# 3. FEATURES OF PUGET SOUND REGION: OCEANOGRAPHY AND PHYSICAL PROCESSES

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## REGIONAL SETTING

Puget Sound is the southernmost of a series of interconnected, glacially scoured channels that include the Strait of Juan de Fuca and Strait of Georgia in Canada.  The entrance to the Sound is about 135 km from the Pacific Ocean.  Glaciers have repeatedly occupied the Puget Lowland. At least three and possibly as many as six episodes of glaciation have rearranged the landscape and left evidence of their passage in the rocks and sedimentary record.  The most recent glaciation, called the Fraser, extended as far south as Olympia.  At its maximum extent 14,000 to 15,000 years ago, the ice sheet was about 7,000 feet thick at the international border and tapered to about 4,000 feet at Port Townsend.  The Puget Lobe of the most recent glacier created the north-south fabric of the topography and deposited in its wake the Vashon Till that currently blankets much of the region.

On most geographic maps, Puget Sound is defined as the total body of water south and east of a line between Partridge Point on Whidbey Island and Point Wilson at Port Townsend.  This definition includes the water east of Deception Pass, which is at the north end of Whidbey Island. These waters are generally divided into four major basins: Hood Canal, South Sound, Whidbey Basin, and the Main Basin.  The latter is further subdivided into two parts: Admiralty Inlet, which extends from the northern limit of Puget Sound to the southern tip of Whidbey Island, and the Central Basin, which extends from the southern tip of Whidbey Island to Commencement Bay.  Each of the basins forms a depression on the seafloor in which a shallower sill separates the relatively deep water from the adjacent basin.  The study area's bathymetry and topography are shown in Figures 9 and 10.  The shoreline lengths, volumes, and depths of the Puget Sound basins can be obtained from several sources (Ebbesmeyer et al. 1984; Burns 1990; Duxbury 1987; Bostick 1955).  There are slight differences among these sources, apparently because of the tidal datum of the calculation.  The data of Duxbury (1987) are summarized in Table 1.

**Table 1:    Comparison of basin physical characteristics for Puget Sound**

| Region | Area* km²/% | Volume* km³/% | Shoreline* km | Mean Depth* m | Tideland km² |
|---|---|---|---|---|---|
| Admiralty Inlet | 437.1/17.0 | 15.2/9.4 | 171.3 | 34.7 | 18.2 |
| Central Basin | 747.5/29.1 | 74.0/45.7 | 535.3 | 98.5 | 48.5 |
| Whidbey Island | 378.6/14.7 | 24.0/14.8 | 471.0 | 63.0 | 130.3 |
| Southern Basin | 618.4/24.1 | 28.0/17.3 | 620.9 | 45.1 | 63.6 |
| Hood Canal | 385.6/15.0 | 20.9/12.9 | 342.6 | 53.8 | 42.4 |
| Total | 2567.2 | 162.1 | 2141.0 | 62.8 | 303.0 |

Source:  Duxbury 1987
Note:    Admiralty Inlet and the Central Basin comprise the Main Basin.
*Based on MHW datum

Though the study area lies entirely within the Central Basin, some comparisons among the basins are of interest. A detailed comparison can be found in Burns (1990). The total length of shoreline is 2,141 km (1,330 mi) consisting of shore platforms, coastal bluffs, numerous beaches, tidelands, and embayments. The Main Basin (Admiralty Inlet and Central Basin) is the largest, comprising about 46 percent of the surface area and more than 55 percent of the water volume. The Central Basin has the greatest average depth of nearly 100-m. The deepest point in Puget Sound at more than 280 m (920 ft) is located in the Central Basin just south of the Kingston-Edmonds ferry route. The average depth of Admiralty Inlet is less than half that of the Central Basin. The main sill of Puget Sound is located at the north end of Admiralty Inlet where the water shoals to a depth of 65 meters at its shallowest point between the north Quimper Peninsula near Port Townsend and Whidbey Island north of Admiralty Bay.

About 43 percent of Puget Sound's tideland is located in the Whidbey Island Basin. This reflects the strong influence of the Skagit River, which is the largest river in the Puget Sound system. Skagit River sediments are responsible for the extensive mudflats and tidelands backing the east side of Skagit Bay.

The waters of Puget Sound function as a partially mixed, two-layer system, with relatively fresh water flowing seaward at the surface and saline oceanic water returning landward at depth. The seaward surface flux is balanced by the landward flux at depth. The seaward flux is augmented by the freshwater inflow from several large rivers and many smaller streams. Primary contributors to the freshwater input are the Skagit and Snohomish Rivers, both of which discharge into the Whidbey Basin. These rivers, along with the smaller Stillaguamish, contribute 60 percent of the freshwater inflow and account for about 50 percent of the drainage area of Puget Sound. About 50 percent of this freshwater is thought to enter the Main Basin of Puget Sound while the remainder works its way through Deception Pass into Rosario Strait (Barnes and Ebbesmeyer 1978). The freshwater input directly into the Main Basin, primarily from the Puyallup and Duwamish Rivers, accounts for only 20 percent of the total drainage into the Sound (Burns 1990; Downing 1983). As a result of the small freshwater inflow into the Central Basin and the large amount of tidal energy, the water is not strongly stratified most of the year. Stratification is greatest in summer because of the combined effects of river discharge and solar heating. The Central Basin is the least stratified in winter because of winter cooling and the mixing effect of increased wind.

## TIDES AND SEA LEVEL

The tides in Puget Sound are mixed-semidiurnal (i.e., two high and two low tides each lunar day with unequal amplitude). The tidal range increases southward into the Sound from less than 3 m in the north to more than 5 m near Olympia. Most of the tidal flow (about 98 percent of the tidal prism) enters the Sound at Admiralty Inlet, where the outer sill is 65 m deep. The inner sill separating Admiralty Inlet from the Central Basin has a depth of about 105 m. Approximately two-thirds of the water column in the Central Basin lies below the depth of the shallower sill in Admiralty Inlet.

**Figure 9　　WRIA 8 Nearshore Bathymetry and Topography**

**Figure 10    WRIA 9 Nearshore Bathymetry and Topography**

Because of the large amount of tidal energy, turbulent mixing takes place at the outer sill of Admiralty Inlet. Water in the surface layer exiting Puget Sound entrains water from below and is mixed downward as well. As a result of this mixing about half of the flow is recycled and returned to Puget Sound (Ebbesmeyer et al. 1984).

In the Central Basin, the estuarine circulation mainly consists of outflow in the surface layer and inflow at depth. Studies by Ebbesmeyer and Cannon (2001) indicate that the null-velocity depth (i.e., the depth of zero mean flow) is at approximately -50 meters. At this depth, the estuarine flow changes from outflow to inflow. An exception to two-layer flow occurs in the southern part of the Central Basin, where geometry has a significant effect. In East Passage, the net flow at all depths, except for a very thin surface layer, is southward. In Colvos Passage west of Vashon Island, residual flow is northward at all depths because of the tidal circulation around Vashon Island caused in part by the strong northward ebb out of the Narrows (Lavelle et al. 1988).

Sea level is changing slowly in the Puget Sound region. The isostatic (rebound) adjustment after the retreat of the last glacial maximum is no longer thought to be important to sea level changes in this region. The mean continental adjustment is associated with the crustal subduction and underthrusting of the oceanic and continental plates off the coast. Near Seattle, the crust is subsiding as much as 2mm/yr while on Vancouver Island the land is emerging at a rate of 1 to 3 mm/yr. Combined with the observed sea level rise of about 1 mm/yr, the land around the southern end of Puget Sound is sinking at an annual mean rate of 2 to 3 mm/yr while that on much of Vancouver Island is rising at an annual mean rate of 1 to 2 mm/yr. This scenario does not take into account the possibly rapid and catastrophic readjustment that may follow a major earthquake (Newton et al. 1997).

## WIND PATTERNS

The topography adjacent to the Sound constrains the wind within channels, which are primarily oriented north-south. From October through March the flow is predominantly from the south-southwest. Through the spring, this flow gradually reverses direction until it is predominantly from the north. The patterns of flow have been confirmed by long-term (1930-1978) measurements at West Point and, to a lesser extent, by measurements at Sea-Tac Airport. Highest monthly wind speeds are in the range of 6 to 9 m/sec and are from the south between September and May. Highest net wind speeds from the north are of lower velocity and are in the range of 5 to 7 m/sec. The winds do not show a significant sea breeze effect as is evident in the Strait of Juan de Fuca and along the open coast (Coomes et al. 1984).

## WAVES

Wave conditions in the Central Basin are generally mild even though storm winds are occasionally severe. Waves are locally generated, and height and period are limited by fetch and somewhat limited by the narrow channels. There are no long-term (order of several years) wave measurements within the Sound. However, a wave buoy was installed at a site 2 miles southwest of West Point in 1993 and recorded data from September 1993 to December 1994. The largest significant wave height, defined as the average of the highest one-third of the waves in the record, was 3.3 ft with a wave period of 5.1 seconds (Shepsis et al. 1995). This measurement implies a maximum wave height of about 5.8 ft. Shepsis reports that wind waves with

significant heights from 1.0 to 1.3 ft were observed 40 percent of the time; waves of 1.3 to 2.25 ft, 25 percent of the time; waves 2.25 to 3.2 ft about 15 percent of the time; and waves greater than 3.2 ft were observed about 10 percent of the time.  Remaining periods were calm.

Most wave studies have been conducted on a project basis and may involve a short measurement period coupled with wave estimates based on wind conditions and accounting for orographic effects and bottom refraction.  Simpson (1995) conducted such a study to evaluate wave conditions and run-up at Richmond Beach near Edmonds.

## SOURCES OF SEDIMENTS

Lavelle et al. (1986) studied the sources and accumulation rates of sediments in Puget Sound, primarily along the axis of the Central Basin, using $^{210}$Pb.  The study showed that bottom sediments are accumulating at rates of 0.26 ±0.03 to 1.20 ±0.16 g cm$^{-2}$ yr$^{-1}$.  Sedimentation rates, though variable, are largest in the central area near Elliott Bay, are much lower to the north near Admiralty Inlet, and are smaller to the south through East Passage.

Sediments in the Central Basin can be contributed from several possible sources: (1) rivers such as the Duwamish and Puyallup, which discharge directly into the Central Basin, and the Skagit, Stillaguamish, and Snohomish, which discharge into the Whidbey Basin; (2) slumping and submarine erosion of the side walls of the basin where slopes of 20 percent are common; (3) bluff erosion along the shoreline; (4) atmospheric, biological, and waste water inputs (thought to be small); and (5) possible influx through Admiralty Inlet from sources outside of the Central Basin.

Though some (i.e., Carpenter et al. 1985) have suggested that river sediments are sufficient to account for all of the observed sediment accumulation, a considerable amount of those sediments are trapped in the rivers' lower reaches and deltas and do not contribute to the basin.  Dredging records indicate that 87 percent of the sediment load of the Duwamish is deposited in the lower section of the river.  The sediment load from the Skagit, Stillaguamish, and Snohomish Rivers is two to three times that of the Duwamish and Puyallup combined, but those three rivers discharge into the Whidbey Basin and their sediments have formed an extensive delta and tidal wetland.  It is as yet unknown whether a significant portion of the sedimentary material from the Whidbey Basin rivers finds its way into the Central Basin.  In localized areas, small independent drainages (i.e., Des Moines Creek, Picnic Point Creek) deliver sufficient sediment to the nearshore to create small deltas.  Delta materials may be redistributed by littoral drift (see below).

Bluff erosion may make a significant contribution to deep sediment accumulation.  Lavelle, et al. (1986) indicates that, if spread evenly across the bottom of the Central Basin, the material derived from bluff erosion and collapse would result in an areally averaged deposition rate of 0.14-g cm$^2$ yr$^{-1}$.  Sediments entering through Admiralty Inlet do not contribute to the total supply estimates in the Central Basin.

The nearshore sediments within the Central Basin, except in the areas dominated by river deltas, are primarily derived from steep glacial till bluffs.  Natural beaches forming at the toe of the bluff are coarse grained, poorly sorted material up to gravel and cobble size.  Waves and currents transport material downdrift in a direction that is dictated by bottom topography and the

orientation of the shoreline relative to the prevailing waves and currents. Under natural conditions, periodic slumping of the bluffs and the resulting redistribution of the material by waves and currents renourish the beaches.

## DRIFT CELLS

A drift cell, also called a littoral cell, is a partially compartmentalized zone along the coast that acts as a closed or nearly closed system with respect to transport of beach sediment (Johannessen 1992). In other words, drift cells are systems in which sediment is suspended by waves or currents and transported along the shoreline in a repetitious cycle of suspension and deposition. The direction of the transport of sediment is determined by the dominant direction of the waves and currents in that cell. Although wave and current direction varies frequently, over time each cell shows a direction of net transport. The drift cells and directions of net transport in WRIAs 8 and 9 are shown in Figures 11 and 12.

Drift cells are important because they are the mechanism that supplies nearshore environments with the majority of the sediments they require. Drift cells nourish beaches, provide fine sediments to flats, and maintain sand spits and other coastal landforms.

Reach 1 – Elliot Point to Edwards Point (Figure 1). The sediment transport direction is north and northeasterly in the entire reach between Elliot Point and Edwards Point as indicated by offsets of stream deltas, sediment accumulation on the southwest side of shoreline obstructions, and northward movement of nearshore bars. The net shore drift is driven by the predominant southerly and southwesterly waves within the reach. At the southern end of the cell, the Edmonds Ferry Terminal interrupts the drift and no appreciable northward drift can be observed. To the north and south of that point, however, drift is northward (Johannessen 1992).

Reach 2 – Edwards Point to Meadow Point (Figure 1). The prevailing drift direction is to the north in this reach from just south of the King-Snohomish county line and around Point Wells to Edwards Point, where it degrades to no discernable direction near the Edmonds Ferry Terminal. Evidence for northward drift is found in the decrease of mean sediment size and in the large volume of sediment and drift logs accumulated against the southwest side of the riprap breakwater of the Edmonds Marina near Point Edwards (Johannessen 1992). The drift divergence zone occurs just north of Carkeek Park, with southward drift extending from that area, around Meadow Point to the riprap, and the northern jetty at the Shilshole Bay Moorage within reach 3 (Schwartz et al. 1991). Evidence for southward transport is seen in the southern offset of small streams and southern location of finer shoreline sediments.

Reach 3 – Meadow Point to West Point (Figure 1). The drift direction continues southward from Meadow Point to the Shilshole Marina, although evidence is lost because of construction and activity associated with the marina. Sediment accumulation on the north side of groins just south of the marina in Salmon Bay confirms the southward net drift. On the north side of Salmon Bay the sediment is finer and is eventually lost to the dredged channel (Schwartz et al. 1991).

On the south side of Salmon Bay, a divergence zone runs along Shilshole Bay and the north shore of Magnolia Bluffs. East of the divergence, transport is to the east into Salmon Bay while

on the west side transport is reestablished to the south. This transport continues to the south and west, eventually forming the cuspate spit along the north shore of West Point.

Reach 4 – West Point to Alki Point (Figure 1). Magnolia bluffs occasionally slump and supply sediment to the shoreline. Most of this area has been highly developed and regraded from Elliott Bay Marina to Alki Point. The shoreline consists of multiple uses, which include industrial zones, port and dock facilities, marinas, and parks. Alki Beach is Seattle's largest public beach and is backed by a seawall. Though glacially derived bluffs exist at Duwamish Head and significant slides occur during periods of severe rain, there is no significant input of new sediment to the nearshore. Except for a small section of beach near the Smith Cove waterway, where the littoral drift is eastward and north into the cove, the prevailing drift follows the shoreline from Alki Point to West Point. Within Elliott Bay no natural intertidal beaches exist, making it difficult to infer drift direction (Schwartz et al. 1991).

Reaches 5, 6, and 7 – Alki Point to Three Tree Point (Point Pully) (Figure 1). The longshore drift cell that begins approximately 1 km north of Secoma in Seahurst Bay and continues north along the shoreline to the east side of Duwamish Head is the longest continuous drift cell in King County. This cell includes the shoreline of Lincoln Park on the north side of Fauntleroy Cove (reach 6), which was the site of progressive beach erosion until an extensive beach nourishment project began in 1988. The loss of beach material at this site was probably related to the loss of sediment supply from the system and possibly to a seawall and promenade built in the 1930s (Canning and Shipman 1994). There is a divergence zone near Seahurst, and from that area to Three Tree Point transport is to the south. The headland of Three Tree Point shelters the drift cell from waves generated to the south and southwest. Apparently, wave refraction and bathymetric controls along this area are sufficient to reverse the net drift direction from that observed over the majority of the WRIA 8 and 9 shoreline.

Reach 8 – Three Tree Point to Dumas Bay (Figure 1). A zone of divergence exists just south of Saltwater State Park (South of Des Moines). North of the zone, drift is to the north; south of the zone, drift is to the south. Drift in the southern sector originates along a zone of active bluff erosion and is indicated by fine sediments toward the south and material accumulation on the north side of small groins and beach structures. North of Saltwater State Park, northward drift is continuous except for an isolated section near the breakwater at Des Moines Marina. Breakwater construction has interrupted the northward flow, and diffraction around the structure has induced a local reversal of drift. North of the marina, at Covenant Beach Camp, bluff erosion contributes to beach sediments, which continue to drift northward under the influence of waves from the south and southwest.

Reach 9 – Vashon Point to Point Robinson (Figure 1). Drift on the east side of Vashon Island begins at a divergence zone at Vashon Point from which the sediments move to the east and south along the shoreline. Sediment drift is toward the major headlands along the east side of Vashon Island with convergence zones at Dolphin Point, Point Beals, and Point Heyer, and along the north shore of Maury Island at Point Robinson (Schwartz et al. 1991).

**Figure 11    WRIA 8 Nearshore Drift Cells**

**Figure 12    WRIA 9 Nearshore Drift Cells**

Reach 10 – Point Robinson to Piner Point (Figure 1). Drift along reach 10 is northeast from Piner Point to a convergence zone at Point Robinson, with no reversals in direction.

Reach 11 – Piner Point to Neill Point (Quartermaster Harbor) (Figure 1). The drift of sediments within Quartermaster Harbor is primarily to the north. On the east side of the harbor, sediments move from a divergence zone near Piner Point to the west and follow the northward-turning shoreline into the harbor. On the west side of the harbor, Neill Point is a zone of active erosion and landslides that supply sediments to the beach. Drift is northward along the west shore of the harbor and around the Burton Peninsula. Within Quartermaster Harbor, there are local reversals of transport and convergence zones where fine sediments are deposited in coves and embayments (Schwartz et al. 1991).

Reach 12 – Colvos Passage (Figure 1). Though the net movement of water in Colvos Passage is northward, the net drift of sediments is complicated by local reversals induced by eddies around the headlands, which provide wind and wave shadows. Along the west side of Vashon Island, convergence zones of sediments are observed at the following places:

- Vashon Point
- within Fern Cove
- Peter Point
- at a cuspate feature south of Peter Point marked by a navigation aid
- in the mouth of Green Valley Creek
- Christianson Cove
- Sanford Point, and
- in the mouth of Tahlequah Creek (between Point Dalco and Neill Point).

The steep coastal bluffs from Neill Point to the west and then northward up Colvos Passage, along with contributions from coastal streams, provide material to the beach. Details of the drift cells around Vashon Island, and evidence for their direction, are best obtained from Schwartz et al. (1991).

**Figure 8 General Conceptual Model, with Example for Evaluating Effects of Shoreline Armoring and Mitigation Actions**