Excavation is not practical at larger projects or projects with moderate to large volumes of nourishment sediment added, and has generally only been carried out at backshore-only nourishment projects (several are detailed in Appendix A). The reason to complete excavation below the preproject grade is to allow for excellent drainage and wave-energy dissipation. Excavation in the range of 1.5–2.5 vertical feet has been appropriate for achieving these goals. Where excavation has been carried out, it has typically been to remove fine-grained sediment from the lower portion of the backshore nourishment area. This excavated sediment has been useful for placement along the higher, landward edge of the project area, and has provided excellent substrate for backshore vegetation planting.

Differing standards for the degree of beach surface grading apply to sites with different uses and wave energies, and for residential and park project sites as compared to habitat restoration or enhancement sites. Residential and park settings often require more careful (and expensive) grading in terms of spreading sediment to within specific low to moderate tolerances from the design. This may not involve much work for small sites; however, for larger park or similar public settings there is often no acceptable alternative to completing consistent site grading. Typical grading standards for this type of site should be plus or minus approximately 0.3 ft.

Beach nourishment projects that are carried out solely for habitat restoration or enhancement can often have much looser grading standards, particularly when placing sediment in the intertidal or within reach of normal waves. This can mean placing a specified volume of sediment in one or more general locations with minimal or in some cases almost no grading at all. Typical grading standards for low- to moderate-wave-energy restoration or enhancement sites can be on the order of plus or minus one foot. However, in moderate- to high-energy sites, seasonal storms can complete the grading up to the reach of waves without any effort or expense on the part of the project proponent. In these conditions, implementation can be planned for months with higher storm occurrence, such as October through March. With these conditions met, it is perfectly reasonable to place sediment in elongated piles in the intertidal with almost no grading at all. For example, the project at Lummi Shore Road in Whatcom County involved mitigation of revetment impacts to sediment supply at a highly utilized surf smelt spawning beach through the placement of ungraded beach nourishment sediment in early February of a number of years (Figure 7.1-8). Within several weeks of the pictured winter nourishment, the sediment was well distributed alongshore and cross-shore.

Figure 7.1-11. Beach nourishment placement with almost no grading at Lummi Shore Road, Whatcom County, WA, immediately after February 1999 placement (photo by J. Johannessen).

Completing reasonable grading above the normal reach of waves, typically above MHHW plus 2 ft, is important at all sites. Irregularities or low points left in the backshore after a project is complete can last

for years. Low-elevation areas can cause localized erosion or damage as high-water storm waves can penetrate further inland than in other portions of a site.

Cost

Due to the higher number of beach nourishment projects in Puget Sound and the slightly better level of documentation relative to other design techniques, reasonable information can be provided on relative construction costs. Construction costs for beach nourishment projects had a wide range that depended on the project scope as well as general ownership and use. Projects on public lands were generally significantly more expensive than on private lands, due to a generally higher design and construction standard, as well as the cost of working around public infrastructure. Known construction costs were adjusted to 2012 dollars by using information from the US Bureau of Labor Statistics (using the CPIU). Cost for larger projects—both those surveyed in this study and a limited number of others on public lands with documented project costs—ranged from $810/FT at Marine Park Bellingham to approximately $1,092/FT at Seacrest Park in West Seattle to $1,232/FT at Seahurst Park South (Table 7.1-2). The Mount Baker terminal project, which was constructed as mitigation for an industrial project, had the highest cost per foot for the eight sites with data at approximately $1,820/FT.

Construction costs for small projects at private sites typically involved lower costs. Documented construction costs for the residential projects surveyed in this study ranged from $50 to $178/FT adjusted to 2012 dollars. The East Lummi Island project had the lowest cost, with a low to moderate nourishment density of 2.4 CY/FT and minimal transportation costs for gravel. The North Orcas Island project was quite low cost for its volume density as it had a good amount of volunteer design and permit work. Also this project saved money by giving the gravel pit many months to produce the desired gravel blend when they had down time and also giving the grading contractor extra time to perform their work.

Table 7.1-3. Beach nourishment construction costs for projects with adequate data (Sources: CGS files, Shipman unpub., Hummel et al. 2005, Pentec 2011).

Project Name	Project Length (ft)	Year Installed	Density (CY/FT)	Cost 2012 Dollars	Cost Per LF-2012 Dollars	Cost Per CY-2012 Dollars
East Dungeness	1,500	2006	1.2	267,632	178	149
Snakelum Point	50	2002	0.8	8,551	171	214
Marine Park Bellingham	300	2004	10	243,085	810	81
North Beach Orcas Island	510	1992	4.9	75,277	148	30
East Lummi Island	181	2004	2.4	9,116	50	21
Seacrest Park	1200	1988	-	873,350	728	-
Seahurst Park-South	1,050	2005	7.5	1,293,156	1,232	164
Mount Baker Terminal	1,100	2005	12.7	1,998,514	1,817	143
Blakely Is.-Driftwood Bch	650	1999	2.5	110,249	170	68

Monitoring

Monitoring is an important element of beach nourishment projects. Monitoring determines a project's success from an erosion control standpoint as well as an ecological one. Monitoring can also tell us if and when maintenance is required. It is common practice to monitor larger projects on an annual basis. Monitoring projects immediately after winter storms can provide time-sensitive information as to the extent of changes and potential management concerns.

Monitoring often consists of beach profile measurements that can be accurately and consistently repeated over time. A higher standard of monitoring includes full beach topography, which is often only incrementally more work in the field and much more useful in that volume change can be calculated. Erosion and accretion areas can also be accurately delineated and quantified through comparison of different topographic surfaces from different time periods. Profiles and or beach topography should extend from the landward extent of backshore areas and down to a minimum of 0 ft MLLW, preferably to approximately -5 ft MLLW or lower. Other parameters that are useful to map and monitor include the waterward vegetation line, drift logs, position and elevation of storm berm and active berm crest, potential and utilized forage fish spawning areas, and the inner margin of eelgrass beds. Beach sediment should be characterized from several distinct and consistently monitored elevations along selected beach profiles. This should include the upper intertidal within potential forage fish spawning elevations where ever feasible.

Monitoring at smaller beach nourishment projects ideally would include all of the above discussed topics, but is often more limited due to lesser concerns and budgets. Recommended minimum monitoring includes annual and post storm photographs from fixed photo points covering the entire project area, augmented by less-frequent quantitative data. Measuring beach profiles and characterizing beach sediment along profiles is recommended every two years.

Maintenance

The primary maintenance element for beach nourishment is the need for renourishment. With beach nourishment, “renourishment should occur as needed”, as stated by Terich et al. (1994). However, designers such as Wolf Bauer and others following his general approach have worked hard to avoid the need for frequent renourishment. Bauer’s intent was to have initial nourishment projects last on the order of 20–30 years without the need for renourishment. This appears to be the trajectory of a number of projects such as Tolmie State Park (Appendix A), Golden Gardens in Seattle, and Driftwood Beach on Blakely Island in San Juan County. This is in contrast to the much more frequent renourishment required at many sand beaches on the US East Coast (Leonard et al. 1990), which are exposed to greater wave energy and have much finer sediment.

When renourishment is required at a Puget Sound project, it is often limited to adding a small volume of gravel to one end of the project area. Typically, renourishment projects consist of less than 20% of the original placement volume. Some of the older projects have had renourishment. At the Marine Park site, renourishment volume was less than 10% of the original volume. These efforts are limited in the amount of work required. In most cases, simple placement on the upper beach with limited grading is the usual extent of renourishment.

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Chapter 7. TECHNIQUE 2
LARGE WOOD

Description

Large wood placement designs typically consist of large tree trunks with and without rootwads that are designed to enhance the elevation of the backshore in order to diminish wave induced erosion of the landward shore. Large wood was naturally and historically much more common on Puget Sound shores that it is at present (Maser and Sedell 1994). Logs of all sizes, typically with rootwads, were more prevalent Puget Sound wide, and in very high densities in river estuaries. The need to place large wood in the nearshore for increased habitat complexity and other structural functions is justified by the reduction of large woody debris (LWD) over time in Puget Sound nearshore environments, both from direct removal and reduced recruitment (Maser and Sedell 1994, MacLennan 2005).

Large wood can be placed singly or in groups, with or without rootwads, partially buried and/or anchored, or simply placed on top of the beach substrate, to produce the scale and function required for each application. The placement of large wood can be designed to achieve the following objectives: enhance shoreform structure, reduce shoreline erosion rates, and enhance marine riparian ecotone, aquatic productivity, and/or habitat complexity. Wood placement can provide erosion control functions by enhancing the elevation of the storm berm, thereby increasing wave energy absorption and structure of the upper beach. Large wood placement often occurs in conjunction with other design elements such as small volumes of beach nourishment (backshore only), vegetation, and strategic boulder placement. Most large wood placement projects include some form of anchoring, burial, or both.

While the placement of large wood is a structural management technique, if designed and installed properly it can mimic the natural process of wood recruitment to the beach or salt marsh that might otherwise take many years to occur naturally in a restoring system (in the absence of a major event that alters the natural development trajectory of the system). Large wood placement designs can be tailored to trap additional LWD and sediment resulting in increased habitat complexity and biological processes like the germination of certain plants, microclimates for beach fauna, and attachment substrate for sessile invertebrates and boring organisms. Large wood placement can also be used to reduce shoreline erosion and replicate historic processes beneficial to many organisms, including salmonids.

This technique does not include the design of large rigid log structures, such as crib walls or designs that more resemble log bulkheads. These topics are discussed in engineering documents addressing traditional engineering approaches included in Technique 5, *Hard Armor*. Design guidance is also not included for large wood placed exclusively for recreational value (such as a place to sit on the beach), or logs placed in dense arrangements below mean high water with the intent of largely obstructing wave energy.

Application

Large wood placement can be applied on most Puget Sound geomorphic shoretypes, excluding rocky shores. Success has been more frequently observed along shores with low elevation backshores (“no bank” sites) such as barrier beaches, low to no bank pocket beaches, and within embayments. Fewer successful installations have been documented in deltaic environments and along bluff-backed beaches, although such projects could be successful if wood were present there naturally. Large wood placement projects are most suitable for sites with low to moderate wave energy, however case studies

documented project success on sites with high and very high exposure categories (See Appendix A). LWD is not the optimal technique for sites with high background erosion rates and structures in close proximity. Because this technique is likely to slow rather than halt erosion entirely, it is best suited for sites in which baseline conditions (wave energy, erosion and risk) are more moderate. LWD project sites also require adequate backshore width for the construction of the design feature itself.

The response time of a large wood installation depends on the specific objectives and the scale of engineering associated with the installation; however most applications will provide an immediate response. The lifetime of an LWD project is likely to be greater when baseline conditions (mentioned above) are relatively moderate. Assuming that design is well aligned with the site characteristics, large wood installations can allow for a more natural range of shoreline dynamics, particularly when compared with bulkhead installations.

Many existing shore protection structures (e.g. bulkheads) on Puget Sound were constructed decades ago and are or will soon be reaching the end of their design lifetime. Where feasible, bulkheads and other hard armor could be replaced with soft shore protection that incorporates large wood placement. The deposition and retention of LWD can also be increased through enhanced vegetation in the backshore or beach nourishment. This is consistent with state Shoreline Management Act policies that favor alternatives to 'hard' armoring where technically feasible and encourage property owners to demonstrate the need for armoring when no other alternatives are deemed practical. LWD installation projects, where suitable, provide an avenue for private landowners to comply with the regulatory framework and slow erosion on their properties. Planting additional vegetation in backshore and bluff areas will eventually provide on and off site benefits in that fallen trees can provide logs that can be recruited to the beach. Where applied along public shores, large wood placement can offer opportunities for educating the public about beach processes and habitats, particularly the role of large woody debris, through signage, volunteer monitoring and maintenance, and demonstration value (Clancy et al. 2009).

Effects

The added structure and elevation of the LWD-enhanced storm berm can reduce wave-induced erosion, promote deposition of fine sediment in areas with wind-blown sand (aeolian sediment transport), and facilitate increased species richness in backshore vegetation. Winds transport and deposit fine sediment on the leeward side of LWD in some exposed areas in the region, such as along the shores of the Strait of Juan de Fuca. The accretion of fine sediment enhances beach microtopography such as storm berms or depressions in salt marshes. Buried LWD is a natural and historic structural element of Pacific Northwest beaches and can also function as substrate for backshore and riparian vegetation resulting in increased species richness (Guttman 2009, MacLennan 2005). LWD on beaches is also associated with increased invertebrate abundance and biomass (Tonnes 2008) that serve as food for a number of nearshore species, including salmonids. LWD on beaches produces microclimate effects, such as increased soil moisture and temperature (Tonnes 2008), with known benefits to surf smelt (*Hypomesus pretiosus*) embryo survival (Rice 2006). Barrier beaches are often associated with larger quantities of LWD due to the depositional nature of the shoreform. Figure 1 shows a barrier beach with moderate amounts of naturally-deposited LWD, which is one of a number of natural models for large wood installation.

Figure 7.2-1. Barrier beach in developed area with abundant, natural LWD, northeast Whidbey Island (Johannessen).

The effects of a large wood placement project are dependent upon site characteristics and specific design elements. The typical objective of a large wood placement project is to slow erosion. If designed appropriately, the LWD pieces should be a component of a natural storm berm that serves to absorb wave energy, particularly during storms that occur at high water. Results of case study analyses showed that most LWD placement projects (four out of five; Appendix A) were effective at mitigating erosion with very few to no negative impacts to nearshore processes and habitats. The only case study site that demonstrated a low level of effectiveness was along a bluff backed beach with high wave energy (Birch Point). This combination of shoretype and wave energy does not fit the current recommended site characteristics for large wood installation projects.

Research from other geographic areas has included documenting the role of LWD on relatively high energy gravel-dominated beaches. At these sites LWD is deposited during high wave events generally positioned at the top of the storm berm (Kennedy and Woods 2012). LWD acts to trap sediment at the uppermost limit of wave swash and hinders the inland penetration of waves during storm events. As a result the beach height in the New Zealand study area was on average 1.6-3.3 ft higher on beaches with woody debris and the beachface was almost twice as steep as beach profiles without LWD. During intervening calm periods the LWD-dominated storm berm is inactive with waves reworking sediment at lower elevations on the beachface. Kennedy and Woods (2012) concluded that LWD on gravelly beaches appears to act as a buffer to waves during storm events, while remaining inactive during intervening calm periods.

Because LWD placement projects typically form a discontinuous log placement area that slows rather than halts erosion, sediment supply, sediment transport, and (cross-shore) LWD recruitment are largely preserved. Case study results (Appendix A) show that most LWD is placed above MHHW, which prevents the burial of upper intertidal spawning areas. Most case study sites had a low level of sediment

(nourishment) incorporated into the design to further enhance the elevation of the storm berm. A slightly steeper beach profile and coarser sediment composition were documented at the case study sites in which gravel beach nourishment was a design element and was not attributed to the log placement.

Geochemical processes can also be directly affected by large wood placement as LWD is a major component of the carbon nutrient cycle, and can serve as substrate for nitrogen-fixing vegetation (Hood 2007). This management measure can also provide refuge from predation for migrating fish that forage upon prey items residing on or around LWD. An example is juvenile salmonids that feed on amphipods and insects in high intertidal habitats (Cornu et al. 2007, Toft et al. 2004, Sobocinski 2003, Williams and Thom 2001). Large wood placement can also benefit other wildlife as the wood provides habitat for nesting, foraging, and feeding for a number of bird species found in the Puget Sound region (Brennan 2007).

Design

As large wood placements are not as well understood as beach nourishment, hard armor, or other techniques in these guidelines, the feasibility of installing large wood is covered in this section. Other design steps include specific design elements unique to large wood placement projects, including: the specific location within the beach profile that the LWD will be placed (elevation and orientation), LWD size and type to be used, whether it is placed atop the current beach grade or buried (and to what depth if buried), and the type of anchoring mechanism, if anchoring is necessary. This guidance is divided into the following sections:

- Feasibility assessment
- Large wood placement elevation
- Large wood placement orientation
- Large wood characteristics
- Anchoring
- Cost

As an overview to the design section, large wood projects can be well suited for barrier beaches, pocket beaches, and transport zones with low to moderate wave energy and erosion rates, where risk to infrastructure is not high. Beach nourishment and vegetation planting can augment large wood projects, particularly at moderate wave energy or sites with moderate erosion. Common design errors to be avoided are placing logs too low on the beach profile, the use of anchor systems that are completely rigid and do not allow logs to move, and not embedding logs into the beach substrate. The topics are covered in the following sections.

Feasibility Assessment

The first step in developing a large wood placement design is to clearly identify the project objectives and the design elements required to achieve the identified goals. Any constraints that could present solid boundaries to the design area should be outlined early in the process, such as property boundaries or infrastructure. If the project will include additional design elements such as beach nourishment, this should be clearly established early in the design process. As with all projects, the available budget will influence the extent of engineering elements that are possible. Lack of site access for construction can also limit project feasibility. For example if design materials cannot be purchased and delivered to the

site, then barge access should be explored, otherwise large wood installation may be infeasible. These preliminary steps will provide a framework which the project design must work within.

The subject site should then be evaluated to determine if the conditions for large wood placement are appropriate and identify any potential constraints that could limit project success. The determination of feasibility for a large wood placement project relies on several site characteristics that will also inform design. The most critical site characteristics relevant to feasibility and design include the combined effects of shoretype, wave energy, existing berm elevation, beach substrate density and existing LWD (Table 7.2-1).

Table 7.2-1. Site characteristics and associated design considerations for large wood projects.

Site Characteristic	Associated Design Consideration
Shoretype	Barrier beaches, pocket beaches, and embayment shores generally feasible. Bluff backed beaches with low exposure are also potentially feasible depending on drivers of erosion.
Wave energy	Not suitable for high wave energy unless on barrier beach or pocket beach. LWD density, LWD size, placement in beach profile, need for anchoring
Existing berm elevation	LWD placement on beach profile and if beach nourishment should be included.
Beach substrate thickness and underlying deposit strength and density	Type of anchoring mechanism. Different anchor styles are suited for different substrates.
Existing LWD supply	LWD can be placed to trap natural drift logs if in moderate abundance, or for enhanced berm only

Favorable General Site Characteristics of Successful Large Wood Projects

- Barrier beaches, pocket beaches, transport zones
- Low to moderate wave energy
- Low to moderate background erosion rates
- Moderate to high setback distance (low risk)
- Medium or high infrastructure risk
- Enough room in the backshore for log placement

In addition to the site characteristics listed above, a feasibility assessment for large wood placement projects should include a thorough understanding of local coastal processes, the existing erosion rate (if an objective is to reduce erosion rates), the presence of critical habitats, the anticipated wave runup, and the presence of additional stressors such as altered sediment supply or substantial vessel wake. Understanding the larger net shore-drift system (also see Chapter 4) can determine how intact current processes of sediment supply and transport and LWD recruitment and storage are as compared to historic conditions. Identifying any additional sources of disturbance, such as vessel traffic, is important at this stage. At the site-scale, measuring the maximum fetch is a critical first step in the feasibility and design assessment process. The maximum measured fetch can provide insight into the wave regime at the site. The higher the wave energy the higher on the beach profile the large wood should be placed.

This is important to the design because adequate space is required to place the large wood, especially if multiple LWD pieces are included in the design. Wave run-up could be calculated if wind-data are available, but if considerable LWD occurs naturally at the site, the landward limit of LWD can also be indicative of the highest tidal inundation and wave run up.

Examining adjacent unmodified sites can also inform feasibility and design, particularly if the subject property has incurred modifications to the natural topography of the backshore. The substrate composition of the upper beach and backshore should be noted along with the density of the substrate specifically in the backshore. The natural elevation of the storm berm and the extent of LWD deposits (vertically and horizontally) along adjacent shores should be assessed and compared to the subject property. If LWD appears to be in transport or deposited regularly it should be noted. The dune/backshore vegetation assemblages should also be assessed, particularly if vegetation plantings will be included as part of the design.

Large wood placement projects are not well suited for every site in the Salish Sea and compromises must be made if site characteristics push the limits of feasibility. Synthesis of each parameter will cumulatively inform where to place the large wood and the best anchoring mechanism for the individual site. The design model/decision framework presented in Figure7.2- 2 should be used as a guide in this process.

The following example of the synthesis and associated compromises required to design a large wood placement project was created to outline this process:

- If the wave energy at the site is high or very high, then the infrastructure must be adequately setback,
- large wood placement should be placed above normal tidal elevations but within the maximum extent of wave run-up (if possible)
- If the site is a barrier beach that is rapidly eroding due to a drastic reduction in littoral sediment supply then the site should also have low risk to infrastructure,
- If the berm is in a low elevation eroded state, the site could benefit from additional upper beach elevation, and enhancement to the storm berm via beach nourishment,
- If the site has a high existing natural supply of LWD, logs could be placed oriented to trap natural drift logs,
- The large wood pieces should be partially buried and anchored to assure that they are immovable if inundated in the future,
- Vegetation plantings should occur adjacent to and landward of the large wood. The finer the substrate the more species are likely to volunteer.

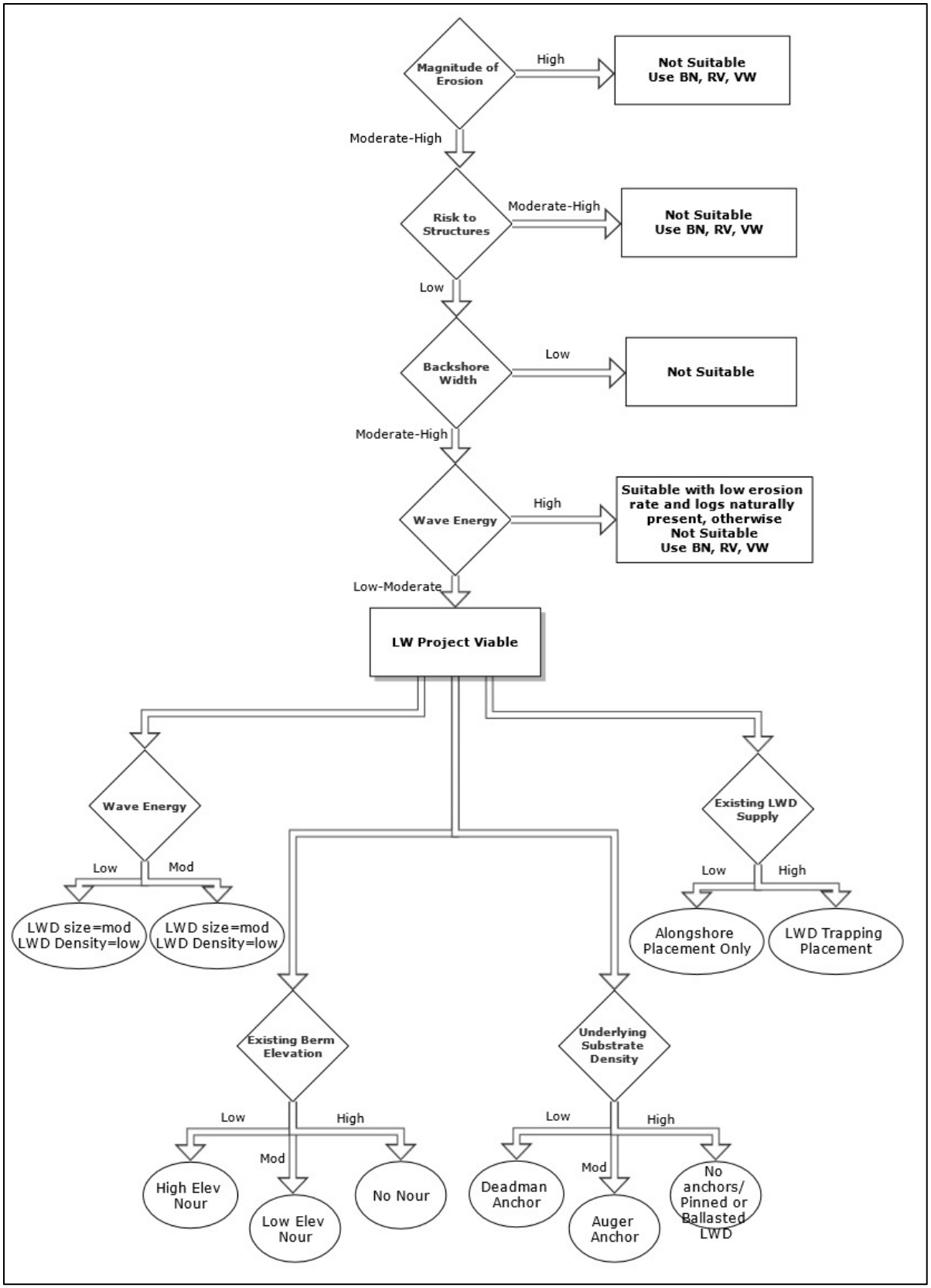

Figure 7.2-2. Design model for large wood projects.

Large Wood Placement Elevation

One of the most critical design criteria for project success is the elevation where the large wood is placed. Logs are typically placed several vertical feet above local MHHW. Large wood placement should mimic the upper limits and elevation of naturally deposited large wood along local reference sites. In areas where no LWD is found on the beach from which to reference, historic air photos can provide insight. In addition, other indicators or documentation of maximum wave run-up should guide large wood placement elevations. Sites with higher wave energy will have greater wave run-up and the large wood should be placed higher and further landward. The landward limit of appropriate large wood placement is commonly defined by the presence of upland vegetation or infrastructure. Examples of log installation for erosion control are show in Figure 7.2-3. Frames a, b, e, and f in this figure shows an example of a common placement located within the natural elevations of LWD deposition. Frame d in the figure shows logs anchored within the zone of natural log deposition, but placed within a constructed dune.

If large wood is placed too low in the beach profile it can result in beach scour beneath the structure resulting in project failure. With the exception of very low energy sites, large wood should never be installed at or below MHHW unless wave energy is relatively low and risk to a nearby building or other structure is high. Logs placed lower can become scoured with sediment removed from below and waterward of the logs. One case study site had logs anchored in the intertidal (Bloomquist site in Zelo et al. 2000, Figure 7.2-3 frame c), but beach erosion did not appear to have occurred at this site when observed in 2012 and the project has fared quite well. Another site with anchored logs in the intertidal in Suquamish has reportedly experienced scour around the logs (Waldbilling pers. com. 2013).

A large wood project on Indian Island constructed by the US Navy, included anchored LWD along with other erosion control measures. Logs were anchored above and slightly below MHHW, waterward of preexisting dunegrass. The 1997 installation also included vegetated geogrids, fill, vegetation, and other measures landward of MHHW, to protect an old landfill from erosion, as summarized in Zelo et al. ("Indian Island" project, 2000). Subsequent to that report, consultants for the Navy determined that these logs were causing more harm than good to the beach through increased scour and not enough erosion protection for the west end of the landfill. In 2003, 6 years following installation, the Navy removed the logs and extended the revetment further west.

Large Wood Placement Orientation

Large wood orientation is also an important element of large wood placement. In most cases large wood pieces are aligned parallel to the shoreline (Figure 7.2-3, most frames), but in some cases pieces may be oriented to facilitate beach access or to trap additional LWD pieces in transport (similar to the key piece of a fluvial log jam, Figure 3, frame b). This is effective if the project site is within a drift cell with a moderate or high density of natural drift log transport. In the case of the limited known projects which have attempted to trap natural drift logs, the main approach was to offset the end facing the predominant wave approach (up-drift) log end the logs at a 30-40 degree angle away from the trend of the shore, with that log end elevated several feet above the beach level to provide the tracking mechanism. This also requires that up to one third or so of the opposite end of the log length to be placed below grade to be stable. Key large wood pieces and all pieces placed within reach of waves on an annual basis should be partially buried in order to prevent groups from scouring beneath the logs and most or all conditions. Key pieces should be oriented to pin other pieces in place. These larger pieces

a) Backshore linear logs, minor nourishment (Oak Bay)

b) Complex log pattern to trap logs (NW Whidbey)

c) Upper intertidal

d) Logs interlocking with dune (East Dungeness)

e) Un-anchored and placed high on the beach

f) Minimizing end erosion at the ends of bulkheads.

Figure 7.2-3. Examples of log installations for erosion control in the Puget Sound. Arrows point at anchored logs at anchoring locations, except c) all logs shown are anchored and e) thin arrows indicate logs placed without anchors. Case study sites indicated in parenthesis; see Appendix A.

should be oriented towards the dominant wave direction in order to act effectively as traps for LWD in transport. Large logs can be placed singly or in groups to produce the scale and function required for each application.

Placement of large diameter logs should not be used for creation of dry land. On some Puget Sound project, logs were placed stacked almost two high and very close end to end and secured in a way to allow for filling of gravel landward of the logs and establishment of lawn (Figure 7.2-4). The figure shows logs which were placed further waterward than design with a greater volume of gravel fill used than designed or permitted. Logs should be kept high on the beach and not used for retaining fill for a long time or for the creation of dry land. This also points out the need for permit agencies to follow up and view projects after completion to determine if they were constructed to design.

Figure 7.2-4. Example of inappropriate large wood project on Whidbey Island which was constructed with fixed, stacked logs placed lower and more vertically than designed, here retaining fill gravel and creating usually dry land where beach existed prior.

Logs have sometimes been used as a transition feature from a bulkhead to a more natural shore. In these applications logs have been used to try to reduce the effects of end erosion in the area immediately adjacent to the end of a bulkhead Figure 7.2-3,

frame f). The intent is to provide an enhanced upper beach/backshore area where wave refraction from the end of the bulkhead is most pronounced. These installations can transition from higher to lower elevation and material density moving away from the bulkhead.

Large Wood Characteristics

Large wood size is also an important design element. LWD should be of a size that can remain functional in the application for a substantial period of time. Larger pieces will degrade more slowly than smaller

pieces. Log diameters in the case studies ranged from 19-34 inches, with an average of 23 inches. Generally, the larger the LWD the better. Large logs with intact rootwads are optimal because, if partially buried, the complexity and width of the rootwad helps to anchor the log in place. Logs with branches still attached or logs with bends or other irregularities can be advantageous to use in beach applications. These complex shapes can help catch and retain additional logs. Large wood with rootwads or other complex shapes also function better as traps for fine sediment and organic material (including additional wood). The more complex shape of a root wad can provide refuge from predation for migrating fish that forage upon prey items residing on or around LWD (Cornu. et al. 2007, Toft et al. 2004). Logs can be delivered to a site in a dump truck, on a flatbed, or by barge.

Selecting appropriate species of logs is important, as the wood of many species rots much quicker than several of the native species. Whenever much effort is put into a project, such as if anchors are used, Douglas fir and western redcedar logs should be used to protract longevity in these moist and salty environments. Redcedar is the most rot resistant and should be used when possible. Larger and more complex placements that require high strength logs should use Douglas fir where possible. Deciduous woods will not last well in or near the marine environment, but can be used for restoration or enhancement depending on the application. Treated wood should never be used.

Anchoring

Large wood placement for erosion control on a beach that is actively eroding should be anchored in place. Erosion control projects where wave energy is quite low may not need anchors. If large wood is simply to be reintroduced to the local system for habitat, anchoring is not needed. Anchor systems add cost and complexity of implementation, and can introduce elements that are undesirable. These elements include metal hardware which can become exposed or separated from the original anchors, resulting in aesthetic impacts and safety hazards to people.

A variety of anchoring mechanisms have been employed in large wood placement projects in the Puget Sound Region. Large wood pieces are most often attached to buried anchors for additional stability in high wave events, but the durability of some anchoring methods and hardware, such as stainless steel cable, may be less than expected. Small anchors such as Manta Ray or duckbill anchors have been used, but the long-term reliability of these is not clear (Figure 7.2-4). The surface area of the anchors and resistance to movement need to be considered based on the anticipated forces of breaking waves and the different soil conditions in which anchors area placed. For sandy or sandy fine gravel beach or glacial/non-glacial deposit substrates, small anchors may not be sufficient. Additionally it is not possible to drive auger or earth anchors into some dense soils. Buried deadman anchors such as large concrete blocks placed well below an existing grade offer a reliable and economic approach (Appendix A). Disturbance when installing these larger anchors can be greater than with auger anchors (as pointed out by Gerstel and Brown 2006), but it appears that this disturbance is extremely short in duration as natural change can be substantial in most beach environments. Anchoring techniques or installation methods that did not follow the approved design have led to the loss of anchored logs in several projects. These include the use of rigid posts for anchors in Narrows Park (as discussed in Gerstel and Brown 2006), with erosion resulting in the logs being suspended in the air. Several sites, such as the Northwest Maritime Center in Port Townsend experienced the separation of large logs from anchors,

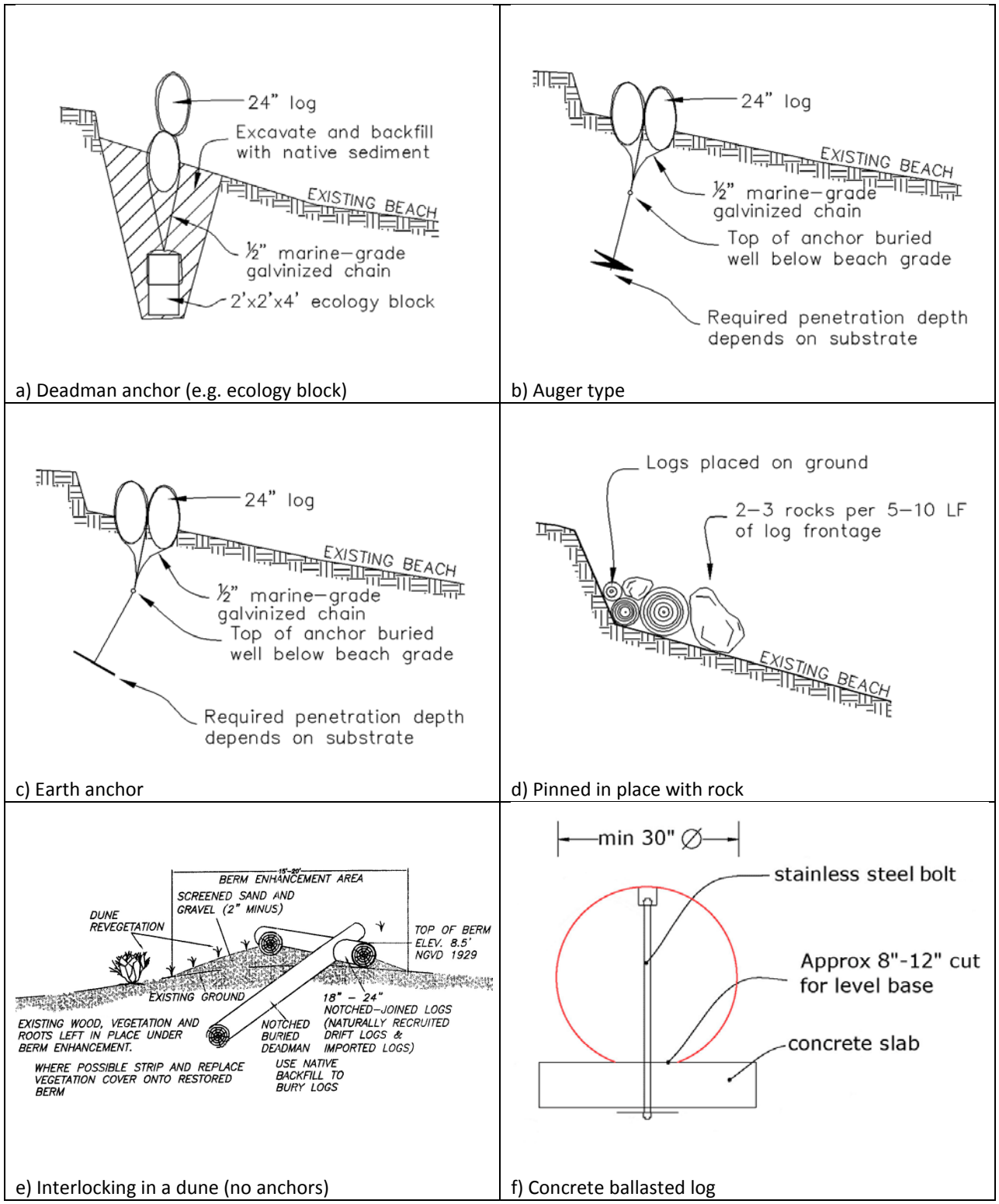

Figure 7.2-5. Example of different anchoring approaches and hardware used in Puget Sound projects. Credits: a–c, f) Coastal Geologic Services; d) Warren Demetrick; e) Four Seasons Engineering.

only to later discover that upon excavation, the contractor had used a much cheaper form of anchor system than the design called for. This resulted in the need to excavate anchors and replace the anchors and some attachments.

Other anchoring designs used in the region have been used where excavation or below gravel penetration was not allowed due to the presence of cultural resources which could not be disturbed. Several approaches to attaching concrete weights to the bottom of logs have been used in these situations (Figure 7.2-4). Project designers should take steps to prevent risk of damage to infrastructure if anchors and cables partially release or create focused, repetitive impacts in the event of partial scour and mobilization. For this reason, logs should never be anchored to the face of a bulkhead or similar structure, or in close proximity, except perhaps in very low energy environments.

Cost

Cost for installation of large wood projects very widely. However large wood installation projects are on the lower end of the range for the various design techniques discussed in this document. The primary considerations for cost of a given project are:

- size and number of imported logs
- difficulty of access for equipment and materials
- if additional measures are included beyond blog placement

Most projects require importing logs to achieve project durability and desired function. This typically involves larger diameter cedar or Douglas fir logs, as discussed in the above sections. In most cases, this size and quality of logs is not available on site. Therefore, logs must be sourced from commercial suppliers and transported to the property. Obviously projects which require fewer logs will be considerably cheaper than projects with dense blog placement.

The ease or difficulty of accessing the site will influence the cost. Sites that can be accessed with a dump truck or long-haul truck approaching relatively close to the beach will typically have higher costs than sites that are difficult to move equipment or logs across. Sites that require barge access are typically the highest and cost, and loss project is of great length and the economy of scale is cost-effective for the mobilizing the barge and tug. This is usually not at all the case for residential applications.

The major factor affecting the cost is the materials and labor required for constructing beach nourishment, registration, or other associated treatments. The mounting costs of beach nourishment settlement purchase and placement is one of the key issues affecting costs, should nourishment be included. Refer to chapters 7.1 and 7.3 for more details on the beach nourishment and vegetation.

Monitoring

Physical monitoring of large wood placement should include topographic mapping/surveying conducted prior to and following wood installation as part of a baseline survey. Subsequent annual monitoring should be carried out in the same season and should aim to measure changes in log locations or elevation, beach/berm topography, sediment composition, position of ordinary high water mark, vegetation assemblages, etc.

For smaller projects, in absence of topographic mapping simple measures from reference locations to logs can be valuable. For example, one could measure the distance from the top of a large wood piece to the beach grade. Photographs taken seasonally with the same perspective and clear reference points

can also be very helpful for observing change across the years. Specifically, monitoring data and photos should be reviewed to document loss of elevation to the storm berm, movement of logs, scour anywhere around the project, overtopping, and/or failure of the anchoring mechanism. Repairs and maintenance should be conducted if any of the aforementioned conditions are observed.

Maintenance

High water events could result in mobilization or loss of unanchored and contrasting conditions from what the large wood placement project was designed to endure. Monitoring large wood projects will identify when maintenance is required and is therefore critical to insuring these projects endure the changing conditions associated with climate change. Maintenance for large wood project can consist of reattaching logs or adding additional beach nourishment sediment. Increased storm frequency, magnitude and occurrence of high water events (associated with *El Nino* conditions as well as storm surges) are all anticipated as a result of climate change.

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Chapter 7. TECHNIQUE 3
RESLOPE-REVEGETATION

Description

Bank or bluff resloping (or recontouring) and revegetating (RE) consists of reducing or lowering the gradient of the slope in order to increase its stability and subsequently planting at the site, preferably with native riparian vegetation. Resloping commonly involves grading the upper portion of a steep slope or bank to “lay back” and “unload” the crest or headscarp, and may involve the full length of the slope, such as at the West Lummi Peninsula site pictured in Figure 7.3-1. The addition of vegetation reduces surface erosion by intercepting precipitation and inhibiting surface water runoff, creating a root network to reduce erodibility of surface soils, and improving soil cohesion throughout the rooting zone as larger plants and trees become established. Vegetation also improves soil drainage through aeration and evapotranspiration. Planting can be applied to an existing bank or one which has been resloped.

Conventionally, slope stabilization by resloping has an engineered structure component such as gabion walls, crib walls, soil nailing assemblies, or other soil-retaining structures. Because the objective of this document is to provide more natural alternatives for bluff stabilization, design concepts that include such structures are not included. Gray and Leiser (1989), MacDonald and Witek (1994), and other reference volumes listed in these guidelines (as well as more technical engineering publications) offer concepts and designs with engineered structures that might be suitable for higher risk and problematic sites.

In some cases, resloping is combined with beach nourishment (Technique 1), placement of LWD (Technique 2), or other treatment options presented in these guidelines specifically to address potentially destabilizing slope toe erosion from waves.

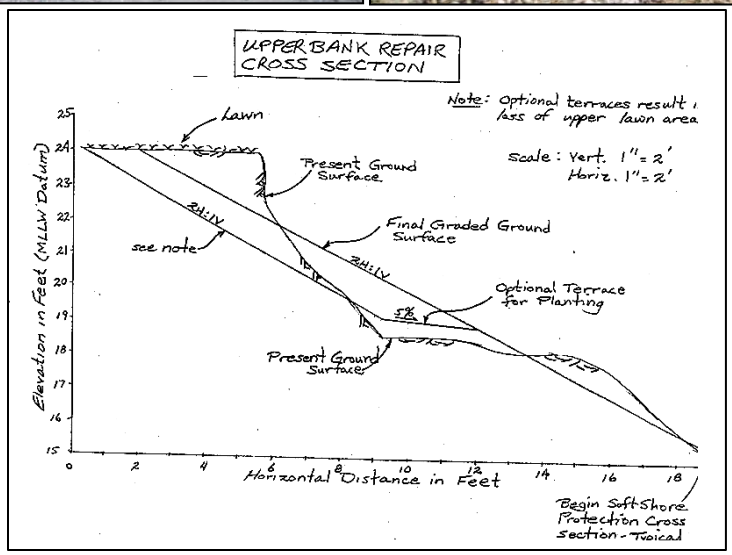

Figure 7.3-1. Example of reslope revegetation project in the Puget Sound. The two photos show before (top left) and after (top right) reslope and revegetation treatment of a medium-high bank site in northern Puget Sound. Treatment was initiated as a result of a soil slump that left the upper portion of the bluff oversteepened and unstable, and the deposited sediment at the toe. The sketched cross-section shows the postslump profile of the slope and the design plan for regrading. In this case, the entire slope was regraded to about 30° and planted with kinnikinnick (Arctostaphylos uva-ursi), dunegrass (Leymus mollis), and several other species.

Application

Changing the gradient of a slope, which generally implies lowering it, is a common technique of slope stabilization, often applied where a steep or near-vertical bluff is either a cause or a consequence of mass wasting. A steep bluff face may reflect the characteristics of the sediment it exposes, such as dense till, or may indicate active and retrogressive erosion of softer material. Lowering or reducing the gradient of a slope makes it more stable by reducing the driving forces inherent in a bluff face that exceeds the angle of repose of the sediment in which it has formed. Resloping is generally applied to the upper portions of a slope, but can also be successfully applied to the entire slope (Fig. 7.3-1). Figure 7.3-2 shows another example of a successful resloping project (not included as a case study in this document).

Figure 7.3-2. The three photos of a site on Eld Inlet, South Puget Sound, where coarse unconsolidated sediment overlies denser sand, silt, and gravel. The top photo shows the differential rate of erosion between the two geologic units prior to treatment, the effects of groundwater perching on the lower unit, and the greater stability of the lower unit except for some surface rilling on the steep face. In the lower right photo, a natural-fiber geotextile is visible fastened to the slope to reduce the potential for surface soil erosion until vegetation is established. Additional challenges at the site included burrowing mountain beavers in the sloughed sediment at the base of the bluff, springs discharging along burrows, and mortality and poor "pruning" caused by the beavers. According to the property owners, slope crest retreat prior to the planting appeared subsequent to increased development upslope and an associated increase in stormwater runoff. In this case, toe erosion is not an issue (bottom two photos by Ben Alexander).

In developing the appropriate design for resloping, it is imperative to first identify the cause or causes of the instability before designing any slope modification. Upland processes involving surface or stormwater runoff are often the cause of erosion and slope failure. Inappropriate management of surface water or excess recharge of groundwater (such as recharging perched aquifers via poorly placed retention, irrigation, or infiltration systems) can cause slope failure when pore-water pressures build within the slope. Without proper site management, upland features such as impervious surfaces, such as roofs, driveways, patios, as well as dry wells, gutter down spouts, etc., can concentrate water to vulnerable and sensitive slopes.

The best solution for a given drainage issue may be the construction of one or a combination of drainage features as simple as a lined stream channel, or as complex as curtain drains, catch basins, open and closed ditches, French drains, dry wells (where appropriate), etc. Any of these must be designed and located with care, as each may be the best approach at one site and the worst at another. More information about the management of runoff can be found in Chapter 6, Passive Techniques, and in the references cited in that chapter.

Changing the configuration of a coastal bluff slope, with or without additional engineered structures, has impacts and possibly unintended consequences to adjacent properties or nearby shores. However, it can be a reasonable slope-stabilizing treatment in cases where cost or permitting restrictions limit mitigation options. As always, an assessment by a qualified professional should first determine whether modifications in upland drainage management could address the problems, or whether additional earthmoving action is needed. Subsequent vegetation of the regraded portions of the slope, and possibly other remaining portions of the slope, should be done when planting conditions (seasonal precipitation, plant availability, soil moisture content, access, and other relevant site conditions) allow.

There is no standard process for property owners to follow in the case of an emergency situation with catastrophic coastal bluff changes. In this case, property owners are encouraged to contact state and local officials immediately to arrange consultation.

At high bank sites, recent landslides leaving steep unstable slopes or cliffs can present a significant hazard to residents and risks to structures. Reducing the gradient of the headscarp may be a viable emergency action. However, landowners should be made aware that the remaining steep lower portions of the bluff may still pose a hazard.

Effects

Two reslope and revegetation projects (West Lummi Peninsula and East Drayton Harbor) were evaluated for this study and are presented as case studies in Appendix A. Each had a slightly different design focus, which introduced some challenges in evaluating project design appropriateness and performance. A third project (Weyer Point), evaluated as a bulkhead-removal treatment, did involve a short section of resloping and revegetating where a vertical concrete bulkhead was removed, but was not rated on that aspect of the treatment. Evaluated benefits and impacts for the two reslope-revegetation case studies were based on their intended mitigation of slope instability and to a lesser degree, successful establishment of native vegetation, rather than being rated on erosion control. Both case study projects were located on bluffs of low to medium height where establishing connectivity of sediment source to beach was not an objective of the project.

The West Lummi Peninsula site (Fig. 7.3-1; Appendix A) involved a designed reduction of the entire bluff slope gradient with subsequent vegetation planting. Because the objective of the project design was to mitigate the effects of a recent earth slump and resultant retrogression of the slope crest, there was a consequent reduction in the potential for sediment input into the beach environment. Continued erosion of the slope toe, with or without resloping, would likely reactivate such slumping and retrogression. The addition of plantings, coarse gravel, and a large shore-parallel log greatly reduced that likelihood.

The East Drayton Harbor case study site (Appendix A) involved primarily a vegetation management design with no slope regrade. To date this has had little effect on landward erosion, and undercutting of

the slope with accompanied slumping of surface soils continues to provide sediment input to the beach environment.

Vegetation can be a potential contributor of LWD and detritus to the beach environment if allowed to topple and move naturally downslope and onto the beach. In both projects surveyed, there appeared to be only limited large wood available or larger trees planted as part of the treatment. The formation of a functioning marine riparian zone therefore seems unlikely in the short to medium term and producing large wood did not appear to be an objective of these projects. Backshore vegetation was enhanced where treatment provided for maintaining the appropriate beach elevation during prevailing waves.

Because a general objective of resloping is to mitigate the effects of slope movement and resultant retrogression of the slope crest, there is a consequent reduction in the potential for sediment input into the beach environment. Depending on the overall project objectives, this may either be a negative or a positive consequence of treatment.

Vegetation, particularly shrubs and trees, increases the strength of soil and sediment through apparent root cohesion, soil moisture depletion, and precipitation interception. Along with these benefits to soil and slope stability, vegetation contributes to water quality; provides wildlife habitat, habitat structure, and large wood; creates shade; delivers nutrients to the beach at low tide and to marine waters at high-tide; produces fish prey; creates microclimates; contributes to human health and safety; and enhances aesthetics (Brennan and Culverwell 2004, Brenna 2007).

Resloping is a viable technique for slope stabilization where enhancing or preserving sediment input to the shore environment is not a short- to medium-term objective for the site, and where structure setback is adequate to allow for the necessary and appropriate relocation of the slope crest without creating additional risks to structures.

Design

Slope Grading

Slopes can be graded to a variety of different configurations that might be uniform or compound (i.e., terraces or steps). The selected design configuration may be driven by aesthetics or shoreline access infrastructure, but should consider controlling geologic conditions such as stratigraphy, variable soil/sediment strength properties, and groundwater conditions. Orientation of geologic bedding has an effect on groundwater movement, as does the permeability and porosity of different substrates, collectively creating a predisposition for certain units or layers to be weaker than others.

More competent geologic units are those with greater angles of internal friction and cohesion, particularly when made up of well-graded (or poorly sorted) sediment that includes a component of silt and clay, and that was likely compacted through glacial loading. More competent sediments—lodgment till is an example—naturally hold steeper exposed faces and can be graded to steeper slope angles than weaker units of poorly graded (well-sorted) and less-consolidated sediment. Clean sand would be an example of the latter (Figure 1-7).

Where less competent sediments overlie consolidated sediments (for example recessional outwash sand overlying advance outwash deposits or till), a stepped or “compound” grading approach can be applied, with the upper unit being graded to a shallower slope angle than the lower (Figure 7.3-3). This reduces

the footprint of the project while improving stability and reducing the potential for surface erosion. It can also provide more favorable and stable conditions for plants to be established.

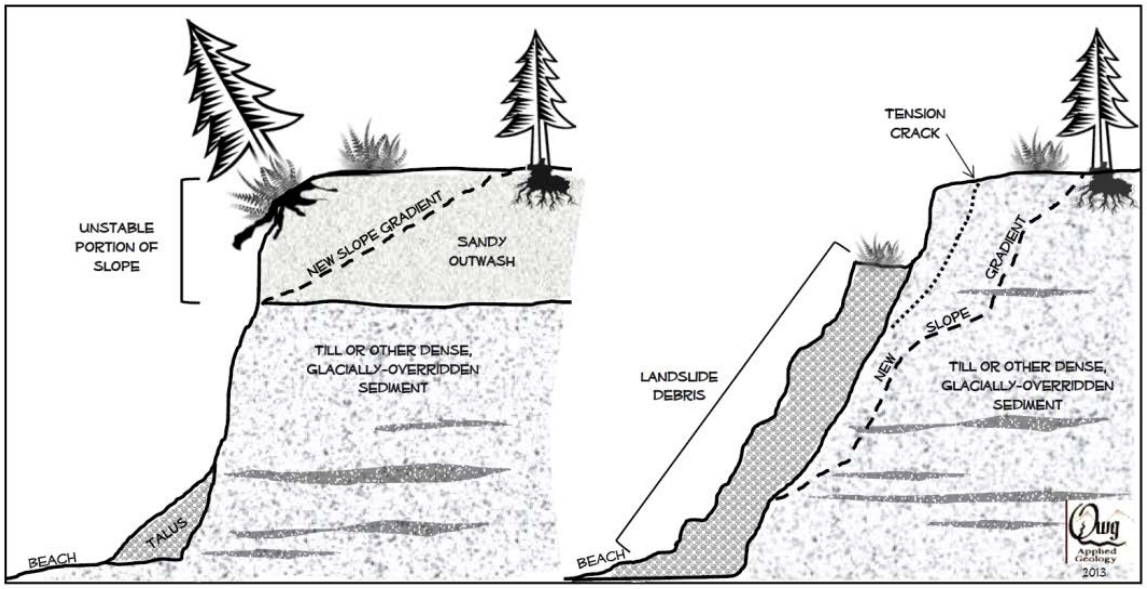

Figure 7.3-3. Two different possible slope configurations in different types of geologic sediments, showing resloping (left) and benching (right). Long dashed line in each drawing shows slope gradient created through project treatment.

Although the created slope angle at which soil or sediment will be stable (angle of repose) is important in design considerations, most project managers will admit that resloping is carried out somewhat subjectively or intuitively. More often than not, slopes are regraded without the benefit or application of sediment gradation and strength data, and therefore not designed quantitatively for a particular sediment type, but rather, driven by site conditions such as residential structure setback and equipment operating room, earthmoving and equipment costs, equipment access, safety concerns, surface treatment and planting plans, and other project logistics.

Clearly there are challenges in determining the appropriate angle to which a slope should be regraded. A denser substrate might maintain a stable steeper gradient and thereby limit the area being disturbed; however, topsoil, mulch, and plantings are harder to stabilize and establish on steeper slopes. Conversely, stabilizing less-consolidated sediments requires gentler slopes. These result in more site area being disturbed, but provide more stability for topsoil, mulch, and plantings. For this reason, project objectives may be achieved by necessarily synchronizing and compromising on various project aspects and criteria, and not necessarily by designing exactly to engineering specifications for material properties.

As an example, a slope in clean sand would need to be graded to less than 33° to be stable unless vegetation was established quickly and for the long term. Similarly, till or other dense, generally fine-grained sediment might be stable at near vertical slope angles as long as surface erosion was not a concern. In all cases, the suitability of the geologic material in supporting healthy plant growth must factor into the design.

In excavating the upper limits of a slope or scarp, the transition to adjacent unmodified slopes should be rounded and smoothed. This avoids creating a slope configuration that could propagate instability by leaving an oversteepened face, or concentrating surface- or groundwater.

Vegetation

Because grading work generally leaves exposed sediment that is subject to erosion, subsequent planting is an important component of this stabilizing treatment. Vegetation improves soil cohesion, improves soil drainage through aeration and evapotranspiration, and reduces surface erosion through precipitation interception and inhibition of surface water runoff. The planting configuration should be based on the slope gradient, nature of the sediment (or substrate), type of erosion being addressed, and plant species being installed.

Numerous techniques and plant species exist for vegetation installations, including but not limited to contour wattling, brush layering, fascines, live willow staking, brush matting, direct seeding, hydroseeding, cuttings, and transplants. The propagation and planting technique used should depend on site conditions, plant availability, season planted, and suitability of the plant for the site.

The following provides an example of one planting technique, installation of fascines:

> *Dig a shallow trench that follows the contour at the toe of the slope. The trench should be deep enough to bury ¾ of the fascine below the soil surface. When digging the trench, place soil on the upslope. Any soil that is not replaced into the trench during installation will end up there through the course of gravity and surface runoff. If more than a single fascine is needed to run the length of the trench, overlap the fascines enough to eliminate gaps. Use stakes to anchor the fascines at intervals of 3-4 feet. Use standard, untreated wooden stakes or live stakes, 2-3 feet in length, and pound the stakes into the soil immediately down slope and angled slightly away from the fascine. For extra stability, pound tapered wood stakes through the middle of the fascine at a 45° angle to the slope, staggered between the down slope stakes. Finally, shovel the soil back over the top of the fascine and into the trench, and stomp it down well to work the soil through the fascine. Following backfilling, only the very top (10-15%) of the fascine should be visible.* (From http://www.soundnativeplants.com/sites/default/files/uploads/PDF/Fascine_installation.pdf)

In the case of steep slopes, shallow-rooted plants such as grasses may be inappropriate (Figure 7.3-4), and deeper-rooting species might require special techniques to stabilize the soils until root systems can expand and enhance soil stability. It should be mentioned that root systems do little to mitigate failures occurring below the rooting depth of plants; however, vegetation can mitigate the potential for deep-seated failures through precipitation interception and evapotranspiration processes (MacDonald and Witek 1994; Myers et. al. 1995).

Figure 7.3-4. The slope shown above in unconsolidated sediments was too steep and the roots of the grasses planted are too shallow to hold up without some combination of deep-rooted vegetation, contour brush layering, stepped slope contouring, and temporary geotextile or other engineered structure (preferably including vegetation).

Because surface erosion is a common cause of bluff instability, plants can be installed in a variety of ways to repair erosion gullies, small debris flow headwalls, and other erosion features (Figure 7.3-5). As always, the cause of the erosion should be determined first, and addressed directly if possible.

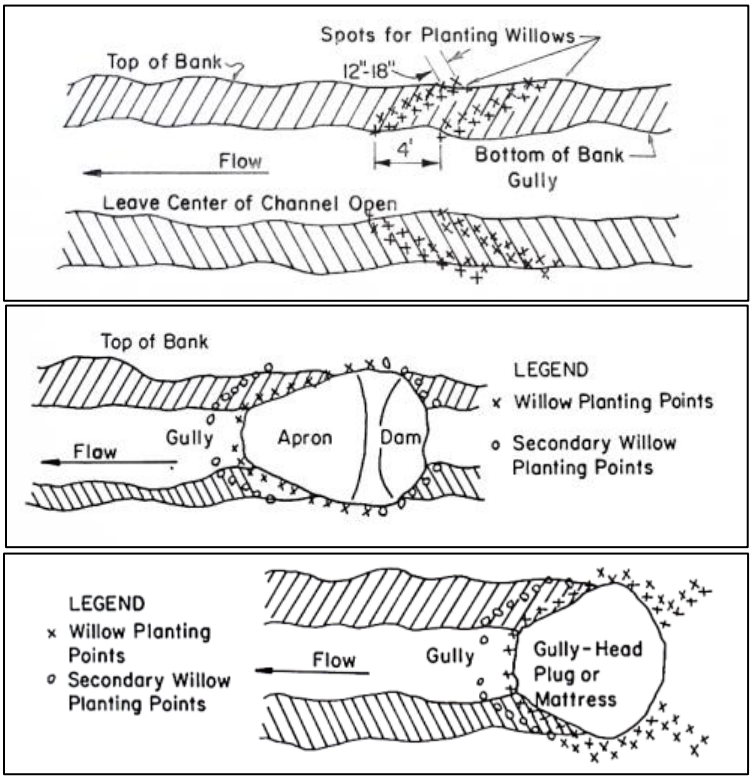

Figure 7.3-5. Some examples of using planting arrangements to mitigate lateral and headward surface erosion features. Source: Gray and Leiser (1989).

For stabilizing dune or beach sands such as those accumulating at the base of a sloughing bluff or backshore area, one of the most effective native plants is American dunegrass, also called dune wildrye (*Leymus mollis)*, which is discussed further in Technique 1, *Beach Nourishment*. It permeates sand easily and spreads vigorously via roots and rhizomes. American dunegrass is the native species that grows in backshore areas in the range of salt spray and occasional salt water inundation. Other similar grasses such as American beachgrass (*Ammophila breviligulata*; native to the American Atlantic coast), or European beachgrass or marram grass (*Ammophila arenaria*) have proven too aggressive and are now classified as exotic invasive species. For this reason, these should never be used.

In slope and upland areas, to bridge the time between establishing early low-growing plants and larger trees, smaller native trees such as alder, shore pine, vine maple, service berry, cascara, and hazelnut are good choices as they establish relatively quickly on disturbed sites. For longer-term stabilization objectives, Western redcedar, Douglas-fir, and Pacific madrone provide shade, moisture retention, evapotranspiration, and once established, a well-developed root system that contributes to soil cohesion.

Many other native plant species serve well to anchor soils against wind and water erosion, retain moisture or evapotranspire, produce organic detritus, reduce rainwater impact, etc. Table 7.3-1 provides a summary of plant applications and some recommended species.

For additional plant lists, appropriate site conditions, potential benefits, and long-term management, also see Menashe (1993, 2004), Guttman (in press), and on-line fact sheets posted by Sound Native Plants (http://soundnativeplants.com/information-sheets).

Because vegetation alone cannot be expected to mitigate all slope stability concerns, it is critical to plan for appropriate setback of any residential structures, as well as to thoughtfully consider drainage and surface- and groundwater management for a site. These considerations will also need to be factored into the long-term maintenance costs.

Table 7.3-1. Biotechnical slope protection—application and performance (modified from McDonald and Witek 1994; Myers 1993).

Type of application	Method of application	Appropriate use	Role of vegetation/ stabilization mechanism	Some sample recommended species
Conventional plantings including those for long-term contributions to soil cohesion and eventual large wood for beaches	Grass seeding Transplants	Control of surficial rainfall and wind erosion Minimization of frost effects Slow bluff retreat rate	Binds and restrains soil particles Filters soil from runoff Intercepts raindrops Maintains infiltration Changes thermal character of ground surface	Red alder willow Douglas-fir Northern black cottonwood Red osier dogwood Twinberry Ninebark Cascara Salal Salmonberry Snowberry Douglas spirea Vine maple Red-flowering currant

Type of application	Method of application	Appropriate use	Role of vegetation/ stabilization mechanism	Some sample recommended species
Woody plants used as surface-soil reinforcement and as barriers to soil movement	Live staking Contour-wattling Brush layering Reed trench terracing Brush mats	Control of surficial rainfall erosion (rilling and gullying) Control of shallow (translational) mass movement	Same as above, but also reinforces soil and resists downslope movement of earth masses by buttressing and soil arching	Pacific and other willows Red osier dogwood Vine maple Ninebark Cascara Salmonberry Snowberry Salal Douglas spirea Red-flowering currant Twinberry
Woody plants grown in interstices of low, porous structures or benches of tiered structures	Vegetated revetments (riprap, grids gabions, blocks) Vegetated retaining walls (open cribs, gabions, stepped-back walls, welded wire walls)	Control of shallow mass movement and resistance to low-moderate earth forces Improvement of appearance and performance of structures	Reinforces and indurates soil or fill behind structure into monolithic mass	Pacific and other willows Red osier dogwood Vine maple Ninebark Cascara Salmonberry Snowberry Salal Douglas spirea Red-flowering currant Twinberry

Materials Required

Resloping implies removal from or relocation at a site of materials such as native soils, sediment, or unwanted fill. A different suite of materials may be required to be added and include topsoil, mulch, and plants. If the slope gradient allows, topsoil (4-6 in.) and then mulch (10-12 in.) are usually applied to the regraded area.

If possible, topsoil should be scraped off and stockpiled before resloping, then reapplied after. Plants may be acquired from the site, neighboring sites, or commercial nurseries specializing in native plants. Irrigation systems and a water source may be required for the first year, but project design should limit the need after that. Geotextiles, preferably of a natural biodegradable type, may be needed to get plants established on less hospitable sites.

If deemed necessary during initial site evaluation, erosion of the slope toe may require a component of treatment presented in other sections of these guidelines. This may include rock or large wood placement, or beach nourishment.

Soil Erosion Control Fabric

To ensure that plants become well established, it is important to keep topsoil from being eroded during the initial period following slope regrading. Immediately following grading, it is common to incorporate some type of geotextile as a soil stabilizer until roots take hold. A geotextile is any permeable textile fabric used with soil, sediment, or rock to increase stability and decrease erosion. It is designed to allow

water to flow through it, either freely or at some slowed rate, while holding substrate in place. Geotextiles can be natural or synthetic; woven, knitted, or nonwoven (Figure 7.3-6). Different site conditions and performance criteria require different fabric composition and construction. Woven geotextile (similar to burlap), is particularly suitable where high soil-strength properties are needed, but where filtration requirements are less critical.

Figure 7.3-6. Examples of natural (left) and synthetic (right) geotextiles. Additional geotextile fabrics incorporate a combination of natural and synthetic fibers. Generally, natural-fiber fabrics deteriorate more rapidly than synthetic, and may be an appropriate choice where soil instability is a short-term issue and additional stabilization is only needed until plants are established. (Source: Wikipedia public domain; http://upload.wikimedia.org/wikipedia/commons/c/c8/Geotextile-GSI.JPG)

Depending on the objectives of the project, a geotextile may be selected for its properties to:

1. **Separate** differing layers of soil to maintain design thickness.
2. **Filter**, allowing water to move through the soil while retaining upstream soil particles. For example, this may prevent soils from migrating into drainage aggregate or pipes.
3. **Drain** less-permeable soils by creating a lining on or through which to carry water.
4. **Reinforce** soils by producing a composite system that improves strength and deformation properties over those of unreinforced soil.
5. **Control erosion** by intercepting rainfall impact and surface water runoff.

Depending on the intended function of the fabric and nature of the soil and sediment, a geotextile may not be necessary, or a temporary natural fabric might be useful for the very fact that it will degrade in the first few years, contributing natural mulch to the soil. Some examples of natural fibers used in geotextiles include jute, coconut, flax, and hemp.

For more challenging sites where severe erosion is likely, a wide variety of longer-lived synthetic or blend fabrics are available and may be necessary. Synthetic geotextiles are petrochemical-based, and may persist long after their intended usefulness. Any application of geotextiles consisting of synthetic fibers should consider the fact that they cause environmental pollution in their manufacture and use, and may ultimately end up as garbage on the slope and beach.

Hydroseeding can be used independent of or in combination with geotextiles to stabilize surface soils and prevent or control erosion.

Timing Considerations

Grading should be carried out to minimize the length of time soil is exposed and should be staged to allow for planting shortly after. In western Washington, grading is usually carried out during the drier summer and early fall months to avoid runoff and excess sedimentation to nearby streams or coastal waters. Planting can then take place in winter to take advantage of subsequent rainfall that reduces the need for irrigation. South-facing slopes may need irrigation in summer regardless for the first year or two.

Risk and Uncertainty

An assessment of the risk to infrastructure and public safety should be a part of any site being evaluated for resloping. Both long- and short-term considerations should evaluate at the very least, appropriate slope angles, slope height, disposal of excavated materials, site use, and expected vegetation growth and position (particularly for large trees).

As with any project, there are uncertainties in the long-term success of the project that may result from unclear objectives, poor design, unintended site use, inadequate or poor-quality project materials (plants, mulch, etc.), changing site conditions, off-site conditions transferred to the site (surface and groundwater), or external forces such as large storms, waves, and tides. Continued erosion of the slope toe, with or without the resloping, has the potential to reactivate landsliding and bluff retrogression, and runoff from upland areas can reactivate or introduce rilling, erosion, and landsliding.

Cost

Resloping and vegetating is generally a very cost-effective means of bluff stabilization once it is determined to be appropriate for a site. Ideally, planted vegetation will mimic adjacent slopes and possibly have the added benefit of natural seeding and spreading. Regrading a slope generally requires the use of large machinery, but only for the initial work and for a relatively short period of time. Eliminating the need for an engineered structure such as a retaining wall also provides cost and time savings.

Costs associated with resloping and vegetating can vary greatly. The primary controlling factor is the length of slope being treated, with the largest portion of the project cost likely being the earthmoving. It is therefore important to get estimates of cost per lineal foot or per unit area to develop the earthmoving portion of the budget. This part of the budget should also consider the volume of earth to be moved, and whether it will be reused on the site or whether and how far it will need to be removed from the site. Mobilizing earthmoving equipment to and from the site can constitute a large portion of the cost and should be limited to one round trip; therefore staging the project carefully is very important.

Other costs to the project include mulch, plants, and planting. These are difficult to summarize as they depend on site conditions, site access, nursery availability, and who does the planting. Projects might be able to enlist assistance and even grant funding from local nonprofit groups or university extension offices. Because of the great variability in cost for the various equipment and materials, a well-developed design is critical in informing necessary quantities for the various project components.

If topsoil is not available on-site (e.g., stockpiled), it may also need to be purchased, particularly for poor soils with little to no organic material.

Drainage management structures can increase project cost significantly, and appropriate surface- and groundwater management is critical to the success of any project. Addressing drainage issues early in the assessment and design process will save money in the long run. Drainage management may include anything from constructing appropriate slope angles and planting appropriate vegetation to complex collection, storage, and conveyance systems.

The cost of ongoing maintenance, such as ensuring vegetation health described below, also needs to be factored into project costs.

Monitoring

Monitoring of reslope–revegetation projects can be used to evaluate site conditions and processes before and after a treatment is installed, as well as provide a measure of the success of the treatment. Neither is possible without clearly documented project objectives and final construction documentation, known as "as-builts." Monitoring should be built into the initial concepts of a project so that project performance can be measured and lessons learned can be applied to subsequent projects. On the site scale, monitoring results determine whether project objectives are being met, and can guide any necessary project maintenance. On a broader scale, monitoring contributes to the success of overall restoration goals, as well as improving the cost-effectiveness of similar projects in the future.

Measuring the success of a reslope–revegetation project can be a matter of perspective, necessarily considering the objectives for the site and project. For instance, mitigation of landward erosion would be measurable as one objective. If sediment input is a desired outcome of a restoration project involving resloping, then the results of such measurements would have a different interpretation and the resloping might be considered a negative impact. As always, clear project design objectives should be discussed, documented, and monitored with the appropriate questions in mind.

For a project involving reslope–revegetation, some of the most important project components to monitor should include, but not be limited to, the following:

- stability of surface soils
- stability of underlying sediment
- performance of surface- and groundwater management features
- condition of slope toe (existence or/and extent of erosion)
- survival, health, and propagation of plantings
- required maintenance of slope substrate and/or plantings
- continued meeting of project objectives

Maintenance

Management of vegetation often requires ongoing control of invasive plants and possible replanting of some native species found to be unsuitable for a particular site (soil moisture, aspect, etc.). Irrigation may need to be a component of the first year or two of a project to get plants established. The need for irrigation depends on aspect, soil moisture, availability of site-adjacent plants, and practicability of regular maintenance.

As a potential contributor of LWD and detritus, vegetation can be successful and beneficial if allowed to topple and slide to the beach through natural processes. Trees can be managed as they grow to allow for views (Menashe 1993), and a professional arborist should be consulted to achieve the view

objectives while preserving the health of the tree(s). Project objectives can guide vegetation planting plans to provide the site-appropriate combination of improving slope stability, establishing healthy native plants, and maintaining views. Deviation from the plan through changes in long-term management strategies might compromise any or all of the original project objectives.

Because vegetation alone cannot be expected to mitigate all slope instability, it is critical to plan for appropriate setback of any structures as well as to thoughtfully consider drainage and surface- and groundwater management for the sites. These will need to be factored into the long-term maintenance costs of sites evaluated for any reslope–revegetation projects.

Any sign of rill or gully erosion should be immediately investigated and repaired as needed (Fig. 7.3-5).

Browsing by deer can also damage and kill new vegetation. Excluding deer from an area requires fencing at least 6 ft high. Other methods that have had mixed success include applying liquid deterrents (such as coyote urine).

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Chapter 7. TECHNIQUE 4
BULKHEAD REMOVAL

Description

Landowners install bulkheads and other forms of shore armor to stop wave attack and erosion, or to reclaim tidelands for upland uses. Armor has been installed in many locations throughout the region where erosion is not a real threat. For example armor exists along many shores with insubstantial erosion in which the bulkhead is more of a landscaping feature. Another example or unnecessary armor includes bulkheads used to curb erosion in locations where the natural process is not a pending threat to infrastructure. There are many examples of armored waterfront parcels in which no roads or structures occur. As awareness expands on the impacts that shore armor has on nearshore ecosystems and stricter regulations are put in place to prevent new armor on shores where it is largely unnecessary, bulkhead removal projects are also becoming more popular.

There are several examples of armor removal projects in the region, with a large number of projects recently completed or underway. Complete bulkhead removal can restore nearshore processes and habitats by returning the beach and backshore areas to natural or predevelopment conditions. Existing unnecessary armor is also increasingly being relocated (landward) or reduced in scale (length), to lessen the impact and enhance or restore coastal processes. Either complete or partial removal can ameliorate degraded nearshore conditions associated with the armor such as sediment input from feeder bluffs, littoral (longshore) drift, the exchange of nutrients and other organic material, and to restore intertidal and backshore habitat areas. Armor removal can also enhance recreational values by improving beach access, increase beach area and aesthetics, and lowering the slope of the beach.

The most common types of bulkheads removed include rock revetments, rockery walls, and vertical bulkheads constructed with concrete, large rocks, treated wood, or wood piles. Examples of these are shown in cross section, some of which have fill placed landward of the bulkhead which may need to be removed (Figure 7.4-1). In many cases, bulkhead removal is applied in combination with other techniques such as backshore and marine riparian vegetation plantings (Reslope/Revegetation), beach nourishment, or large wood placement.

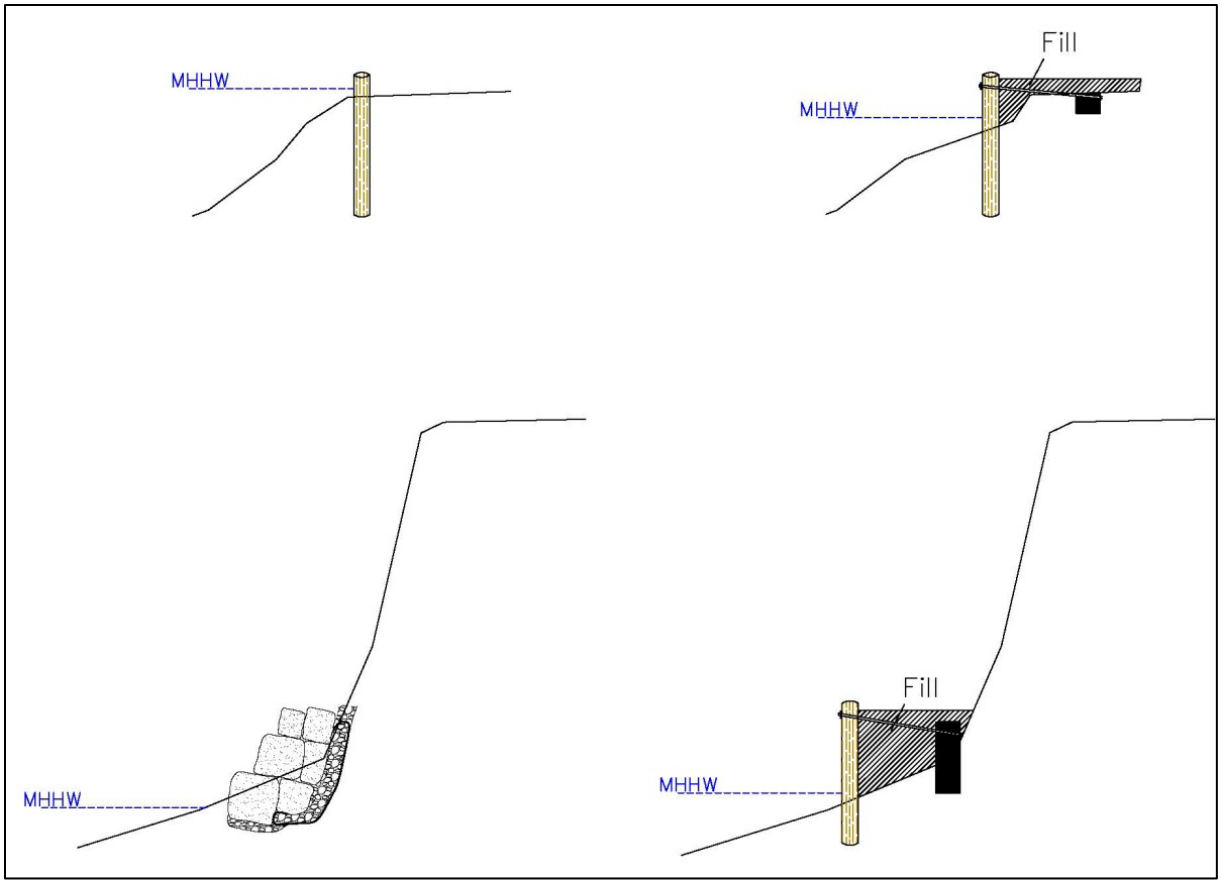

Figure 7.4-1. Typical barrier beach and bluff bulkhead cross sections with and without fill. Top left: Typical barrier beach site with no or minimal fill landward of vegetated (soldier) pile bulkhead. Top Right: Typical barrier beach site with fill placed landward of vertical bulkhead, along with tie-backs and deadman anchors. Bulkhead at MHHW. Bottom Left: Typical bluff site with no or minimal fill landward of (rockery wall) bulkhead, which is above MHHW. Bottom Right: Typical bluff site with fill placed landward of vertical bulkhead, which extends below MHHW.

Application

Bulkhead removal or modification is appropriate to consider at most beach and bluff shores where a bulkhead is present, though it may not be feasible at every location. Bulkhead removal can be deemed feasible if the existing structure is unlikely to be threatened by bluff/bank recession now or in the future, or if a (potentially) threatened structure is deemed unsafe or is being relocated landward out of harm's way. If the site has low to moderate erosion rates and a reasonable setback distance, removal may be feasible. If no structure or road is present landward of the armor then it is likely feasible. Additional data from the site assessment (discussed in Chapter 3) should be evaluated to further explore feasibility.

Bulkhead removal and modification are conducted to meet a variety of objectives although in most cases the project's objective is to restore or enhance beach and backshore areas to approximate natural or predevelopment conditions for recreational and other uses. A coastal processes and coastal hazard assessment should be conducted before considering bulkhead removal; if removal would not result in considerable risk to infrastructure on the property, then it is reasonable to move on to the design stage. As discussed below, complete bulkhead removal is not feasible at all sites. Bulkhead removal in Puget Sound has become more common on public lands, including projects located on land owned by cities,

counties, Washington State Parks, and the Washington Department of Natural Resources, as well as Tribal lands.

Bulkhead removal projects can involve a single property or a group of adjacent properties. Even when a bulkhead removal site is focused on a single property, it is important to inform adjacent property owners and assure that additional erosion will not place their structures at risk. Removing armor from two or more adjacent bulkheads has occurred in recent years, where landowner willingness was acquired from all of participants across a reach of shoreline. Such was the case at the North Orcas bulkhead removal and beach nourishment site in Appendix A.

Bulkhead modification may include changing the location or dimensions of a structure, with the goal of reducing its size and impacts (Clancy et al. 2009). This often consists of shortening a bulkhead or reconstructing a reduced length structure in a more landward position. Modifying existing armoring structures may be appropriate where circumstances preclude complete removal, such as where the risks to upland development from natural erosion are unacceptable. Complete bulkhead removal, however, is typically much less expensive than bulkhead modification.

Engineered erosion control structures placed on marine shores are subjected to wave attack, log battering, end-scour, undermining, and material deterioration. The structures are the strongest the day that construction is completed and weaken from that day forward; with typical functional lifespans of 20 to 50 years (depending on the material and quality of construction and design). Examples of highly degraded bulkheads are shown in Figure 7.4-2. Considerable lengths of shoreline armor were installed prior to the shoreline management act and are likely reaching the end of their functional lifespan. Between January of 2005 and December of 2007, 389 existing bulkheads were replaced on Puget Sound shorelines primarily due to structure deterioration (Carman et al. 2010).

Figure 7.4-2. Degraded bulkheads deteriorating in place.

Property owners may be more willing to consider relocation or removal alternatives when they are contemplating replacement of an existing structure. For many unstable bluffs, it is often more cost effective over the long run to relocate houses (or other improvements) landward than to permit, build, mitigate, and maintain a bulkhead in a chronically eroding location. This is due to the repeated expenses of repairing structures and surrounding areas following damage, including the many design, impact avoidance, and permit requirements, in addition to mobilization and construction. Simply allowing a

bulkhead that is constructed of natural materials such as on treated wood to deteriorate in place can be a viable option to achieve bulkhead removal overtime at virtually no cost.

Effects

The primary intent of bulkhead removal is to restore natural coastal processes and habitats. Bulkheads have varying degrees of impact generally related to disruption and alteration of shoreline processes (Shipman et al. 2010) which removal aims to reverse. The benefit area ranges from the footprint of the armor at the site to extensive reaches of shore off-site. The greatest spatial extent of benefit resulting from a bulkhead removal project would be the extent of down-drift shore within the drift cell (which would include the down-drift shore from both adjacent cells if the project occurred within a divergence zone), or the full extent of the shoreform, if the bulkhead was removed from a pocket beach. Direct restoration is achieved by recovering buried nearshore habitat directly beneath bulkheads and other types of armoring. Physical processes restored by bulkhead removal include sediment input (feeder bluff function); littoral drift; sediment deposition at down-drift shoreforms such as spits; and large woody debris (LWD) input, which can enhance the stability of down-drift shoreforms (Figure 7.4-3). Restoration of upland and alongshore connectivity of sediment, hydraulics, and vegetative successional processes can facilitate animal movement by helping to connect habitats, which include the marine riparian zone (Clancy et al. 2009). Removal or modification of bulkheads that infringe on the intertidal zone can also improve the connectivity of juvenile salmonid migratory habitats.

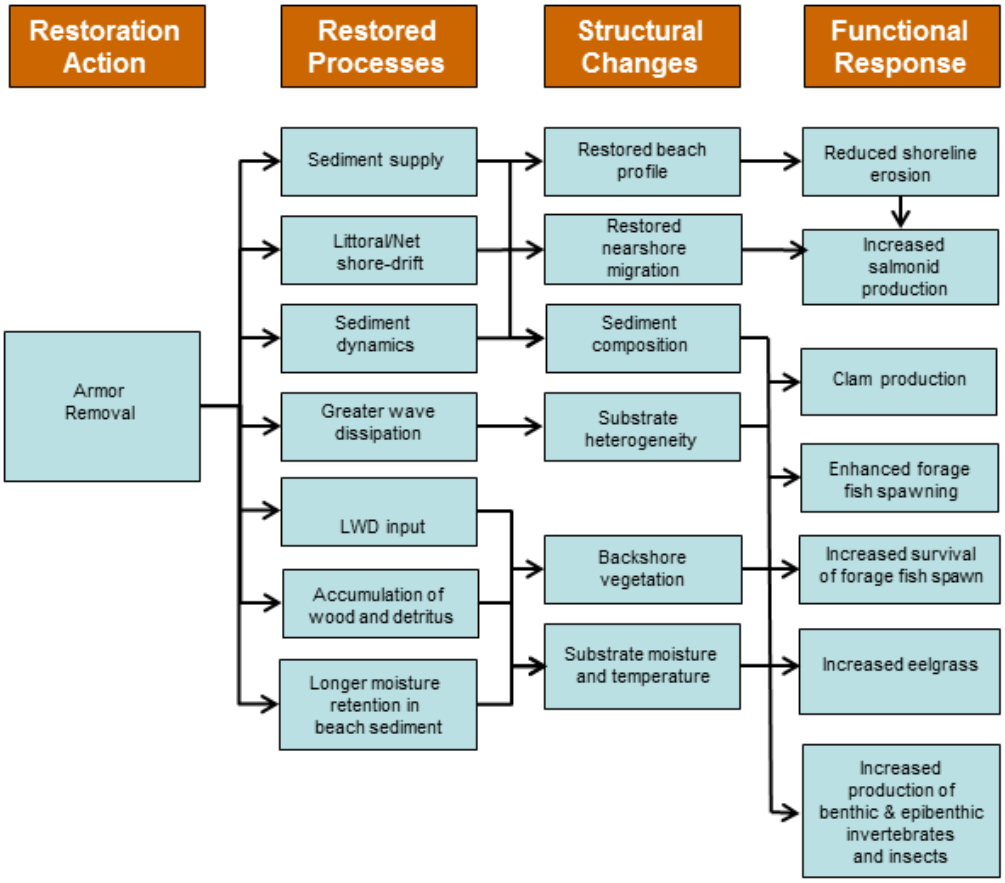

Figure 7.4-3. Conceptual model from the Management Measures Technical Report (Clancy et al. 2009).

Bulkheads alter or disrupt wave energy, which can affect coastal processes and habitat in several different ways. The physical presence of the structure along feeder bluffs can eliminate recruitment of bluff and upland sediment that would have otherwise "fed" the beach through landslides and erosion. Disrupted sediment supply affects beach profiles and substrate characteristics on site as well as down-drift. Bulkheads on all Puget Sound shores, particularly vertical-face bulkheads, can result in increased reflected wave energy, which can lead to coarsening of beach sediment (Kraus 1988, MacDonald et al. 1994) and increased entrainment (causing turbidity) and transport of littoral sediment (Miles et al. 2001). Impacts are greatest when sited where interactions with wave and tidal forces are greatest. Bulkheads can also cause lowering or vertical erosion of the beach profile waterward of the structure (creating a scour trough), end scour along shores adjacent to the structure, and reduced beach width. Erosion at the base of a bulkhead can undermine the bulkhead footing, and cause part or all of the structure to topple. Each of these impacts will likely be exacerbated by changing conditions resulting from climate change and sea level rise. Bulkhead removal is intended to reverse these impacts.

The common benefit seen among all bulkhead-removal case study sites (see Appendix A) was some degree of augmented sediment input. Beach nourishment was not a component of any of the four bulkhead-removal projects; therefore the sediment composition was dependent solely on local sources. The beach sediment at all of these sites matched adjacent reference sites, which assumes that beach (substrate) conditions were successfully restored. The recent Seahurst Park south bulkhead and fill removal project (not covered in Appendix A work) had restoration of feeder bluff connectivity to the beach as one of its primary restoration goals (Hummel et al. 2005), a goal shared by PSNERP for a number of potential projects.

In many Puget Sound locations, diverse landforms with a variety of microhabitats historically occurred close together. The diversity of the se landforms and the microhabitats found therein are in decline due to extensive modifications which tend to simplify and straighten the shoreline (Fresh et al. 2011). Many nearshore fish and wildlife species rely on functioning high intertidal habitats to provide food sources, migration corridors, cover, and spawning habitat (Brennan 2007). Removal of shore armor can reverse the burial of habitats (placement loss) such as backshore areas, where drift logs and vegetation create important microhabitats, and forage fish spawning areas. Restoration of cross-shore connectivity through bulkhead removal can restore overhanging riparian vegetation, LWD recruitment and storage, and groundwater connectivity (Brennan 2007). Bulkhead removal case study sites were considered successful at restoring LWD processes if large wood was made available for recruitment as a result of bulkhead removal or was expected to do so in the future. The mature forest and active deep-seated landslide movement at Kopachuck State Park resulted in considerable LWD input associated with bulkhead removal at the site.

Along bluff-backed beaches, bulkhead removal and the restoration of nearshore sediment sources increase the resilience of down-drift shores, which require continued sediment input to naturally adapt to the landward migration of the shoreline (Johannessen and MacLennan 2007; an example is Kopachuck State Park in Appendix A). Bulkhead removal will also preserve intertidal areas that would otherwise be threatened by sea level rise due to a phenomenon referred to as the coastal squeeze, in which intertidal area is squeezed between a static shoreline (such as along an armored shoreline) and the landward migrating shoreline. Similarly, removing bulkheads increases the available beach area with enhances their aesthetic and recreational value — particularly during higher tides.

Four bulkhead removal case study sites were assessed in the first phase of this project (Figure 7.4-4 shows before and after images; more detail is in Appendix A). The bulkhead removal projects are located in four very different Puget Sound environments with contrasting wave regimes from low (Weyer Point in south Puget Sound) to medium (Kopachuck State Park in central Puget Sound) to very high (Birch Point in northern Whatcom County). In evaluating the benefits gained versus impacts realized in bulkhead removal, slightly different perspectives were applied to each project based on the objectives of the removal effort. These included reestablishment of sediment connectivity, removal of creosoted wood from the marine environment, and enhancement of the restoration of a DNR Natural Resource Conservation Area. In some cases, the objectives overlapped. Example before and after bulkhead removal images from other projects not surveyed for this effort are found in Figure 7.4-5, which show a wide variety of conditions where this technique has been employed in recent years.

Deer Harbor Pool – Before (Johannessen, 2006)

Deer Harbor Pool – After (Johannessen, 2008)

Weyer Point – Before (WDNR, 2005)

Weyer Point – After (2012)

Birch Point – Before (Johannessen, 1999)

Birch Point – After (2012)

Kopachuck State Park – Before (Johannessen, 2006)

Kopachuck State Park – After (2012)

Figure 7.4-4. Before and after images of bulkhead removal projects surveyed for this study (Appendix A).

Powel Site, Bainbridge Island – Before (CGS, 2010)

Powel Site, Bainbridge Island – After (CGS, 2012)

Piner Point – Before (King Co.)

Piner Point – After (King Co.)

Olympic Sculpture Park – Before (*City of Seattle)*

Olympic Sculpture Park – After (2012)

Blakely Island – Before (CGS, 1999)

Blakely Island – After (CGS, 2002)

Figure 7.4-5. Before and after images of bulkhead removal projects from other sites.

Design

The primary purpose of bulkhead removal is typically to restore or enhance nearshore ecosystem processes and functions to increase beach resiliency, habitats, and recreation value. All potential outcomes, including those affecting land uses, should be assessed in the preliminary phase of the bulkhead removal project. The scope and level of detail for assessing feasibility will depend on the project size and location, degree of certainty required (cumulative risk), and documentation requirements of permitting agencies. A small site without upland development near the shore warrants a low level of detail feasibility assessment while a larger site with valuable upland development will require more in-depth analysis to determine feasibility.

Bulkhead removal case studies exhibited a wide variety of materials. A thorough review of the original objectives of the installation, bulkhead design, as well as geologic and engineering documentation of the design parameters should be evaluated at the onset of project planning.

There are many factors to consider in the design of bulkhead removal projects including:

- amount of fill, potential disposal issues (could there be contaminated materials? creosote-treated wood?)
- the degree of anticipated erosion resulting from removal
- effect on adjacent sites
- slope stability following removal
- site access and disposal
- cost
- re-grading approach (natural or machine re-grading)
- new design elements (large wood, sediment/nourishment, slope or backshore vegetation, or structures)

Analysis for bulkhead/armor removal was divided into feasibility, design, and evaluation phases in the *Management Measures for Protecting and Restoring the Puget Sound Nearshore* (Clancy et al. 2009). That document addresses the general stages of analysis for bulkhead removal, including those carried out in several disciplines, which provides a very useful framework. More specific guidance is provided below in this document. Analysis for bulkhead removal typically involves qualitative work and does not rely on numerical models for assessment and design. Only large, complicated sites with significant risk require intensive analysis, such as wave or slope stability modeling.

Project designs should explain the uncertainties that exist regarding geomorphic and engineering parameters. Ideally the range of possibilities for anticipated outcome, and associated risks relative to that range should be discussed. The factor of safety for a residence or large building should be considered more thoroughly than for landscaping or lawn/forest. The scope and design factor of safety should be consistent with the anticipated outcome of the project (bulkhead removal vs. modification), specific location, and type of change anticipated.

Fill and Anticipated Erosion

A site feasibility assessment will help determine if bulkhead removal is a viable option for a given site. Of the highest importance is to analyze the amount of fill that may have been placed at the site at the time of bulkhead installation, and to estimate the likely erosion that may occur after the bulkhead is

removed. Estimating the volume of fill at a given location can be achieved by examining the original bulkhead designs (if available), aerial photographs (if of suitable quality to measure shoreline geometry), or the soils directly landward of the bulkhead. Generally speaking, the greater the volume of fill, the more rapidly that material will erode as the beach naturally adjusts to a more natural (landward) shoreline position. Ideally, if the fill material is non-native, then it should be removed so that the beach can naturalize.

Determining how the fill material (and shoreline) will respond to bulkhead removal can be conducted by comparing and analyzing historic (and current) conditions at the subject site. Historic analyses would typically include comparing the current and historic position of the shoreline using regional GIS data (Collins and Shiek 2005) with maps or aerial photographs. Historic (vertical) aerial photography can be georeferenced and analyzed to measure historic erosion rates at the site. Ideally historic site trends can be explored (both the erosion/accretion) prior to bulkhead removal. However, this is not always possible due to limited data and the ability to assess historic conditions at some shaded sites using air photos.

If historic data sources are lacking and examination of soils is non-conclusive, another method of estimating erosion or accretion trends following removal can be the use of an appropriate nearby reference site. Reference site selection is critical. A site with very similar wave energy, orientation, shoretype, sediment type, and littoral drift is best for analysis. The reference site needs to be an unarmored site with very similar coastal geomorphic and geologic conditions. Ideally, a reference site from the same drift cell is used in order to reduce variables, or if that is not possible, a reference site from a nearby area which closely matches site conditions should be used. A reference site with different conditions can be very misleading and should not be used.

Assessment of site suitability and design development for bulkhead removal must include characterization of wave climate (Chapter 4, *Coastal Processes*). For most Puget Sound sites this consists of characterizing the major and minor wave fetches to determine the general level of wave energy reaching a site. Sites which are exposed to southerly quadrant fetch experience a relatively greater degree of wave forcing and usually have greater potential erosion rates than sites without southerly fetch.

Effect on Adjacent Shores

If either adjacent property to the bulkhead removal site has a bulkhead extending to the shared property line, consideration must be given to potential erosion which may be caused by end effects on the site following removal. An example where a bulkhead is contained within a property with no adjacent bulkheads, and one where bulkheads are present immediately adjacent is shown in Figure 7.4-6. End effects from the armored shore are likely to exacerbate erosion along the newly exposed bank or beach. This is due to wave refraction occurring around the end of the adjacent armor and focusing scour on the project shore. If the site is erosional or subject to moderately high energy waves, implementation of additional design techniques to abate end effects may be needed to avoid erosion adjacent to the remaining armor. These may include beach nourishment, large wood installations (See Figure 7.2-3f for an example). See *Potential Additional Design Elements* section below.

The length of the subject site shore should be considered, as end-effects can extend up to 15-30 ft from or more from the end of the armor. The length of shoreline subject to end-effects is a function of the

bank/beach geology, wave energy at the site, the angle of wave approach, angle of the return wall, up-drift sediment supply, and the construction material of the structure.

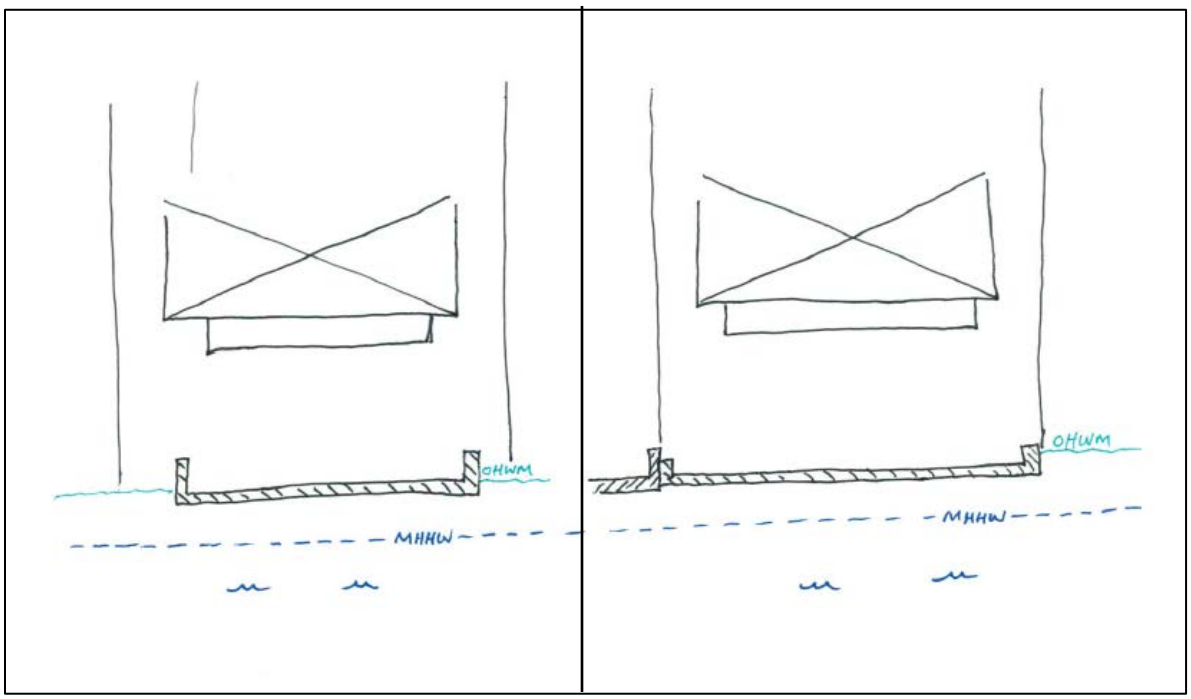

Figure 7.4-6. Sketch of 2 different bulkhead removal scenarios with and without bulkheads on property line. Where adjacent bulkhead meets removal area (right), design will have to consider potential end erosion from remaining adjacent bulkhead.

Slope Stability

In order to predict with certainty how the site will evolve over time after bulkhead removal, an understanding of geologic slope stability evaluation is required. This is particularly important when the bluff is high or there is risk to structures or safety. Data from the site assessment and coastal processes assessment (Chapters 2 and 3) are essential to the determination of slope stability for bulkhead removal Refer to those chapters for more information.

Geologic and geotechnical studies consider;

- the strength and cohesion of on-site soils
- hillslope stability
- the interactions of surface and groundwater

Analysis should include the natural features as well as areas altered by development and address surface water flow and any potential drainage control issues during the design development.

A feasibility assessment should evaluate the risk and uncertainty for bulkhead removal projects. The severity of risk can range from intermittent minor erosion, to damage to site improvements, to loss of adjacent improvements or infrastructure.

Potential Additional Design Elements

Bulkhead removal commonly includes some additional enhancement actions such as beach nourishment, regarding, and revegetation. The necessary steps required to identify critical elements to design and the need for additional design techniques are outlined below.

The design elements considered at a given bulkhead removal site range from: complete bulkhead removal, to removal and replacement with soft shore protection such as beach nourishment, large wood, and/or vegetation installation, to a new or relocated bulkhead structure with fewer negative impacts. Bulkhead removal and modification projects should attempt to maximize the restoration of natural processes while balancing the need for human safety. It is important to consider the anticipated trajectories of the site with and without different elements installed alongside the project goals. Overall, a removal design that includes LWD placement, revegetation, and beach nourishment can provide enhanced habitat conditions and productivity; however, some sites do not require these elements.

An analysis using existing site and adjacent site data should be conducted to determine the need for these additional actions to achieve enhanced habitat and/or other goals of the project. For example, some sites simply require removal of the bulkhead to expose native beach and backshore sediment, while others require a large volume of excavation and removal of nonnative and non-compatible sediment from the bulkhead area. For this reason, some amount of exploratory investigation into soil/material composition must be made prior to developing the detailed approach and design. For small sites this typically consists of hand-dug test pits or a limited number of shallow cores with a hand auger. For larger sites it may require a series of auger holes or test holes excavated with a backhoe or similar equipment. A site with nonnative and non-compatible soils would generally require beach nourishment. (Refer to Chapter 7.1 for details on beach nourishment approaches.) Other sites that have experienced long-term profile lowering due to some combination of bulkhead-induced erosion and cumulative impacts to the drift cell, and that are of suitably low energy to retain placed sediment for some time, should also be considered for nourishment.

Bulkhead removal sites also need to be evaluated to determine if LWD or vegetation would measurably improve habitat conditions and provide a more favorable site trajectory. Some sites have ample LWD input from natural processes transporting LWD alongshore, and the material simply needs space in the backshore to deposit. Some areas have little LWD in the system and would benefit from the placement of imported wood, which may help the site evolve much faster than if wood was not added.

Another approach to removing a bulkhead is to simply allow a failing bulkhead to disintegrate to the point where it gradually is eroded away and the beach restores itself. This is only advised where the bulkhead is constructed of untreated wood, or logs which will become part of the natural LWD in the drift cell. These type of bulkheads typically only contain former beach or bank settlement that was used as fill, however this should be verified before allowing structure to simply disintegrate. If non-native soil such as construction debris or other exotic material is used as fill, these portions of the fill should be removed from the marine apartment as well. Wood that has been treated in any way should always be removed from the marine environment. Rock from rock revetments or rockery walls should also be removed when failing.

Climate change and sea-level rise will accelerate coastal erosion and bulkhead removal sites will be vulnerable to this increased erosion. This makes it important to plan conservatively and realistically so that property owners are not surprised and support continues for this type of restoration.

Potential Engineering Requirements

Several situations may necessitate the need for engineering analysis and design at bulkhead removal sites. These situations include the following:

- A replacement bulkhead in a more landward position or shortened length.
- Reconstructing beach access stairway on unstable slope.
- Replacing utilities near removed bulkhead.
- Redesigned landing for dock, boat ramp or other feature.

Altering or partially replacing a bulkhead, referred to as armor modification in the Management Measures report (Clancy et al. 2009), requires engineering analysis and design. It is always the preference for habitat restoration to completely remove a bulkhead, however sometimes this is not feasible due to potential risk to a portion of the property. Ideally a modified bulkhead is reconstructed in a significantly more landward and shortened configuration as compared to the bulkhead being removed. Design guidance, including for minimizing negative impacts from bulkhead construction, can be found in Chapter 5 *Hard Armor*.

Construction of beach access stairways at bluff properties often rely on a bulkhead for the stairway landing. Bulkheads typically provide protection from wave attack for these landings. If a bulkhead is to be removed with an existing beach access stairway, civil and potentially other types of engineering may be required. Best design practices for minimizing impacts to the beach require the most minimal footprint possible for the stairway landing. Additionally, the use of a short (approximately 4-6 ft long) hinged stair section may be used for the lowermost portion of the stairway. This allows the hinged portion to be folded up during winter or other stormy periods to avoid damage.

In some small barrier beach or other no bank parcels, site utilities may be located in close proximity to the bulkhead being removed. These utilities would need to be relocated further landward as part of the project, requiring engineering and coordination with utility providers. It is important to consider the long term implications of sea level rise and climate change for this type of relocation.

Some coastal parcels have docks, piers, boat ramps, or other water-dependent structures in close proximity to or landing on top of a bulkhead to be removed. A generally greater level of engineering analysis and design would be required for modifying these structures, as compared to other topics addressed in this section. It is beyond the scope of this document to provide engineering guidance for modifying these structures, however the same general principals of minimizing footprint of structures over the beach and back shore, avoiding the use of treated wood or other toxic materials, and siting structural elements as far landward as possible apply.

Modification of any of the above listed structures would also require demolition of the pre-existing structures. Disposal of materials must be completed in approved upland facilities.

Bulkhead Material Disposal

Bulkhead materials require proper disposal. Some materials can be salvaged for reuse, which is recommended as it clearly minimizes both disposal costs and the use of new materials for other

projects. It is very important to ensure that all components of the bulkhead to be removed are inventoried prior to project implementation. Some bulkheads have structures below ground. One example is that most bulkheads are embedded below the surface of the beach for stability. If original design drawings are not available, digging test holes by hand immediately water word of the bulkhead can help quantify the amount of material below grade. Most vertical bulkheads have varied tiebacks and deadman anchors, which are not always apparent from the face of the wall. One feature to look for is bolt and ends or similar on the waterward face of a bulkhead. Again, if design drawings are not available, digging test holes landward of the bulkhead can located these, however this can be laborious. Soldier pile walls almost always have tiebacks and anchors. All of this material should be removed, particularly in light of the fact that creosoted wood was sometimes used for these anchor systems.

Rock is typically easily salvaged and reused; however efficient reuse requires sorting into several different rock sizes prior to exporting the material from the site. However, sorting can be accomplished in a construction yard or other facility with little difficulty.

Concrete removed through bulkhead removal or related activities should be sent for recycling. Recycling facilities are becoming more common and are not difficult to find or reach.

Bulkheads constructed of drift logs or untreated log booms present another variation of the theme of reuse. Wood pieces that are free of contaminants and treatment can be left on the beach after deconstruction. This material will contribute to LWD in the marine system, which is purchased and delivered to restoration and enhancement sites. Creosote treated or other treated wood products must be disposed of in an approved facility. Creosoted wood is highly toxic to marine fish and wildlife (citation—Andrea/Stephanie??). All creosote treated wood including small pieces and fragments should be retrieved and removed from the bulkhead site.

Metal removed from bulkheads or related structures can also be recycled. Allowance may have to made to dispose of parts with more rust or corrosion.

Site Access

Planning for equipment access to the site needs to occur during the design phase. Demolition of the bulkhead, export of these materials, and import of any other material requires equipment that must be brought to the site and then taken away. Different access methods have different associated costs. It will be easy to get to some sites from the land side; others will require a barge. Planning around the maximum size of equipment that can reliably access the site is required.

Access from the land side requires direct road access without constrictions that will prevent heavy equipment access. All standard county and city roads should be suitable for access, however it is the final approach to the site that may be limiting such as narrow, winding bluff access driveways. Minimum access route with and curvature should be determined for planting land side site access. Occasionally, load limits are present for bluff access routes, and these should be investigated as well. Note that these are not always stated or made known in the case of private access routes.

If the site is a barge-only site due to limitations for land side access, constraints to access also need to be investigated. Data needed for planning barge access include the offshore depths, location of eelgrass or other submerged aquatic vegetation, and permit requirements.

Other cost considerations include the location of all utilities, equipment availability, and bulkhead and fill disposal options. Access and demolition staging areas should be planned to avoid excessive impacts to upland vegetation, water features, adjacent habitats, septic drainfields, or wells.

Cost

The cost of removing a bulkhead can vary greatly depending on access and transportation (land vs. barge), the type and quantities of material removed, and the amount of additional measures installed. In general, bulkhead removal costs considerably less than bulkhead construction projects.

One important method to control costs is to have as much of the fill and other materials removed from the bulkhead area used on-site, as this will minimize haul out and disposal charges. This can be accomplished by using fill or structural elements such as rocks for modifying upland landscaping, landward of the beach and backshore. The North Orcas Island site in Appendix A is an example of this, where rocks from the removal revetment were buried landward of the beach and also used for garden features further landward. Hazardous material disposal can be an unanticipated expense that can add significant cost, such as at Kopachuck State Park.

Monitoring

The area of beach and backshore uncovered by bulkhead removal is the most direct measure of habitat improvement. Measuring restored functions (such as increases in backshore vegetation area or density in the vicinity of the project, use of the restored beach by forage fish for spawning, etc.) in and surrounding the footprint of the old bulkhead is valuable and relatively straightforward. However, change in down-drift habitat areas or production is far more difficult to quantify. The rate of sediment input from bluffs where bulkheads are removed can be quantified through repeated bluff toe and bluff face surveying to provide an indication of potential off-site benefits from the project. A total station with reflectorless capabilities or a terrestrial LiDAR system can be used to survey bluff faces negating the need for a person to climb the bluff.

Project proponents should create a monitoring plan to assess post-construction project performance and maintenance needs whenever possible. Including an adjacent reference site in a relatively natural condition is recommended. As always, acquiring pre-project baseline data is critical to an effective monitoring program. This would ideally include pre-bulkhead construction, pre-bulkhead removal, which would then be compared to as-built conditions, and follow up monitoring.

The effectiveness of armor removal or modification can be measured by collecting data or observations on the following (Clancy et al. 2009):

- topographic stability/ sediment erosion and accretion
- sediment characteristics and available habitats
- accumulation of wood
- soil moisture/temperature
- backshore vegetation

Maintenance

The anticipated maintenance of a bulkhead removal site needs to be considered in advance, and also compared to the maintenance of a bulkhead in the same location. Designing for possible beach renourishment, or vegetation maintenance, at a site with improvements close to the shore may be

required for bulkhead removal projects. When completing the design process, it is recommended that an attempt be made to design the project such that no maintenance will be required for a minimum of 15–20 years. This will help to keep the project affordable over time, limit site disturbance, reduce the need to obtain additional permits and prevent the need to gain subsequent access to the site.

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Chapter 7. TECHNIQUE 5
HARD ARMOR

Description

Revetments and vertical bulkheads are two common forms of coastal erosion control structures used in Puget Sound. Together these approaches to mitigating coastal erosion are commonly referred to as hard armor. The design guidance provided in this section is tailored specifically for Puget Sound shores and does not represent an exhaustive review of the topic. When designing hard armor the engineer should also consult the most relevant references available on the topic, most notably the following:

- Coastal Engineering Manual (CEM), US Army Corps of Engineers (Basco 2006, Burcharth and Hughes 2002)
- Shore Protection Manual (SPM), US Army Corps of Engineers (CERC 1984)
- Introduction to Coastal Engineering and Management (Kamphuis 2010)
- Random Seas and Design of Maritime Structures (Goda 2010)
- Basic Coastal Engineering (Sorensen 2006)
- Coastal Processes with Engineering Applications (Dean and Dalrymple 2002)

Revetment

A revetment is a permanent shore armor technique that uses stones to form a sloped, permeable structure. The rock revetment has a long engineering history as a protection measure on both marine and riverine banks. Revetments have several advantages when compared to vertical bulkheads. For example, the rough surface of revetment armor stones reduces wave runup more than smoother types of armor and therefore a shorter design height is possible. Stones are cost effective and readily available. Proper placement of the stone and the underlying filter materials contribute to the success of the protection from a revetment.

The basic features of a typical revetment are shown in Figure 7.5-1. The outer stones that face the waves are called armor stones and are sized to remain in position when subjected to the wave energy predicted for the site (design wave energy). The largest armor stone is placed at the toe which is the most waterward and lowest in elevation. Revetments usually have at least one more layer of smaller rock material beneath the armor stones that creates a bedding layer. In Puget Sound, the quarry spalls which generally comprise this bedding layer also allow for drainage behind the structure. Geotextile fabric is also typically used in Puget Sound as a filter fabric between native sediment and the quarry spall bedding layer. Revetments extend below grade to the embedment depth and extent upwards with a consistent slope to the design crest elevation. Guidance on how to determine the design criteria is described later in *Design*.

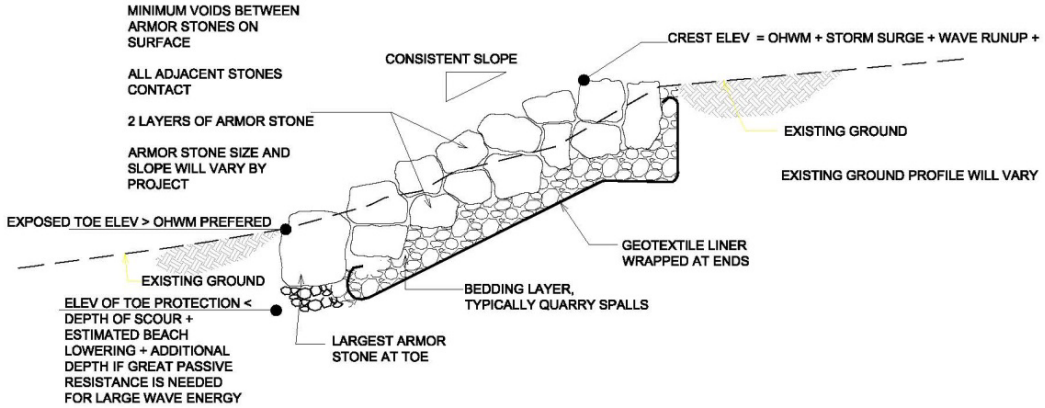

Figure 7.5-1. Cross section of a typical revetment. Design created for this document to display typical revetment design elements.

A variation on the revetment is the near-vertical rock seawall. These seawalls are locally called "rockeries," and are common at single-family residences in Puget Sound. A rockery consists of armor stones placed on top of each other and closely fitted together, forming a steep front face that acts more like a landward sediment retaining wall than a revetment. Armor stones in rockeries are typically larger than those used in sloping rock revetments because the more gradual slope of the revetment supports the weight of the rock on the bedding and allows the use of smaller stones nested together in a tight network. One advantage rockeries have over more traditional revetments is that they cover less beach area. Designers should minimally consult the Rockery Design and Construction Guidelines (Mack et al. 2006) for additional guidance for rockery design as these guidelines describe revetment design.

Vertical Bulkhead

Vertical bulkheads are rigid, vertical structures used as shore protection that stop erosion by reflecting waves and retaining landward sediments. These bulkheads are typically constructed out of cantilevered concrete, anchored sheet piles, or wood soldier piles. Vertical bulkheads use the associated fill around the structure and on top of structure elements for strength and stability against wave attack. Vertical bulkheads attain structural integrity mostly from ground penetration, therefore the depth of embedment and subgrade landward are paramount design elements. Insufficient subgrade design could result in overturning. Once it has been determined that a vertical bulkhead is needed, the type of material should be decided. Common types of vertical bulkheads currently used around Puget Sound are concrete cast-in-place, wooden piles, and vinyl. Cross sections of common Puget Sound vertical bulkhead types are shown in Figure 7.5-2.

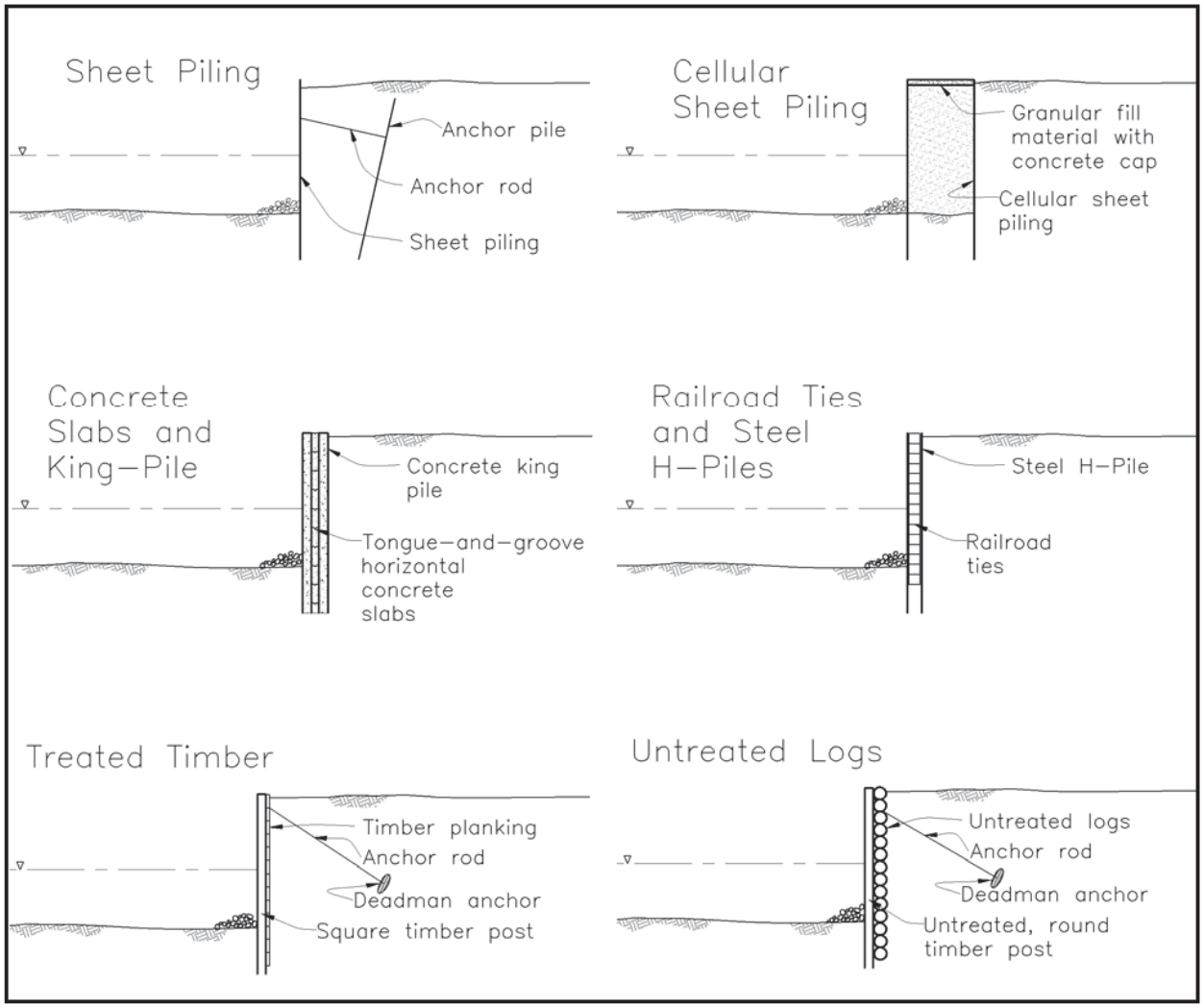

Figure 7.5-2. Typical bulkhead cross sections from CEM Volume 5 (Basco 2006).

Concrete construction is used in cantilevered bulkhead installations. Concrete bulkheads are cast in place and have two typical designs: gravity and zero-clearance. Concrete bulkheads, which have an assumed life span of 50 years, are expensive to install because skilled work is required to excavate the site, install forms, and pour concrete in areas subjected to tidal inundation or wave attack. These projects also often require the use of concrete pumper trucks in addition to concrete trucks, which is a site accessibility constraint. Engineers specializing in structural or geotechnical are also needed for design which increases the design phase costs.

There are two general types of cast-in-place reinforced concrete bulkheads. Typical cross sections for conventional gravity and zero-clearance concrete bulkheads are in Figures 7.5-3 and 7.5-4. Gravity wall construction exposes the bank for footing installation and must have good backfill material to allow for drainage. Most of the time, the backfill material must be imported. Good backfill material, typically quarry spall in Puget Sound, should be angular to allow for interlocking and drainage. The landward excavation requirement for a gravity bulkhead must be considered during the design process since one of the main reasons a vertical bulkhead is viable is due to the small available footprint. Therefore, there might not be enough backshore width to make a gravity wall viable.

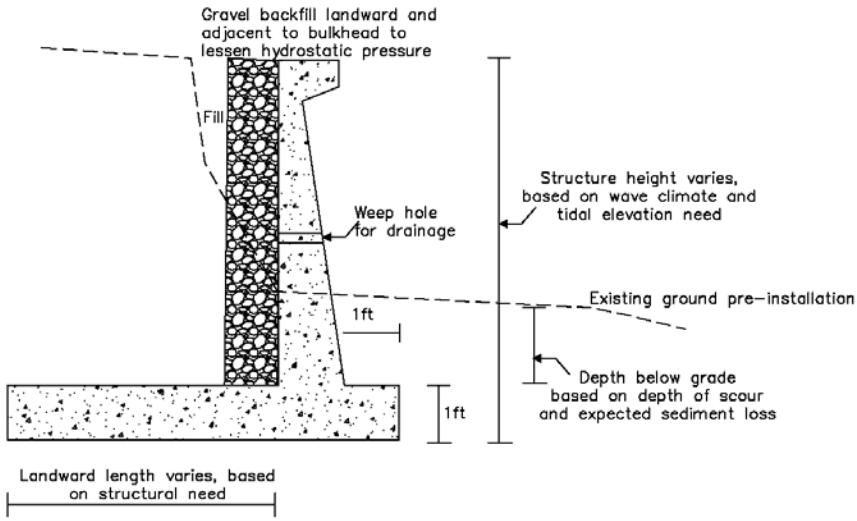

Figure 7.5-3. Typical reinforced, cast-in-place, gravity bulkhead profile (adapted from Cox et al. 1994).

Zero-clearance bulkheads (Figure 7.5-4) allow for minimal landward excavation and can be placed waterward of a failing bulkhead if the available footprint above MHHW is adequate and still allows for proper landward drainage. The natural sediment where the bulkhead is being installed should also be considered when deciding on concrete bulkhead construction.

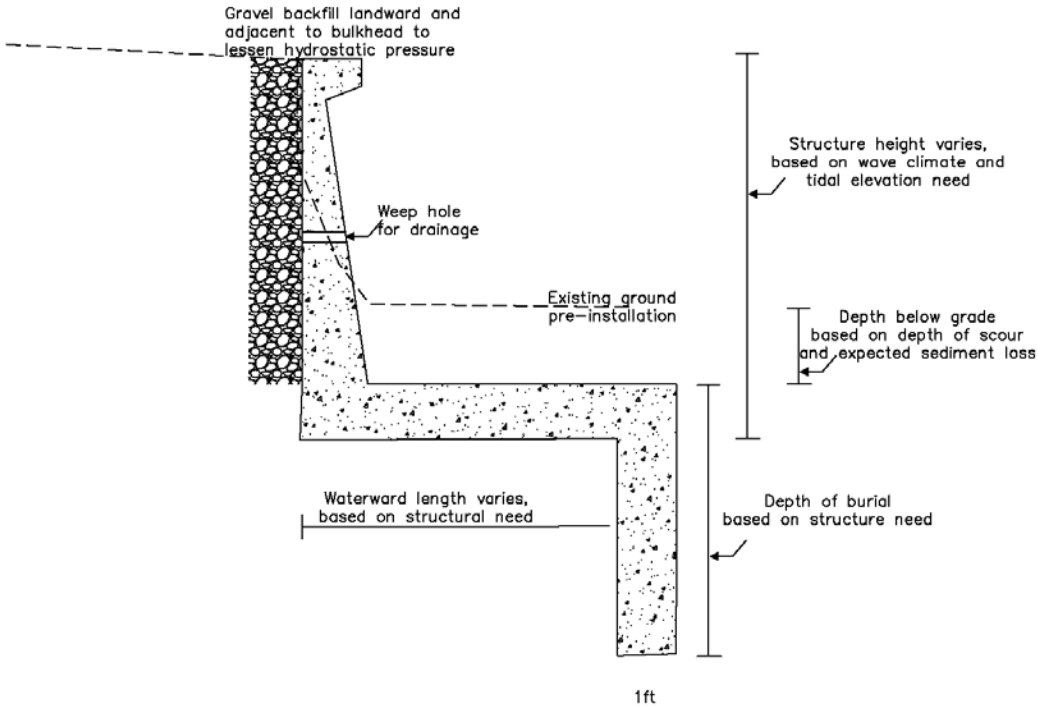

Figure 7.5-4. Typical reinforced, cast-in-place, zero-clearance bulkhead profile (adapted from Cox et al. 1994).

Due to the high costs of concrete bulkhead installations, other types of vertical walls are also used for shore armor installation. Sheet-style walls are anchored bulkheads that can be made from varying material types, but each specific project usually installs rows of consistent material (Figure 7.5-2 above). Sheet walls are made of individual, interlocking sheets driven into depth of refusal or a depth

determined by a geotechnical professional. Some regions of Puget Sound have a preponderance of a certain type of vertical bulkhead material, which appears to be primarily a function of what local contractors are comfortable with. Anchored or tie-back bulkheads use support from embedded systems on the landward side or from piles on the waterward side. These tie-back systems are designed to mitigate waterward structural failure of bulkheads. Vinyl and steel can be used for sheet pile walls as well as noncreosoted treated wooden piles. An additional consideration in vertical bulkheads is the need for special driving equipment for installation at a high cost.

Vinyl is one of the most expensive hard armor installation technique; vinyl sheet walls are expensive because they are manufactured in the southeast United States and trucked across the country. Homeowners like vinyl because of the perception that it does not decay and lasts longer than wood piles. However, use of vinyl walls in the Puget Sound region is too new to know if the assumed design life of 50 years is reasonable in this environment, even though the manufacturer has a 50-year warranty on the material. Vinyl sheet piles were not originally designed to withstand attack from large drift log battering. It is recommended to backfill vinyl sheet piles with concrete to allow for less flex and more strength. Concrete-filled vinyl also allows for less sediment to leak out and enhances material containment.

The most economical vertical bulkheads are soldier pile walls and therefore they are the most commonly installed in Puget Sound. Creosoted wood should never be used and is not permitted due to the residual ecological effects of harmful toxins to living organisms in the nearshore. High mortality rates of nearshore species from exposure to creosoted wood have been documented (Vines et al. 2000). Wood soldier pile walls have a life span of approximately 25 years due to decay and insect intrusion and are therefore the shortest lived vertical bulkhead.

Costs for each type of vertical bulkhead are discussed in a separate section below.

Application

The designer should have arrived at selection of a hard armor technique only after considering its benefits and impacts, as discussed in Chapter 5, *Alternatives Analysis*. Revetments and vertical bulkheads have the highest impacts and should be chosen for their unique characteristics. Each design should be accompanied by compensatory mitigation.

In the past, vertical bulkheads were the most common structure used for coastal erosion control in the Puget Sound region, but due to changing permit requirements and increased scrutiny by regulators, they are now rarely installed on new projects and almost all vertical bulkheads currently installed are replacement structures. These changes are due to observed and documented negative ecologic and geomorphic impacts directly resulting from vertical bulkheads (Shipman et al. 2010). Because of Washington State code, most jurisdictions have enacted regulations that prohibit bulkhead construction unless infrastructure threat from erosion can be demonstrated by a geotechnical analysis (WAC 173-26-201). There is disparity in how different jurisdictions handle bulkhead installation requests; differences depend upon how rigorously a jurisdiction interprets its Shoreline Master Program (SMP) policies and regulations, how recently their SMP was updated, and the interplay between SMP policies and Critical Areas Ordinances.

Site Selection

Revetments and vertical bulkheads are appropriate for sites where all of the following are true:

- Soft shore protection is infeasible.
- Risk to infrastructure is moderate or high.
- Magnitude of erosion is moderate to high.
- Erosion is chronic.
- There is existing infrastructure.

As mentioned previously in this document, passive techniques such as moving at-risk infrastructure landward should also be determined to be infeasible before hard armor is selected as the technique to be installed at the project site.

The cumulative infrastructure risk model (outlined in Chapter 5) should be applied to the project to determine if the erosion potential and infrastructure threat result in a moderate to high risk. Scores of 15 and higher in the cumulative risk model are designated as moderate to high infrastructure risk. Generally, project sites with homes or industrial development with at least moderate erosion and minimal to moderate setback distances classify potential sites for hard armor.

Typically, a revetment is preferred to a vertical bulkhead because an impermeable, vertical face has more negative impacts than a sloped, permeable structure. As long as there is an adequate backshore footprint for revetment installation and the project site is not between or adjacent to other vertical armor, a revetment is viable. Also, additional designer credentials are often needed for vertical bulkhead design and designs can be more costly.

Revetment

Revetments are appropriate for sites where all of the following are true:

- low or medium-height bank or bluff present
- low to medium bank or bluff elevation
- adequate backshore footprint

A bank or bluff must be present at the project site in order to install a successful revetment because at a minimum, revetments need some elevation for design. As discussed in the *Design* section later in this chapter, a typical revetment in Puget Sound has a structure slope of 1:1 and is generally about 5 ft tall above grade. Therefore, an adequate backshore footprint (horizontal distance from the OHWM to the landward extent of the proposed revetment structure) is approximately 7–11 ft (average of 9 ft) wide to allow for structure run out directly proportionate to height (4–6 ft), crest width (2–4 ft), and a 1-ft bedding layer. The adequate structure footprint will be specific to each project due to actual needed stone sizing and crest height, but this 9-ft rule-of-thumb is a good starting point for revetment feasibility. Revetments should consider less steep slopes when feasible and therefore the adequate structure footprint could be larger than 9 ft. If the available structure footprint is substantially less than 9 ft, a vertical bulkhead could be considered, especially if the site is in a high-wave-energy environment.

Vertical Bulkhead

Vertical bulkheads are appropriate for sites where all or some of the following are true:

- narrow or no backshore footprint available
- between or adjacent to other vertical shore armor
- designer and contractor knowledge

Vertical bulkheads are viable when a hard structure is feasible and there is minimal footprint availability. A vertical bulkhead might also be feasible if the project location is immediately adjacent to or between other vertical hard armor.

Effects

Hard armor can provide effective erosion control; however, it negatively impacts the nearshore ecosystem in many ways (MacDonald et al. 1994, Rice 2006, Brennan 2007, Johannessen and MacLennan 2007, Clancy et al. 2009, Shipman et al. 2010, Schlenger et al. 2011). In general, these impacts include the following:

- reduction in natural sediment input
- loss of beach function and habitat by direct burial
- alteration of hydraulic processes
- end-erosion or end effects
- potentially increased beachface erosion ("active erosion")

Hard armor structures are designed to prevent erosion; therefore, a successful project precludes natural nearshore processes of sediment supply from the bluff. When armor is placed at the toe of a feeder bluff the armor prevents wave-induced erosion from destabilizing the bluff, which directly results in a decline in the volume of sediment delivered into the associated drift cell from that bluff. If wave-induced erosion is the main driver of the bluff erosion then this method of curbing erosion is typically effective. However, where upland processes (such as stratigraphy, vegetation clearing, or poor management of surface water) are driving bluff erosion, armor may not be as effective. Additionally, armor is not always effective at curbing erosion in areas that would naturally be flooded (over-washed), such as barrier beaches. Case study results (Appendix A) revealed that two of the four assessed revetment sites stopped landward erosion. The others did not, as one allowed for sustainable erosion at the ends (Lummi View Drive) and the other had scarping landward of the structure due to considerable overtopping (Blakely Island). Climate change and sea level rise will most likely increase overtopping at Obstruction Pass and cause scarping landward of the inflexible revetment, because there is no bank for elevation.

Armor not only effectively impounds sediment input but also large woody debris, other organic matter, and insects. The cumulative impact from extensive lengths of armored shore amounts to a more widespread decline in nearshore sediment supply and LWD input, the indirect results of which include beach sediment coarsening and long-term changes (such as beach narrowing) to down-drift shores. Case study results highlighted the impact of armor on LWD/detritus recruitment and storage when compared to natural adjacent reference sites. Most revetment sites did not have a log band waterward of the structure, whereas the reference sites did. If there was a log band, it was substantially smaller than that at the corresponding reference site.

Wave refraction at the ends of armor structures often creates end erosion immediately adjacent to the structure. Wave reflection waterward of the armor can mobilize fine sediment into suspension, and it is then transported alongshore. This can lead to the development of a scour trough waterward of the structure. It can also result in beach lowering, which can degrade the integrity of the structure over decades. Case study assessment data showed that three (of four) revetments had a beach (profile) slope

that was an average of 15% steeper than the natural, adjacent reference beaches. Blakely Island's waterward slope was the same as the reference beach and Butler Cove had the steepest slope when compared to the nearest reference beach.

The presence of armor obscures nearshore habitat functions, through an effect called "direct burial" or "placement loss". The most dramatic implications of direct burial include the loss of forage fish (surf smelt [*Hypomesus pretiosus*] and Pacific sand lance [*Ammodytes hexapterus*]) spawning areas. For example, the Lummi View Drive project resulted in burial of up to 20 feet of backshore and upper intertidal sediment. The spatial extent of the habitat loss and more generally, the ecological effects of a given armor structure, are largely dependent upon its toe elevation (Rice 2010). The lower the toe elevation of the structure, the greater the placement loss and impacts to shoreline biota (Rice 2010, Toft et al. 2010). Case study assessment results showed that armor installed higher on the beach profile (at least above MHHW and preferably above the OHWM) can allow some alongshore exchange of detritus. The lower the armor extends into the beach the more it truncates or destroys the natural gradient of the intertidal zone and the more species it is likely to adversely affect, as more intertidal habitat zones are encountered.

Other impacts of shore armor on habitat are outlined in Chapter 5. Some of these impacts include decreased overhanging riparian vegetation with an associated reduction in organic matter and insect input (Brennan 2007, Sobocinski 2010), reduction in the supply and deposition of LWD (Holsman and Willig 2007, Tonnes 2008), and the associated loss of habitat complexity and microhabitats, such as the shaded areas created by overhanging riparian vegetation and greater soil moisture offered by LWD deposits (Rice 2006, Tonnes 2008). Decreased species richness of numerous taxa, including insects, invertebrates, birds, and fish (Rice 2010, Toft et al 2010) are also associated with shore armor. Case study data affirmed many of these otherwise documented impacts, as none of the revetment projects enhanced backshore vegetation and only one enhanced marine riparian vegetation landward of the installation.

As reviewed elsewhere and in this research, hard armor techniques impact nearshore ecosystem processes and habitats, and except for successfully curbing erosion they provide few benefits. Case study results highlighted the magnitude of impacts and minimal benefits seen at hard armor locations throughout the Puget Sound region (as reviewed in Chapter 5).

Design

Some design elements of a hard armor installation are needed for both revetments and vertical bulkheads. These include the project site wave climate, design water height, depth of scour, and plan-view geometry.

Significant Wave

The most important elements to determine for hard armor design are the design wave criteria at the project site. Wave hindcasting methods use historical wind data (magnitude, frequency, and direction), fetch, and water depths (along with other elements, depending on the research) to approximate wave conditions. Due to its geography, the Puget Sound region is a fetch-limited wave environment. Therefore, only wind waves and not swell waves will be discussed in this guidance.

Wind speed (measured at 10 m above the water surface) and fetch length are required to estimate the significant wave criteria in Puget Sound using the simple wave forecasting equation below (CERC 1984, Finlayson 2006).

$$U_a = 0.71 * U^{1.23} \qquad \text{Equation 7-1}$$

$$H_m = 1.616 * 10^{-2} U_a \sqrt{F} \qquad \text{Equation 7-2}$$

$$T_m = 6.238 * 10^{-1} \, (U_a F)^{1/3} \qquad \text{Equation 7-3}$$

Where:

H_m = fetch-limited significant wave height

T_m = significant wave period

U_a = wind stress factor

U= wind speed (must be in m/sec)

F = Fetch length (must be in km)

If historical wind data is not known for the project site, 10 m/sec should be used for U for fetch-limited shorelines in the Puget Sound region (Finlayson 2006).

Many scientists, engineers, and scholars have developed methods to estimate wave climate. While this document gives a brief description of the elements use in wave hindcasting, it does not describe detailed methods as there is a reputable model developed that estimates significant wave height and significant wave period for Puget Sound and Juan de Fuca Strait. Areas outside the model study area in San Juan, Whatcom, and the majority of Clallam counties should use this guidance to help estimate wave climate at the project site. The model results regarding significant wave height and wave period are shown in Figure 7.5-5.

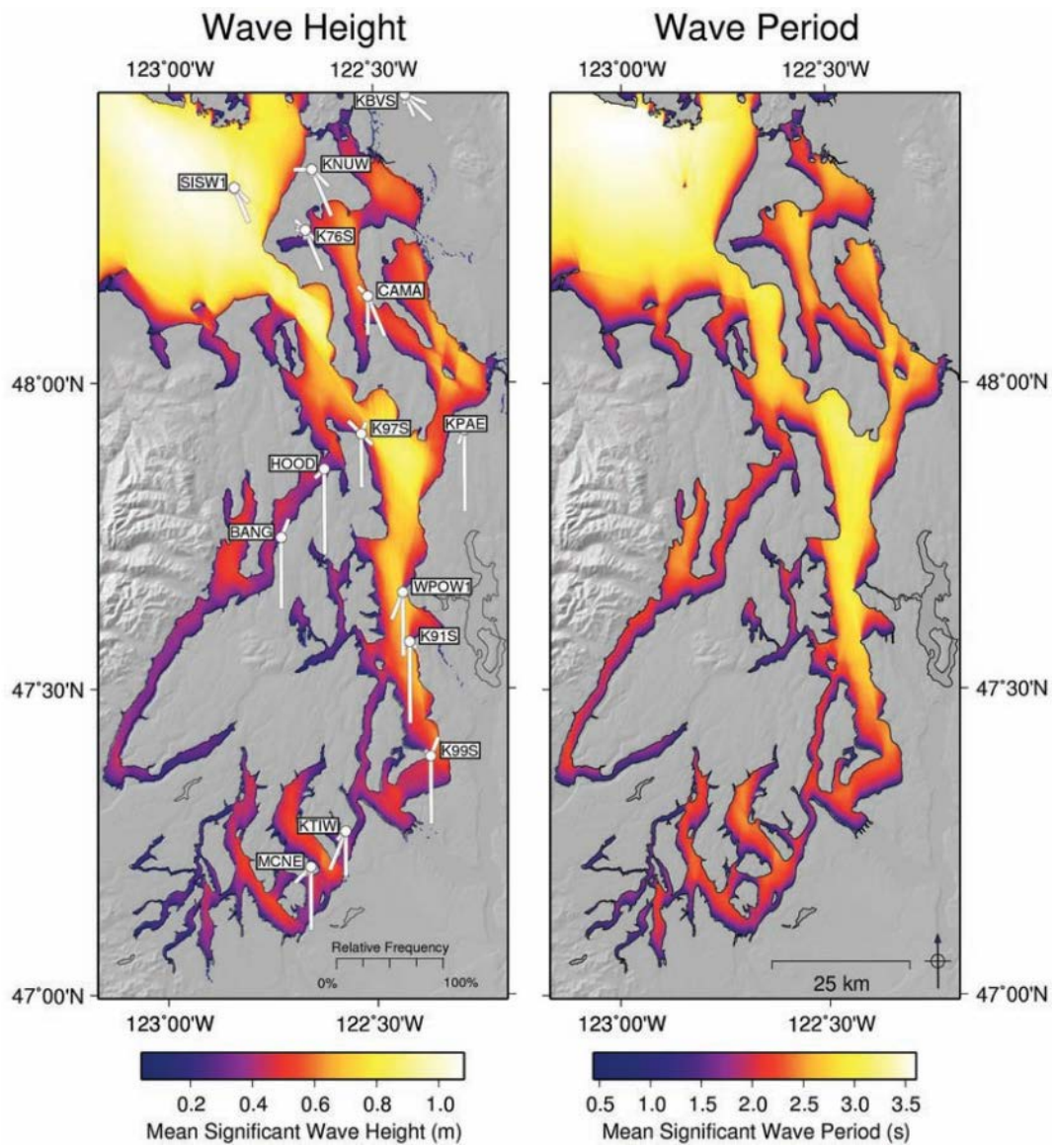

Figure 7.5-5. Model results for estimated storm significant wave height (left) and period (right) (Finlayson 2006).

After the significant wave height is determined, the design wave height should be calculated. The significant wave height, by definition, is the average of the top third largest waves (33%) and the design wave height should at least be equal to the significant wave height; a larger design wave height should be considered if the budget and project objectives allow. Acute large wind gusts and extremely rare larger waves occur. There, when possible, the crest height should be increased to combat these rare events. H_{10} is the recommended height to be used as the design wave height (CERC 1984, Sorensen 2010); H_{10} is the wave height where only 10% of the waves are greater and should be substituted for H_m if a more conservative approach is needed.

$$H_{10} = 1.27H_m \qquad \text{Equation 7-4}$$

Wave Runup

Runup is the maximum vertical extent of wave uprush on a structure above the still-water level (SWL) and is an element to estimate when determining crest height. A definition graphic of wave runup can be seen in Figure 7.5-6. Wave runup increases as the structure slope becomes steeper, particularly in the typical Puget Sound wave climate and with the construction materials generally used, as discussed below. Therefore, the design crest elevation must increase with steeper slopes. This has other implications for structure footprint size and cost when project trade-offs are being considered (CERC 1984, Sorensen 2006).

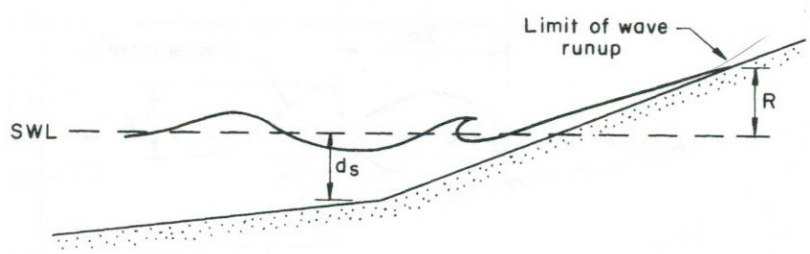

Figure 7.5-6. Definition sketch of wave runup. Runup is the vertical extent of wave uprush above the still-water level (Sorensen 2006).

There have been many studies to predict wave runup when comparing wave criteria, bathymetry, slope, and construction material. The graph below (Figure 7.5-7) is a good starting point for determining wave runup (CERC 1984). If a more precise prediction is desired, consult the list of the references given in the *Description* section above; many studies have documented varying design elements that affect wave runup.

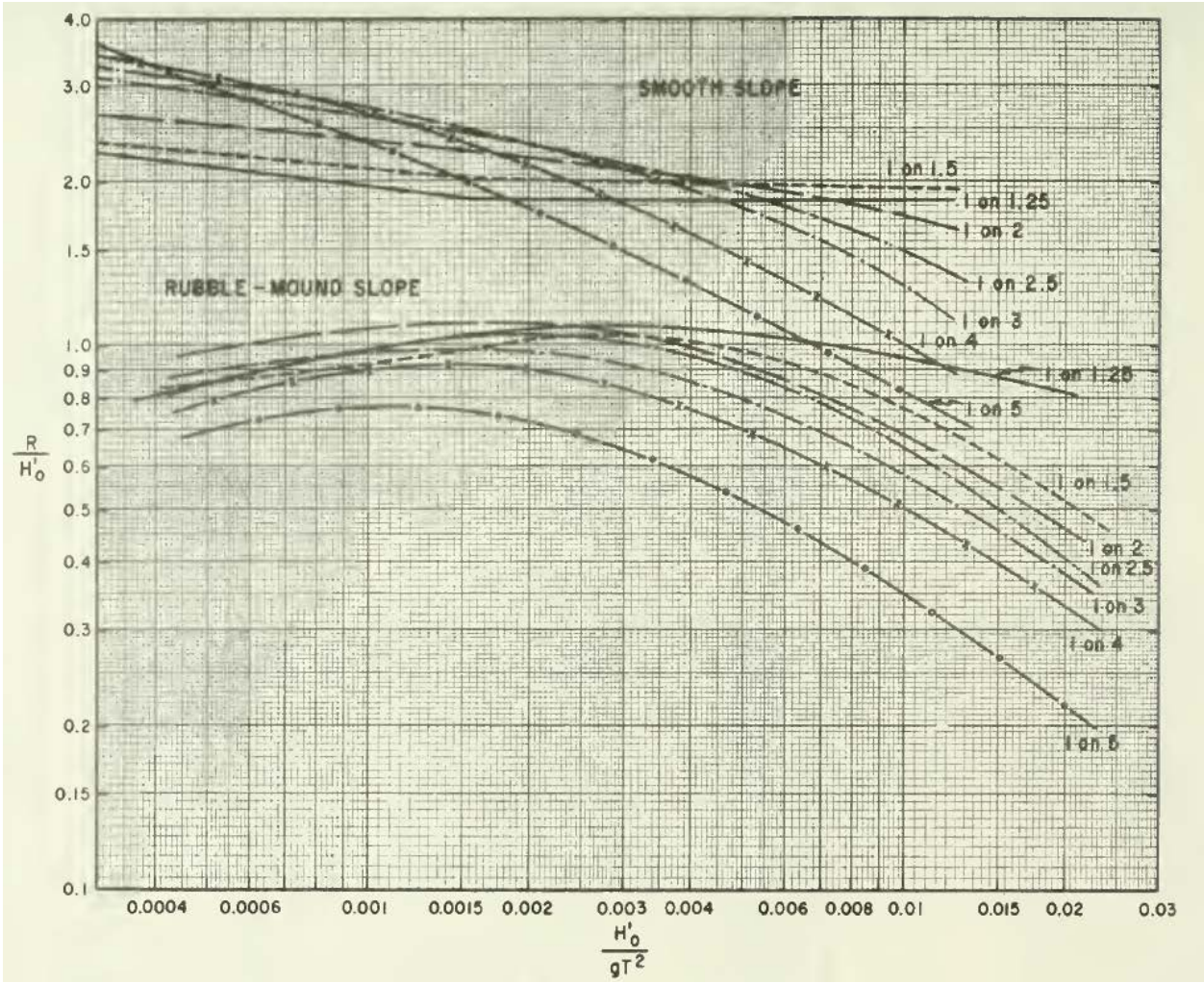

Figure 7.5-7. Comparison of wave runup on smooth slopes and permeable rubble slopes. Note that runup increases as the slope of the revetment becomes steeper (CERC 1984).

For example, in determining wave runup, the largest waves predicted in the Finalyson model shown in Figure 7.5-3 have approximately a 1.0-m significant wave height and a 3.5-sec period, which results in a x-axis in the graph in Figure 7.5-7 ($\frac{H}{gT^2}$) of 0.008. If a revetment slope (also called a rubble mound) is assumed to be 1:2 (V:H), then the associated y-axis ($\frac{R}{H}$) would be approximately 0.76 resulting in runup of 0.76 * 1.0 m = 0.76 m (2.5 ft). Wave runup and allowable overtopping criteria will be used when determining crest height, which is discussed later in this chapter.

Storm Surge

Other factors that affect design height are the still-water depth (SWD) and storm surge. The SWD is the depth of water if there were no waves and should be considered OHWM at a Puget Sound project site for hard armor design conditions. Storm surge is a rise of water associated with low-pressure weather systems. Typically, a design storm surge in the Puget Sound region is +60 cm (2.0 ft) (Finlayson 2006). Another way to determine a design water height in Puget Sound is by using the highest observed water level (HOWL). A designer should use the largest value between OHWM + 2 ft or HOWL for the design

water height. If HOWL is not known, it can be estimated for design purposes with the associated NOAA benchmark data sheet that is closest to the project site. Listings can be found here: http://tidesandcurrents.noaa.gov/station_retrieve.shtml?type=Bench+Mark+Data+Sheets

Crest Elevation

The design crest elevation should consider SWD, storm surge, wave runup, allowable overtopping, landowner budget, and sea level rise. Consideration should also be given to protecting the bank above the hard armor from splash and spray. There are trade-offs when considering crest height as runup decreases with more gradual structure slopes. Therefore, design crest heights and slopes can be maximized for available budget, footprint, and construction materials. A more gradual slope results in smaller armor stones and lower crest elevation. It follows that vertical bulkheads should be designed for a higher crest elevation than sloped revetments with the same design wave constraints, because their vertical slope and impermeable construction materials result in increased wave runup. If budget and project objectives allow, an additional 1.5 ft (0.47 m) should be added to hard armor crest height for 50-year sea level rise (SLR) considerations (NAS 2012).

Toe Embedment Depth

Scour is the removal of sediment in the vicinity of a coastal structure that results in loss of hydrodynamic forces of the structure (Figure 7.5-8). Scour depth, estimated beach lowering, and strength to combat wave attack should be considered when determining the depth of embedment of hard armor structures. Depth of scour, structural integrity of the sediment, strength needed to combat wave attack, and mass of structure should be considered in the depth of footing determination. The footing depth requirement changes with the varying types of hard armor, especially vertical bulkheads. Exposed toe elevation should be greater than MHHW minimally and preferably above OHWM as seen in all plan-view alignments. Most Puget Sound counties have Shoreline Master Program requirements which require structures that do not alter the beach at the OHWM. Also note that if an exposed structure toe design goes below MHHW, federal permitting will be required in addition to local and state permits.

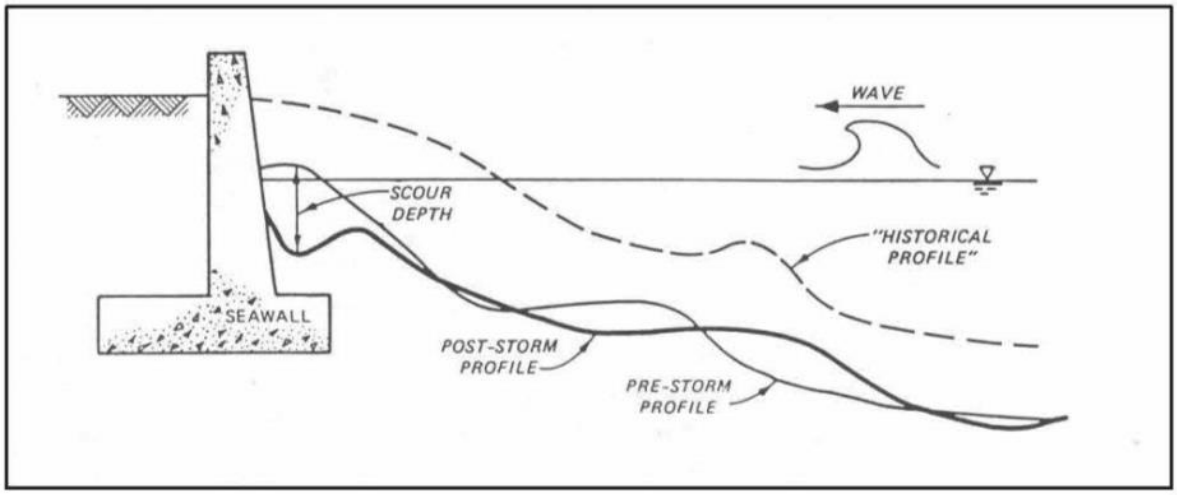

Figure 7.5-8. Scour due to breaking waves at vertical seawall (Kraus 1988).

The hard armor techniques can cause scour waterward of the toe of the structure. Scour depth increases if there are substantial currents at the project site. Maximum scour occurs with vertical walls

and plunging waves. Reducing wall reflection (less steep structure slope) reduces scour. Maximum scour depth is approximately equal to the nonbreaking wave height that can be supported by the water depth at the structure (Burcharth and Hughes 2002). Maximum scour depth occurs at reflective, impermeable structures and is the same height as the significant wave height but inverse. Conditions that promote maximum scour rarely occur in Puget Sound but using the wave height as the scour depth is a good place to start for design. Therefore, the same wave height determined above should be used for scour depth.

The design should consider if there will be any estimated beach lowering due to the structure installation. Highly reflective and impermeable structures installed lower on the beach profile increase the probability of beach lowering. Also, up-drift conditions could result in beach lowering at the project site.

The burial depth of the structure should also consider the strength needed to combat wave attack. If a revetment is being installed, a substantial amount of the armor stone should be buried. The size of the armor stones are discussed in more detail below, but each toe stone should be substantially buried for structural strength. Minimally, the largest toe rock should be two thirds buried below the maximum depth of scour. For a vertical bulkhead, the embedment depth should be greater than for a revetment with the same wave climate and project geology due to the associated reflective and impermeable traits. A structural or geotechnical engineer should determine the depth of embedment for a vertical bulkhead. The subsurface sediment and wave forces should be known and given to the structural and geotechnical engineer for embedment depth determination.

Alignment

The alignment or plan-view geometry of a hard armor structure is based on the site characteristics, property boundaries, and other project and site-specific constraints. The alignment in plan-view should be as uniform and consistent as possible to limit the structure's ability to cause increased erosion from focused wave energy from diffraction and refraction along the structure face. Similarly, the plan-view alignment should limit wave focused energy at the ends from wave refraction, reflection, and diffraction by minimizing sharp corners; instead, curving return walls should be used to minimize erosion immediately up-drift and down-drift. Preferred plan-view geometry to lessen erosion waterward and up- and down-drift is demonstrated below in Figure 7.5-9 in blue. The red alignments in Figure 7.5-9 demonstrate nonuniform alignment and sharp, rigid return wall corners that exacerbate erosion. It should also be noted that all alignments in the figure below have an exposed toe above OHWM which is preferred by permitting agencies. Some rare projects will require other placement.

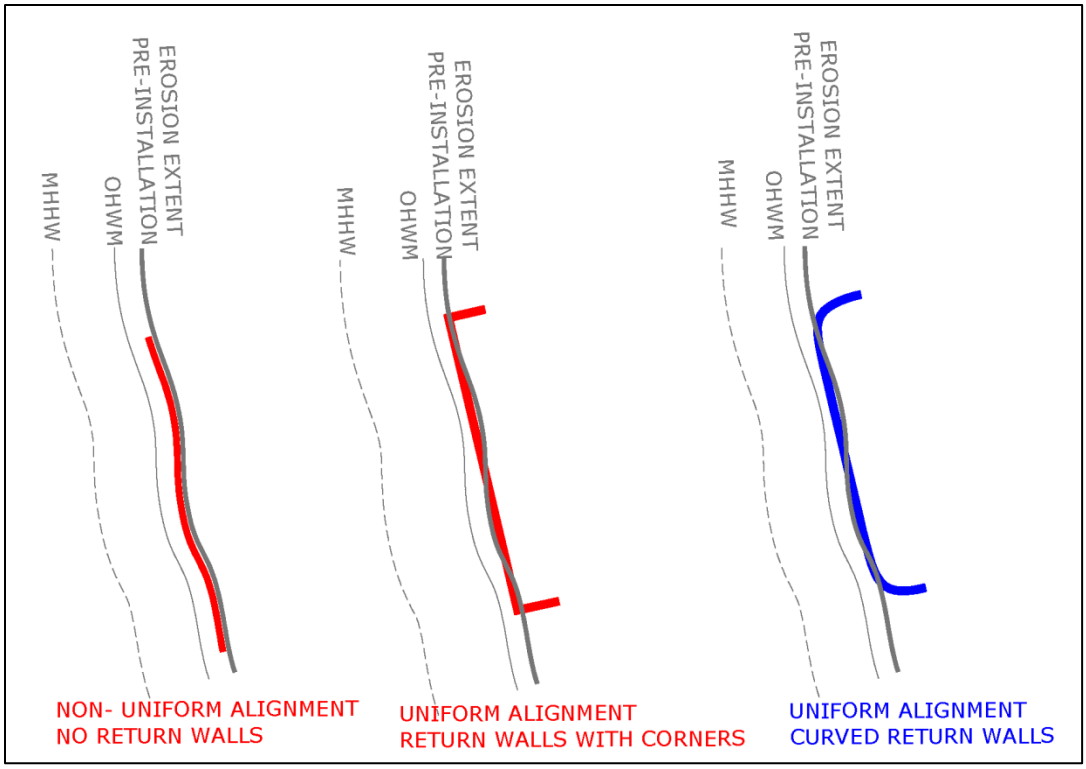

Figure7.5-9. Plan-view alignment options. Blue option (right) is preferred to lessen erosion impacts waterward and up- and down-drift. Figure developed for this document.

Slope – Revetment Specific

As seen in typical revetment design cross sections (Figures 7.5-1 and 7.5-10), the slope should remain consistent throughout the structure both horizontally and vertically for minimum wave focusing and therefore minimum impact to the surrounding environment. The slope maximizes material and footprint availability while considering budget. The design could consider a more gradual slope, which allows for smaller rock size and lower crest elevation but also buries more footprint area (CERC 1984, Burcharth and Hughes 2002, Kamphuis 2010). Typical revetment slopes in Puget Sound are 1:1 or 1:1.5 (V:H). Figure 7.5-10 illustrates a different, more common, variation of Figure 7.5-1 installed in Puget Sound: a revetment installation for an extremely high-wave-energy environment, using a steep 1:1 slope with large armor stones. If a structure slope is needed that is steeper than 1:1, then the structure will actually be a rockery or gravity retaining wall and will have different design constraints than a revetment.

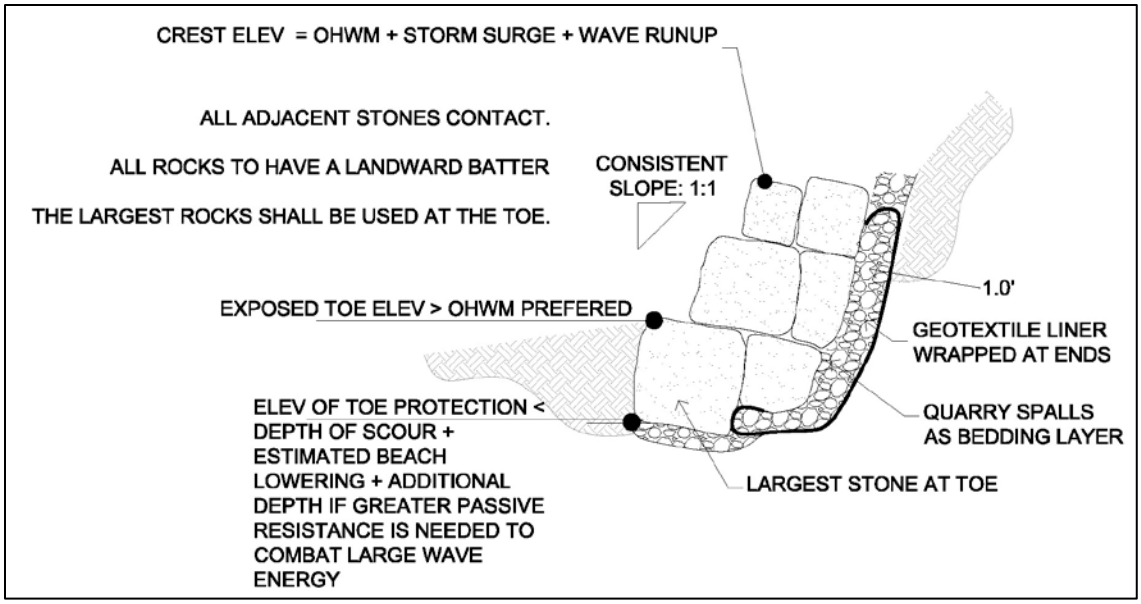

Figure 7.5-10. Typical Puget Sound revetment cross section used on projects with small footprint availability and large wave climate. Typical cross section developed for this document to show all design elements.

Rock Sizing and Placement – Revetment Specific

The proper stone or armor unit size to use on a reveted slope will be a function of the wave height, slope of the revetment, type of armor placement, and the specific gravity of the armor. Armor stones should be angular, sound, hard, and durable rock. Typical density of stone used on Puget Sound is 1.5 tons/cubic yard. Even though most coastal engineering reference documents do not suggest having a steeper structure slope in armor stone revetments than 1:1.5 (V:H) , it is typical practice in Puget Sound to have a slope of 1:1 (CERC 1984, Burcharth and Hughes 2002, Goda 2010), which requires larger armor stones. If the available footprint above OHWM allows for a structure slope of 1:1.5 or more gradual, it should be used.

The Hudson formula is the most simple and researched formula to determine armor stone size. It should be noted that using H_{10} instead of H_s will result in armor stones twice as large. The Hudson formula assumes two armor stones in each layer and is

$$W = \frac{w_r H^3}{K_D (S_r - 1)^3 \cot\theta} \qquad \text{Equation 7-5}$$

Where

W = design weight of a single revetment stone

w_r = unit weight of armor stone (1.5 $\frac{tons}{yd^3}$ or 1,780 $\frac{kg}{m^3}$)

H = design wave height

K_D = stability coefficient (assumed to be 2.2 for typical Puget Sound armor stones in breaking wave)

S_r = specific gravity of armor stone ($\frac{w_r}{w_w}$)

W_w = unit weigh of salt water (1,027 $\frac{kg}{m^3}$)

θ = slope of the structure

To determine the approximate average diameter size of each armor stone (D_{50}), use the following equation.

$$D_{50} = \sqrt[3]{\frac{W}{w_r}} \qquad \text{Equation 7-6}$$

It is also recommended, though not paramount, to know the approximate "man-rock" size using Washington Department of Transportation 9-13.7(1) Rock for Rock Walls (Table 7.5-1) to help determine size in discussions with construction contractors (WSDOT 2012). Man-rock is approximately how many men are needed to move one single stone and the classifications are widely used by contractors and rock suppliers. Most suppliers have sorted larger stones into man-rock categories.

Table 7.5-1. Rock size classes for revetment sizes (WSDOT 2012).

Rock Size	Rock Weight (lbs)	Average Dimension (in.)
One Man	50 to 200	12 to 18
Two Man	200 to 700	18 to 28
Three Man	700 to 2,000	28 to 36
Four Man	2,000 to 4,000	36 to 48
Five Man	4,000 to 6,000	48 to 54
Six Man	6,000 to 8,000	54 to 60

As mentioned above, a more gradual slope will result in smaller armor stones as determined by the cotangent of the angle in the denominator of the Hudson formula (Equation 7-5). A larger number in any denominator with all other variables the same gives a smaller result.

The placement of the armor stones is also important in successful revetment installations. Armor stones should have a landward batter (backward slope) during installation with all adjacent armor stones in tight contact; this results in a minimum of three points of contact with the stone below and both adjacent stones. The armor stones in the typical revetment cross section above (Figure 7.5-10) show a landward batter.

Equally as important in the success of the armor is the placement of the stone and the underlying filter materials. The bedding layer of quarry spalls should be compacted under the armor stones if the subsurface sediment is not glacial till or other geologic sediment with high strength. The quarry spalls should be compacted until they cannot be compacted further when placement on less structural sediment and have a top elevation equal to the embedment depth.

Hard armor design presumes that an adequate filter layer is present as part of the design. Geotextile should be located between spalls and native sediment throughout the installation. Geotextile fabric should be wrapped under armor stone or quarry spall at the extents to prevent the fabric from unraveling and tearing (Figures 7.5-1 and 7.5-10). It is sometimes permissible to not place geotextile fabric below the quarry spalls under the armor stones at the toe.

Armor Stone Toe Protection – Vertical Specific

A professional should determine if a vertical bulkhead will need armor stone toe protection due to the placement on the beach and up-drift geologic conditions. If a beach is expected to lower because of the installation or heavily sediment-starved up-drift conditions, armor stone protection could be needed. Hard armor is not dynamic and will not translate to a new backshore position. Armor stone toe protection may be required at high- to very-high-wave-energy sites where the bulkhead cannot be placed far enough landward to avoid the need. Sites with chronic erosion in these areas are most likely to need toe protection. In most cases, armor stone protection is a maintenance measure placed years after the original installation. Armor stones used for waterward toe protection for vertical walls should be angular, sound, hard, and durable rock. Placement needs to be to a sufficient embedment depth to prevent undermining and stones must be appropriately sized for the wave climate as discussed above in Toe Embedment Depth. All adjacent stones should be in contact when placed. Armor stone sizing should also use the Hudson Formula (Equation 7-5).

Maintaining Fill – Vertical Specific

Vertical bulkheads rely on the weight of the associated fill for strength against wave attack. Therefore, one critical element of a good bulkhead design that prevents or limits loss of backfill is allowing drainage of water through or away from the structure. Drainage releases pressure of excessive water from upland seepage, rainwater, and wave overtopping. Weep holes need to be designed to allow water to drain through the structure. Geotextiles allow water, but not sediment, to filter through the structure. Geotextiles are difficult to install over the full depth of the structure because of mechanical pile-driving. Gravel between the bulkhead and native fill also allows for drainage and mitigates sediment loss (Basco 2006).

Another critical bulkhead design element that helps maintain fill is return wall design. Return walls should be designed to limit waterward reflection of waves but also to retain backfill for structural integrity (Basco 2006). Landward extents of return walls should be designed to maintain sediments while minimizing ecological impacts by not encroaching too far into the marine riparian habitat. Typical return wall geometry is shown in Figure 7.5-9.

Design Example

The Blakely Island revetment site surveyed for this effort (Appendix A) will be used as a design example for using these hard armor technique guidelines. It must be noted that soft shore protection is feasible for Blakely Island under these guidelines but the project site is being used for example purposes.

The following project site data are needed for design:

Fetch: 4.8 mi (7.7 km; from Appendix A)

HOWL: +11.2 ft MLLW (3.4 m from station 9449880 Friday Harbor, WA Benchmark sheet)

MHHW: +8.0 ft MLLW

The significant wave height and period are determined using Equations 7-1, 7-2, and 7-3:

Wind stress factor (using equation 7-1): $U_a = 0.71 * 10^{1.23}$= 12.06

Significant wave height (using equation 7-2): $H_m = 1.616 * 10^{-2} 12.06\sqrt{7.7}$= 0.54 m which is also equal to the maximum scour depth

Significant wave period (using equation 7-3): $T_m = 6.238 * 10^{-1} (12.06 * 7.7)^{1/3}$= 2.8 sec

It is assumed that budget allows for a conservative approach and the design wave height should be

H_{10} = 1.27H_s = 1.27(0.54m) = 0.68 m (Equation 7-4)

Because there is plenty of backshore area on the project site (the setback distance is 31 ft; Appendix A), this example will use two different feasible slopes to numerically depict tradeoffs with slope, crest height, and armor size; however, a slope of 1:2 will be used for the typical design. A slope 1:3 will be used to show the differences in armor stone size needed, backshore burial width, and crest elevation needs. The available backshore area also makes a revetment more viable than a vertical bulkhead.

In order to determine crest height, wave runup (R) must first be determined. Figure 7.5-5 and the series of resulting calculations will be used for wave runup for this example but there are numerous ways to determine wave runup in the references listed.

Wave runup:

$\frac{H}{gT^2}$= x-axis in the graph in Figure 7.5-7 using H_{10}= $\frac{0.68}{9.81*2.8^2}$= .009

$\frac{H}{gT^2}$= x-axis in the graph in Figure 7.5-7 using H_m= $\frac{0.54}{9.81*2.8^2}$= .007

y-axis in Figure 7.5-7 for 1:2 slope and H_{10} = 0.73 = $\frac{R}{H}$ Therefore R=0.73 * 0.68m = 0.50 m

y-axis in Figure 7.5-7 for 1:3 slope and H_{10} = 0.69 = $\frac{R}{H}$= Therefore R = 0.69 * 0.68m =0.47 m

y-axis in Figure 7.5-7 for 1:2 slope and H_m = 0.73 = $\frac{R}{H}$ Therefore R=0.73 * 0.54m = 0.39 m

y-axis in Figure 7.5-7 for 1:3 slope and H_m = 0.69 = $\frac{R}{H}$= Therefore R = 0.69 * 0.54m =0.37 m

Design water height for 1:2 slope: HOWL + Runup + SLR = +3.4m + 0.50m +0.47m = 4.37m MLLW = +14.33 ft MLLW

Design water height for 1:3 slope: HOWL + Runup + SLR = +3.4 + 0.47m + 0.47m = 4.34m MLLW = +14.23 ft MLLW

The following cross section (Figure 7.5-11) of the current revetment at the project site (Appendix A) shows that the exposed toe of the current structure is at a recommended location because it is above MHHW and most likely is very near or at the OHWM. (The latter was not determined in the field the day of the assessment.) For this exercise, +10ft MLLW will be the proposed exposed structure toe elevation which is equal to the approximate current exposed toe. Therefore, the height of the wall is either 4.33 ft if using 1:2 slope or 4.23 using 1:3 slope.

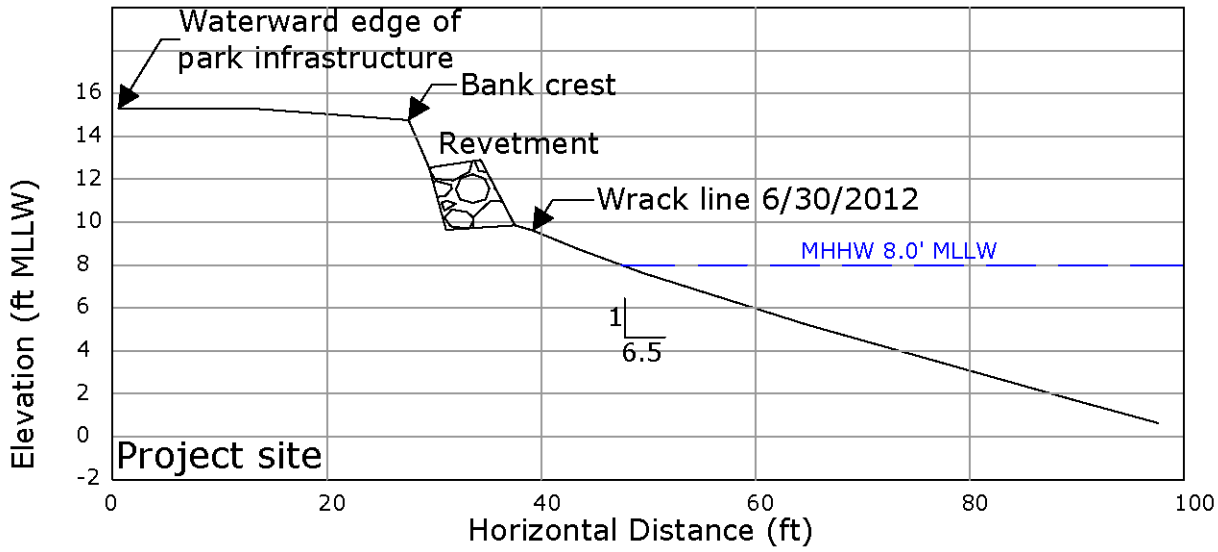

Figure 7.5-11. Blakely Island revetment existing project site cross section (Appendix A).

Armor stone size mass determination using the Hudson formula (Equation 7-5) for a 1:2 slope:

$W = \frac{1{,}780\frac{kg}{m^3}(0.68m)^3}{2.2(\frac{1{,}780\frac{kg}{m^3}}{1{,}027\frac{kg}{m^3}}-1)^3*2}$ = 322.7 kg = 711 mass pounds (for comparison, using H_s would result in 161 kg)

Armor stone size mass determination using the Hudson formula (Equation 7-5) for a 1:3 slope:

$W = \frac{1{,}780\frac{kg}{m^3}(0.68m)^3}{2.2(\frac{1{,}780\frac{kg}{m^3}}{1{,}027\frac{kg}{m^3}}-1)^3*3}$ = 215 kg = 473 mass pounds (for comparison, using H_s would result in 108 kg)

Armor stone size average diameter determination using the Hudson formula (Equation 7-6) for a 1:2 slope:

$D = \sqrt[3]{\frac{322.7kg}{1{,}780\frac{kg}{m^3}}}$ = 0.57m = 1.9 ft or a three-man-rock (or very large two-man-rock) using WSDOT (2012)

Armor stone size average diameter determination using the Hudson formula (Equation 7-6) for a 1:3 slope:

$D = \sqrt[3]{\frac{214.7kg}{1{,}780\frac{kg}{m^3}}}$ = 0.49m = 1.6 ft or a two-man-rock using WSDOT (2012)

Therefore, the burial depth should minimally be H_m + 0.5D = 0.54 m + 0.49 m = 0.79 m = 2.6 ft unless otherwise determined by a geotechnical engineer. A cross section of this design is shown in Figure 7.5-12.

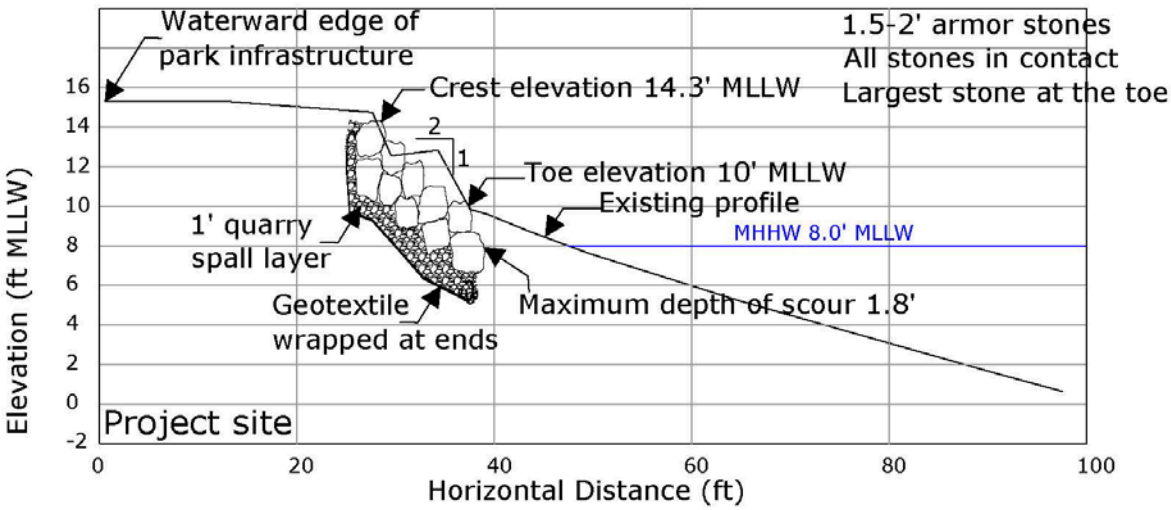

Figure 7.5-12. Cross section of Blakely revetment example developed for this document (2x vertical exaggeration)

Comparison of the existing profile to the design reveals that the original Blakely Island design did not have adequate design height. Field observations showed scarping and LWD landward of the rock structure, as well as inconsistent rock sizing and structure slope as seen in the field photo below. (Figure 7.5-13).

Figure 7.5-13 Field photo from Blakely Island assessment.

Cost

Construction costs are defined for this technique for planning purposes and do not include project site assessment, survey, design, permitting, remote site access, archeological assessment/investigation, or any other project-specific provisions. Smaller projects with fewer linear feet of shore and/or project sites with difficult access generally increase the price per linear foot substantially. Table 7.5-2 lists typical cost ranges for revetments while 7.5-3 lists typical construction costs for vertical bulkheads; however, this information is not based on data from the VB or RV project sites as costs of the four assessed sites were not available. The estimated amounts in these tables are based on professional experience with designing and cost-estimating shoreline and retaining structures, in addition to discussions with construction contractors that specialize in Puget Sound shoreline armor installation. Note that site location is one of the most significant variables when estimating costs. Projects in Snohomish and King County can be up to twice as expensive as other counties for installing the same project because of cost-of-living variations. Non-King and Non-Snohomish locations have been assumed for this guidance document in the tables below. Distance from material suppliers is another reason why project location impacts the costs. Remote access could result in barging equipment and material to the project site and a consequent increase in the overall bottom line. Also, it is typically more expensive to design a vertical bulkhead, especially a concrete vertical bulkhead, than a revetment.

Table 7.5-2. Material and construction costs per lineal foot for residential-scale revetment projects using 2012 dollars.

WAVE ENERGY	TONS OF MATERIAL/LF	CONSTRUCTION COSTS/LF
Low*	2-3	$125 to $175
Medium	3-5	$175 to $300
High	5-10	$300 to $550

Revetment installations at low-wave-energy sites are not optimal or recommended and have extremely strenuous permitting requirements. As stated before, soft shore protection measures must be deemed infeasible by a professional before hard shoreline structures are considered under Sound-wide permitting requirements. This low-energy hard-armor option should only be used for cost comparisons in the rarest cases.

Table 7.5-3. Material and construction costs per linear foot for vertical bulkhead projects using 2012 dollars.

MATERIAL TYPE	WAVE ENERGY	CONSTRUCTION COSTS/LF
Concrete	Medium	$300 to $400
Concrete	High	$350 to $450
Vinyl	Medium	$400 to $500
Vinyl	High	$450 to $550
Wood pile	Medium	$225 to $300
Wood pile	High	$275 to $350

Monitoring

Hard armor installations should be monitored to determine performance and if maintenance is needed. Due to the static nature of hard armor the installations can be assumed to be immobile. Therefore, hard armor installations can be their own baselines. Physical and photographic monitoring techniques can be

used to monitor a hard armor project (Figures 7.5-14 and 7.5-15). Physical monitoring consists of simple twice-annual measurements of topography of the structure crest, structure toe elevation, and beach profiles to provide baseline data and characterize seasonal beach cycles to determine interannual variability. Spray paint or pin flags are used to mark landward extents of tidal waters and wave climate.

Figure 7.5-14. Simple physical monitoring of a bulkhead showing the scalable photographic technique of using a person or measuring tape in the picture. Photographic monitoring should be done yearly at a minimum and in the same location with the same reference. In this case, the same adult should be photographed next to the bulkhead every monitoring cycle. Note pink spray paint line showing king tide elevation extent in the picture on the right.

Hard armor should also be physically monitored for structure-caused erosion (both end erosion and waterward beach coarsening) and rock toppling. Sampling periods are at the end of the summer and at the end of winter. Ideal sampling times are within the last 3 weeks of September (summer beach), and during March (winter beach), when daytime tides are near 0 feet MLLW. Beach sediment composition in front of the revetment is also important to record during sampling events. Photographs taken at the sampling times from fixed locations with a scalable and consistent reference can add valuable information over time.

Figure 7.5-15. Photographic monitoring looking onshore with scalable reference of vertical bulkhead. Photographic monitoring should be done yearly at a minimum in the same location with the same reference for every cycle. In this case, the same station rod or one with a similar scale should be used.

Photographs of the substrate waterward of hard armor should also be documented while monitoring. The technique for photographic monitoring of substrate and other monitoring techniques can be found in Chapter 8.

Maintenance

Revetment maintenance usually involves restacking toppled rock, clean up of revetment-originated beach debris, and placement of beach nourishment sediment waterward of the structure, usually in the up-drift section. Bedding layer rock that filters through the armor layer onto the beach face should also be removed, especially if in documented forage fish habitat. Landowners can perform simple maintenance if needed, but equipment involving permits and site access will be needed to restack armor stones and for placement of sediment for beach nourishment. Therefore, rock sizing and design geometry of the structure should be determined such that no structure maintenance will be required for a minimum of 15–20 years to keep the project affordable over time, limit site disturbance, and limit the difficulty of acquiring permits. Design for possible beach nourishment at a site with revetments could be a permit requirement or needed after monitoring has shown substantial beach and end-area erosion.

By design, bulkheads are used when maintenance is not practical and the risk of structure damage is high. Therefore, when maintenance is required, it is costly and is usually because the structure itself produced increased erosion waterward and/or adjacent. Bulkheads should be designed for a long project life but sometimes maintenance is required due to the challenge of being an inflexible structure installed in a nearshore, dynamic environment. Maintenance could be needed if the structure is no longer vertical or if the footing is exposed. Armor stones have been placed waterward of bulkheads for structure toe protection. The Samish Island site (Appendix A), with one wall reach leaning waterward, was the only vertical bulkhead project that was not consistently vertical, a result of several landslides that occurred after wall installation that threatened the integrity of the wall. The owner mentioned

wanting to remedy the issue with structure maintenance but had not obtained the permit and had not determined what type of structural maintenance was to be done.

Maintenance should take into account the causes of damage to the structure. In-depth analysis of subgrade conditions may be necessary to determine these causes, which could include slippage of soil horizons or increased ground-water loading resulting from development of the site. Without this understanding, possible repair of the structure may not result in enhanced design life.

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Chapter 8. MONITORING

Ideally, development of a monitoring approach begins with the initial site assessment. Although a formal monitoring plan may only be required during the permit application process, aspects of a monitoring plan should be considered during both the feasibility and design phases. The primary features of the site and how they fit into a broader coastal context help determine project "success" not by only meeting the specific needs of the site, but also through the level of impact or benefit provided to the nearshore environment. Monitoring of specific types of restoration and enhancement measures is outlined in *Management Measures for Protecting and Restoring the Puget Sound Nearshore* (Clancy et al. 2009). Bluff monitoring methods are discussed in Thorsen and Shipman (1998).

Statement of Objectives

A clearly stated list of project goals and objectives must be understood by all entities involved prior to implementation. The goals help in development of a list of measurable parameters with which to gauge project performance through monitoring.

Project Goals

Of primary concern for judging project performance is how well the project goals are met. An initial goal typically includes stopping or slowing coastal erosion or restoring habitat and may be put forward by the project proponent. Another set of goals comes from the legal or permit requirements of the project, and often includes a "no adverse impact" approach to important habitats such as eelgrass beds and forage fish spawning beaches. All of these project goals should be itemized to determine what and how much monitoring should be performed.

Monitoring Objectives

The Project Goals feed directly into a set of monitoring objectives: a set of elements by which project success can be measured. These are then used to develop a list of specific data that can be collected and documented in an objective and repeatable way in order to measure success relative to project goals.

Success Criteria

Once specific elements are identified for monitoring, then specific thresholds should be identified against which the observations or data can be compared. Success criteria for project performance in terms of reducing erosion (e.g., damage to a structure) and off-site impacts (e.g., end-effect erosion) are both important when developing a monitoring plan. Of course, not all impacts can be anticipated, and personnel performing the monitoring should be trained to watch for and document potential problems or unanticipated project benefits.

Mitigation Steps

Should the monitoring data not meet the success criteria, then mitigation for the failure or impact should be allowed for. Specific actions could be listed in the monitoring plan, such as a specific trigger for the addition of beach nourishment sediment, replanting, or repair of damaged structures. However, often an impact will require examination by a licensed professional for determination of mitigation steps.

Monitoring Protocol

Geographic Extent

The aerial extent of monitoring should be identified early in the process. At a minimum this will allow enough data to be collected on-site to determine whether the project goals have been met, but potentially impacted sites (e.g., down-drift beaches) should also be included. Ideally, nearby reference sites will be included for comparison to the project site to aid in determining whether potential success or failure stems directly from the project action or from background influences.

Temporal Extent

The length and timing of monitoring efforts should be determined during development of the monitoring plan. Monitoring typically covers at least 3 to 5 years in order to include more than just the initial adjustment phase prior to construction. Project complexity and objectives should be considered when deciding how long to monitor, with simple projects requiring less time, and larger complex projects requiring more time, to determine effects and overall performance.

Timing of each monitoring event should be consistently repeated in terms of season and tide cycle. Spring (March– early May) and late summer (August– September) are often good choices to capture the winter or summer beach profiles respectively. As discussed in Chapter 3, the physical and biological aspects of the nearshore tend to vary seasonally in Puget Sound, so consistent application of timing should be applied to reduce the seasonal “noise” in monitoring observations. For example, dense eelgrass beds seen in middle to late summer may be much reduced in winter or spring; should eelgrass beds in these two seasons be mistakenly compared, erroneous conclusions of heavy habitat impacts could be reached. Monitoring may be performed twice annually, at least initially, to help determine the seasonal variability.

Baseline Conditions

Gathering of baseline monitoring data is particularly important, because without baseline data conclusions regarding performance and post project change cannot be made. Additionally, monitoring elements for the as-built conditions of the project should be measured very soon after project completion.

Common Monitoring Elements

Many monitoring plans are similar in the methods they specify for monitoring the physical and biological characteristics of a coastal site (Table 8-1).

Table 8-1. Common physical and biological monitoring elements and their data collection methods.

Beach characteristic	Examples of monitoring method
Beach profile	Level and stadia rod, two-stick method, total station, topographic survey
Sediment	Grain size analysis, photographs with scale
Driftwood	Map locations, transect counts, photographs
Saltmarsh vegetation	Assemblage mapping, density measurements
Submerged aquatic vegetation	Waterward extent, patch density, turion count
Invertebrates	Benthic coring, drop trays
Forage fish	Sediment sampling with egg counts

Physical

The geomorphic, hydrographic, and other nonliving features of a project make up the physical characteristics of the site. As with all beach monitoring, it is important to perform monitoring with consistent interannual timing to avoid seasonal variability. Beach profiling can be performed using methods ranging from a very simple two-stick method to standard surveying methods using a total station for profile measurement, or ideally full beach topography. Permanent benchmarks are typically required for all methods to mark the locations of profiles and to provide a consistent reference elevation. The most common benchmark is a length of rebar (sufficiently long to be generally immobile) driven into the backshore away from storm waves.

Topographic surveying may be employed for larger sites, or where detailed quantitative analysis of results is necessary. The topographic data produced can be used not only to develop beach profiles, but to determine the volume change of a beach over time. While the results are often considered a reliable way to analyze physical changes, the cost may be prohibitive for some sites such as small residential projects.

Changes in beach sediment over time can be an important indicator of impacts to the nearshore. Coarsening of the beach could indicate increasing wave energy due to focusing or reflection of wave energy (Shipman et al. 2010). The most reliable method of sediment characterization is to collect a sample for grain size analysis. This involves sorting the sample into size fractions using a series of sieves of decreasing size to determine the proportion of each weight class within the whole. Scaled photographs may also be taken of specific beach locations and elevations for a more qualitative analysis of change in time.

Biological

Saltmarsh vegetation plays an important role in the nearshore environment, and should be monitored for changes in coverage and assemblage. The simplest of methods is to identify the elevation, cross-shore width, and primary species of salt-tolerant plants. More advanced methods include the use of random quadrat placement for plant density and abundance measurement. It should be noted that interannual and seasonal variability are to be expected, so a longer-term record may be necessary to determine significant trends.

As with saltmarsh vegetation, submerged aquatic vegetation assemblages provide important habitats for monitoring, with eelgrass species the most noteworthy (*Zostera marina* and *Z. japonica*; Mumford 2007). Submerged aquatic vegetation is primarily monitored to determine the impact a project has on the aerial coverage of the habitat. Monitoring may consist of simple mapping of the landward (and potentially the waterward) extent of the eelgrass bed, but could also include density measurements (e.g., turions per m^2) obtained through dive surveys. The growth period of eelgrass in the project area should be noted to time monitoring for the middle of the summer growth period, and avoid other seasons when eelgrass may be removed by wave action.

Invertebrate assemblages are usually impacted in some way, often negatively, by shoreline modifications, either temporarily through direct disturbance of beach substrate during construction, or through long-term alteration of the character of the nearshore environment (Shipman et al. 2010). Invertebrate monitoring can be used to track how shoreline alterations impact these assemblages in abundance and diversity. Typically sediment cores are collected for laboratory analysis for species diversity and other relationships.

Forage fish are important marine species that are considered a primary food source for adult salmon and a wide variety of marine animals (Penttila 2007). Included are three species that make exclusive use of the nearshore for spawning purposes: surf smelt (*Hypomesus pretiosus*), Pacific sand lance (*Ammodytes hexapterus*), and Pacific herring (*Clupea pallasii*). Pacific herring spawn within eelgrass beds, while surf smelt and sand lance spawn on the upper beachface. Communities of these fish spawn in a variety of locations and seasons throughout the Puget Sound, and spawn presence and timing should be investigated to determine need prior to developing a method of monitoring for spawning activity. For the best available science concerning sampling and analysis for surf smelt and sand lance eggs see Moulton and Penttila (2001).

Qualitative

Smaller projects may not require the level of data gathering (and potential cost) of a large monitoring effort. For small projects qualitative assessment methods may be developed to help streamline the monitoring process while still measuring project performance in a reproducible way. The simplest method is development of a set of “photo points”: from each point a photo is taken in the same direction at regular intervals with some fixed object for comparison year-to-year (Figure 8.X). A landowner may be able to take these photographs at monthly intervals for long periods as well as capture major events such as severe wind storms. Data collected in this way should still be examined by a trained professional prior to determination of project success. Photographic methods can reliably estimate changes in beach elevation and sediment composition over time.

Figure 8-1. An example of the beginning of photo monitoring from a fixed point over the first year post-project looking alongshore.

Reporting Monitoring Results

Monitoring data and analysis should be compiled at least annually in a format that allows subsequent analysis against the established success criteria. Project data is best displayed graphically and in map layouts.

Monitoring Plan Checklist

While each monitoring plan will be tailored to the specific requirements of each project, some elements are common to all such plans. This checklist serves as a beginning point for developing a plan that includes all the relevant information.

1. Statement of objectives
    a. Project goals
    b. Monitoring objectives
    c. Success criteria
    d. Mitigation requirements
2. Monitoring protocol
    a. Geographic extent of monitoring, outlined using appropriate maps and figures showing data collection locations and permanent reference points such as benchmarks
    b. Temporal extent of monitoring, with duration and frequency of monitoring elements outlined to include both seasonal and tidal considerations
    c. Data collection methods and techniques for each monitoring parameter described, including specific equipment and training required
3. Mitigation requirements
    a. Mitigation threshold, explaining method for measuring the need for compensatory mitigation of project impacts
    b. Mitigation steps to be taken should a mitigation threshold be crossed, e.g., specific steps such as addition of beach nourishment or a more general need for determination by a trained professional
4. Reporting protocol
    a. Number and distribution of copies of monitoring report
    b. Formats for reports and data
    c. Frequency of monitoring report submission

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Chapter 9. RESEARCH AND DEVELOPMENT

The marine shorelines design guidelines were developed by integrating new and existing design performance data with applied knowledge from Puget Sound professionals with expertise in the fields of coastal geology, engineering, geomorphology, management, and ecology. The case study assessment data (Appendix A) were compiled specifically for preparation of these guidelines. Although these data have limitations, they can also provide a valuable foundation for future research. The management recommendations described in this document are also dependent on the current state of the understanding of coastal and nearshore ecosystem processes in the region. Throughout the development of this study, a number of additional research opportunities were identified that could refine engineering approaches and designs, help to better management, and enhance local understanding of coastal ecosystem processes.

The case study assessment entailed detailed field data collection from several project examples and adjacent reference sites from each of the 6 original marine shoreline design techniques (beach nourishment, large wood, reslope/reveg, bulkhead removal, and hard armor). Considerable effort was put forth in the quality of the data collected and the ability to replicate the measures if the opportunity arose. Revisiting these same sites to document changes in site conditions could be informative, as the episodic, event-driven nature of Puget Sound geomorphic conditions results in changes that are often difficult to discern across shorter time periods. Many projects had not been installed for many years and long-term monitoring could provide additional information on the longer-term effects and design elements that contribute to longer-term success.

Augmenting the case study assessment data with additional case study sites would also prove valuable. Considerable time was spent identifying sites that met the site assessment criteria and acquiring permission to access the sites. Several potential sites were identified that simply had not been installed for long enough (3-year minimum) to meet the criteria when initiated in 2011, but would fulfill that criteria in the future. Additional sites that meet the project criteria should be surveyed to bolster the data set. With enough additional sites, more robust statistical analysis could be conducted that could aid in the identification of thresholds and further inform the degree to which certain variables drive project success. Effort could also be put into assuring that the full range of conditions was represented in the expanded data set.

Developing a regional database of shoreline design projects that would be regularly maintained by one entity could provide many values such as aiding in enforcement, academic research, and providing data to design professionals. The database would ideally house permit, design and monitoring data for all Puget Sound projects, and could be organized geographically and by project type. The data base should also include ownership data, original design drawings, baseline and as-built surveys, before and after photos, other supporting reports and assessments, contractor information, monitoring requirements, and monitoring results. Long-term monitoring data could help researchers discern background noise or natural variability from subtle changes in the variables that are driving geomorphic trends or the success of a given shoreline design technique. This type of database could enhance the efficacy of project tracking, monitoring success, and eventually be used for a larger meta-analysis that could further inform and refine some of the recommendations offered in this effort.

Considerable research and mapping efforts have been applied across the 2,500 miles of the greater Puget Sound shore in recent years. Millions of dollars are invested annually in restoration projects in the Puget Sound, yet there are still data gaps that need to be addressed for better management. Addressing these data gaps could considerably decrease the uncertainty associated with project success for many restoration engineers and designers. Data gaps include:

- Nearshore bathymetry is highly variable and generally lacking in resolution throughout the region and integral to coastal modeling, which is fundamental to design
- Quantifying the range of erosion rates and sediment input across different drift cells and geomorphic shoretypes within the region would further advance the baseline understanding of geomorphic processes in Puget Sound
- Detailed investigation of the potential impacts to biota resulting from the alternatives to hard armor (and compared to the impacts from hard armor) could be very informative. Similar to recent research conducted by Dethier et al. (XXXX) this potential research could inventory biota from soft shore protection sites along with paired reference sites
- Improving quality and availability of airborne LiDAR, with emphasis on correctly capturing bluff crest and toe positions and elevations in processing

Specific data gaps relative to developing the details of different design techniques include:

- Tracking different size gravel particle transport at beach nourishment sites
- Quantifying sediment volume loss rates at beach nourishment sites
- Detailed observations of wave-log interactions
- Development of low-cost, semi-quantitative consistent ways to evaluate effectiveness of vegetation in stabilizing different soil/sediment types
- Paired sediment mobility/stability with utilization by biota at bulkhead removal sites
- Hard armor-beach interactions at mixed gravel and sand and sheltered coast shores.

Many opportunities exist to expand on the data derived from this effort. Augmenting and formally developing a shoreline design data base could provide exceptional value for managers, researchers, and designers alike. Further research that aims to quantify the range of variability in geomorphic conditions across space and time in the Puget Sound, higher resolution mapping of nearshore bathymetry, and wave data could further inform restoration designs. Together these research and data management developments could lead to greater certainty in the success of restoration designs and result in improved management with reduced negative impacts. Additionally, these data would yield improved local understanding of how Puget Sound nearshore conditions may change across time, particularly in the context of climate change and sea level rise.