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Quantification of Net Shore-Drift Rates in Puget Sound and the Strait of Juan de Fuca, Washington

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MASTER'S THESIS

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Quantification of Net Shore-Drift Rates in Puget Sound and the Strait of Juan de Fuca, Washington

A Thesis Presented

to The Faculty of

Western Washington University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

R. Scott Wallace

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MASTER'S THESIS

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Dean of Graduate School

Advisory Committee

Chairman

ABSTRACT

Quantitative analysis of net shore-drift has been carried out at twenty-six sites in Puget Sound and the Strait of Juan de Fuca, Washington, U.S.A.. Three methods were used to obtain net shore-drift rates: (1) field measurement of sediment accumulation at drift obstructions; (2) extrapolation of spit growth using aerial photographs and historical maps; and (3) evaluation of maintenance-dredging volumes at navigation channels.

The study area was divided into four regions based on physiography, and the effect of wind patterns on the area. The largest volumes of sediment were transported in the west-central region, along the southern coast of the Strait of Juan de Fuca. The smallest transport volumes were recorded along the southern coast of Puget Sound, while east-central and northern Puget Sound were intermediate with regard to sediment transport volumes.

The factors influencing net shore-drift rates are: fetch distance, available sediment, and drift cell length.

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INTRODUCTION

Qualitative studies of net shore-drift have been carried out along the marine coast of Washington, U.S.A. by KEULER (1979), JACOBSEN (1980), CHRZASTOWSKI (1982), HARP (1983), HATFIELD (1983), BLANKENSHIP (1983), TAGGART (1984), SCHWARTZ, MAHALA, and BRONSON (1985), and BUBNICK (1986). These workers used geomorphic indicators to determine the direction, length, and limits of individuial drift cells. This study is based on these previous works as a point of departure for quantification of regional net shore-drift at twenty-six sites in Puget Sound and the Strait of Juan de Fuca; and examines the relationship between net shore-drift rates and fetch distance, available sediment, and drift cell length.

PHYSICAL SETTING

Puget Sound and the Strait of Juan de Fuca fill glacially scoured troughs formed during the Pleistocene Epoch, when the Puget Lowland was repeatedly occupied by lobes of ice from the Cordilleran Ice Sheet. Within Puget Sound, the Georgia Strait, and the Strait of Juan de Fuca many islands and peninsulas remained following glacial retreat. Deglaciation therefore left a pattern of randomly-located obstacles to wind and waves, along with many elongated troughs. The majority of sediment now available for transport in the littoral zone comes from bluffs of glacial drift deposited by the Puget and Juan de Fuca Lobes during the Vashon Stade of the Fraser Glaciation, between 15,000-13,000 years before present (CRANDELL and others, 1958).

The 12 coastal counties of Puget Sound, the Georgia Strait, and the

Strait of Juan de Fuca contain approximately 3,220 km of marine shore; extending from Cape Flattery on the west to Point Roberts on the north, and Olympia on the south (Figure 1) (DOWNING, 1983).

METHODS

Net shore-drift rates were determined for twenty-six locations within Puget Sound and the Strait of Juan de Fuca. Three methods were used to obtain these drift rates: (1) field measurement of sediment accumulation at drift obstructions; (2) extrapolation of spit growth using aerial photographs and historical maps; and (3) evaluation of maintenance-dredging volumes at navigation channels.

Sediment Accumulation at Drift Obstructions

In order to measure the volume of sediment accumulated updrift of an obstruction (jetty, pier, marina) it was neccessary that the obstruction be oriented essentially perpendicular to the coastline, and to assume it to be a total barrier to the alongshore transport of sediment (Figure 2). There is undoubtedly a small amount of sediment that moves into deep water off the seaward tip of an obstruction, but it was not possible in this study to quantify this amount. The accumulated, updrift, sedimentary prism was measured as follows: (A) from the seaward tip of the obstruction to the back of the pre-accretionary beach; and (B) perpendicular to this, from the obstruction, updrift, to the far end of the prograding sediment wedge (Figure 3a). The thickness of the wedge (C) was determined by surveying the elevation difference between the lower foreshore level and the landward upper-edge of the prograded beach (Figure 3b). The beach face was treated as a planer surface in this profile.

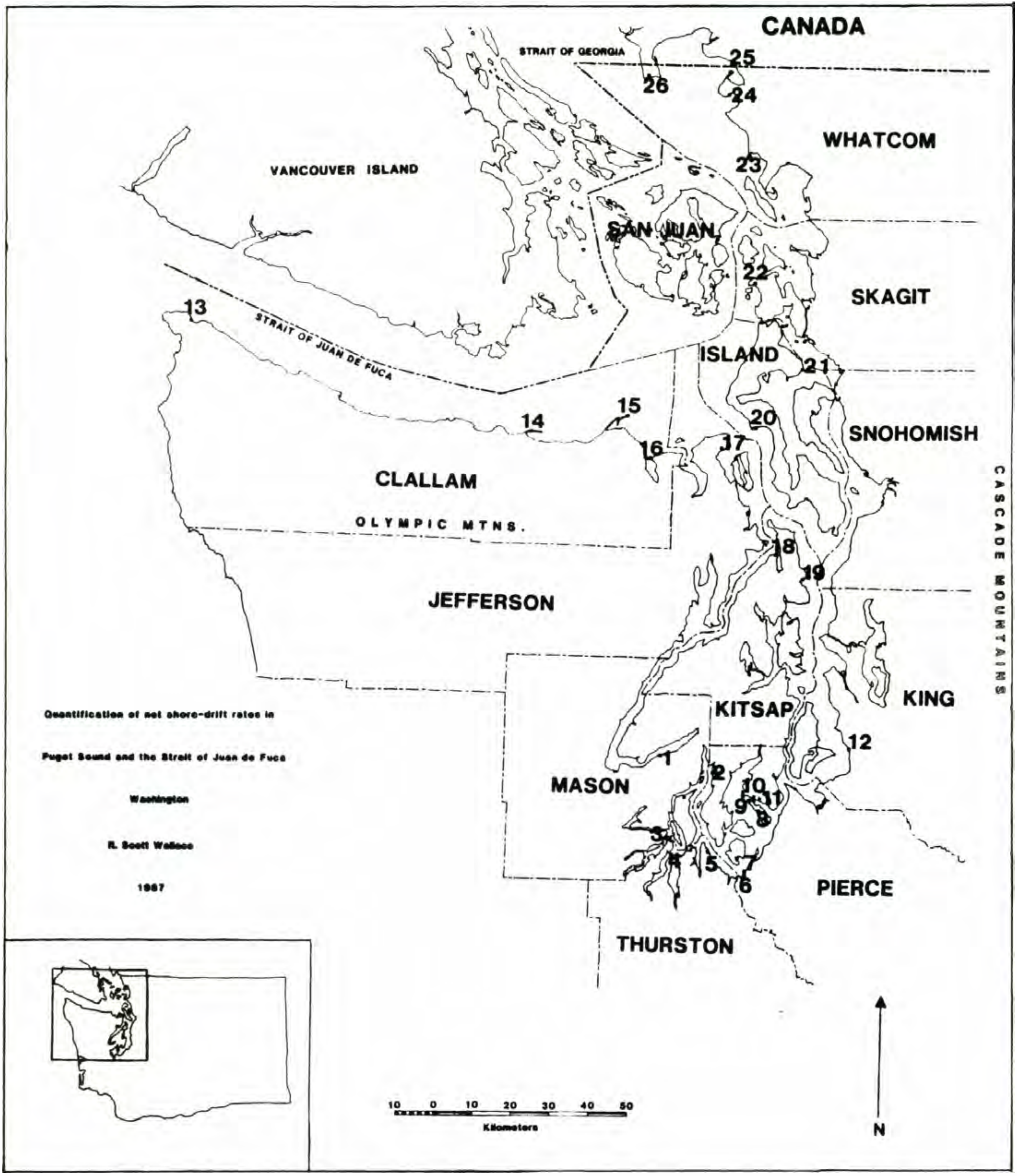

Figure 1. Net shore-drift quantification sites.

Figure 2. Sediment accumulation updrift (left) of jetty at Birch Bay Village Marina.

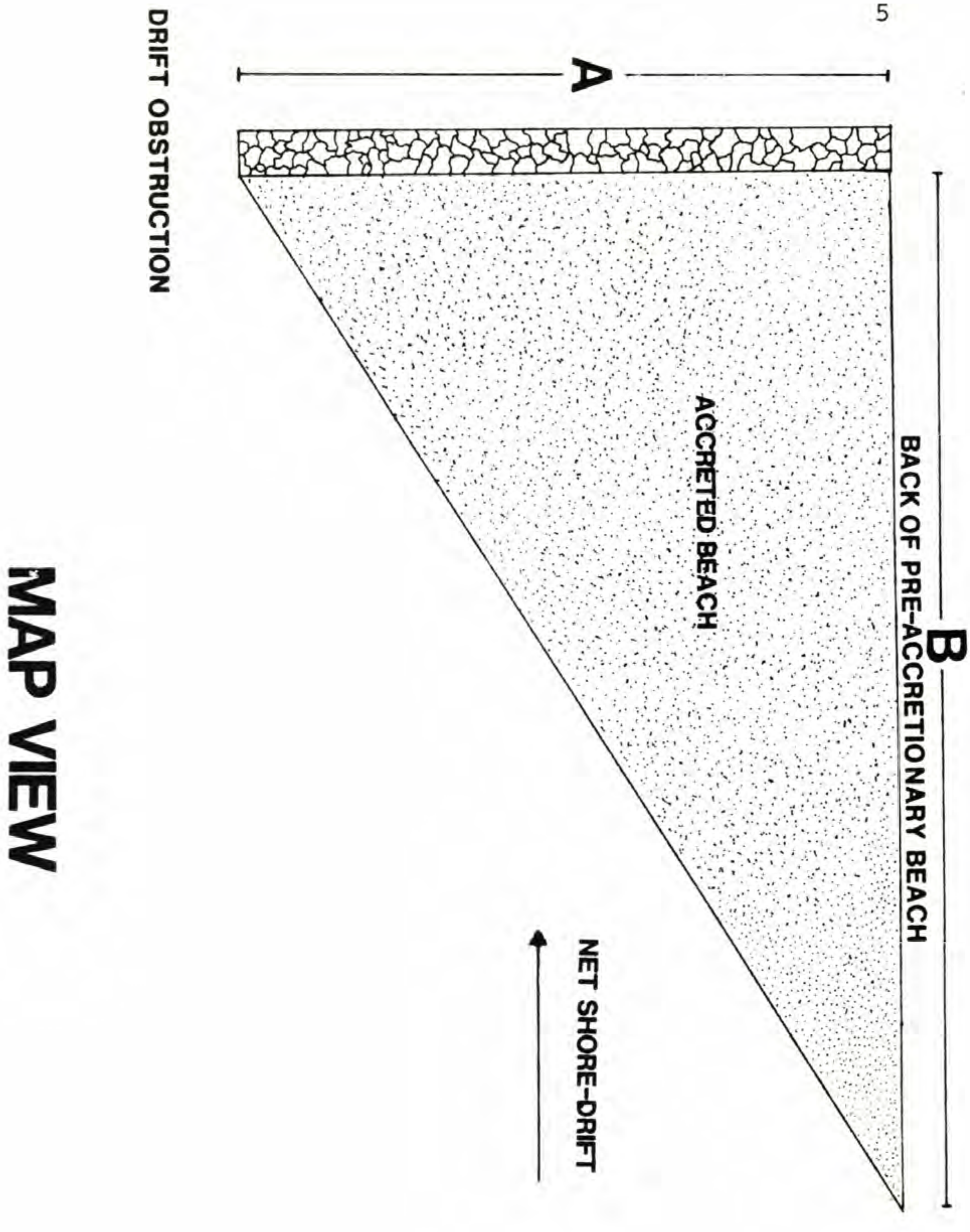

Figure 3A. Map view of accretionary sedimentary prism, A and B represent dimensions of the prograded beach.

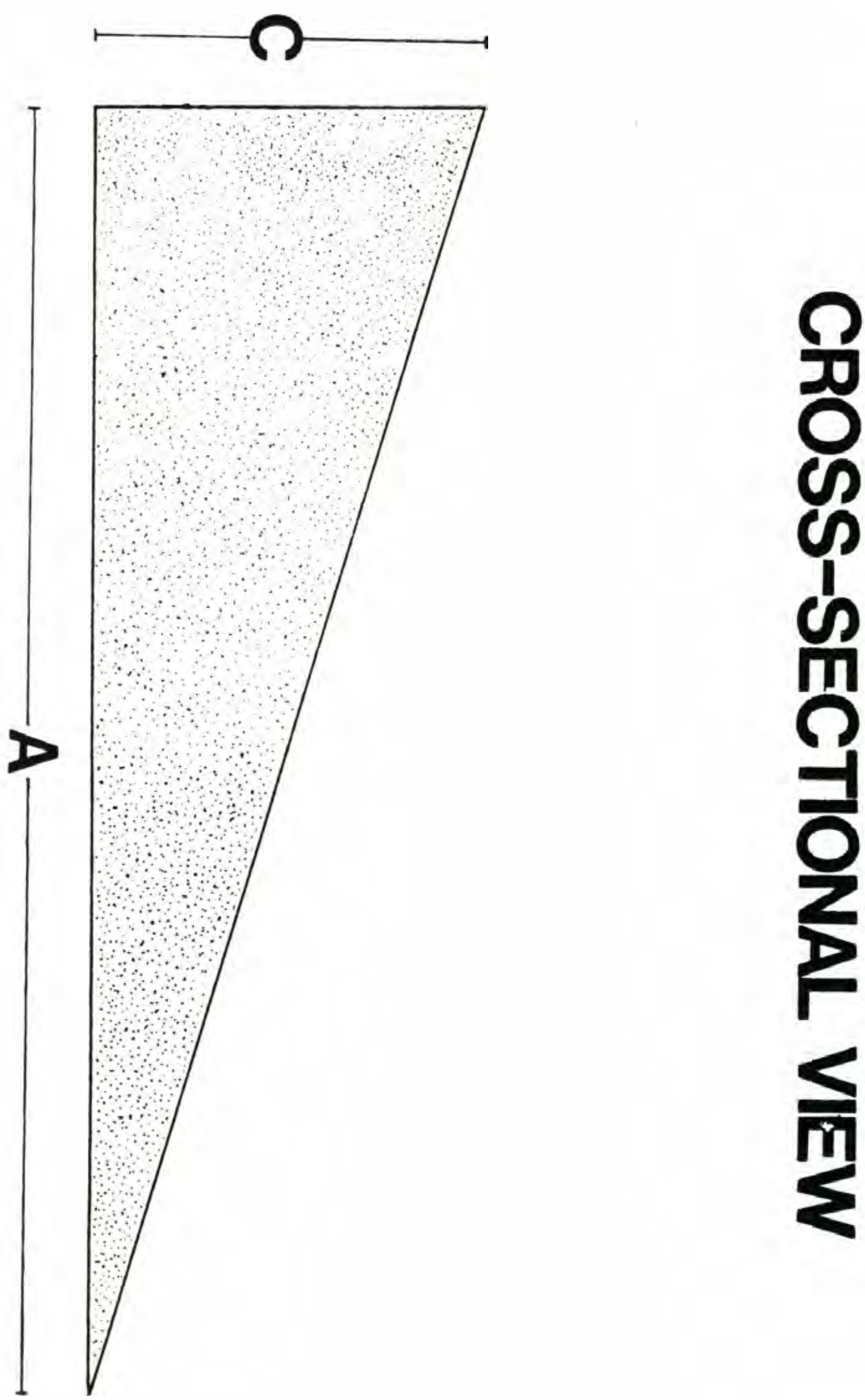

Figure 3B. Cross-sectional view of accretionary sedimentary prism, C represents thickness of the prograded beach.

The approximate volume of the sediment wedge was calculated by: (A)x(B)x(C)x(.25). The volume divided by the age of the obstruction equals the accumulation rate (i.e. net shore-drift rate), in cubic meters per year ($m^3 yr^{-1}$).

Spit Growth

Spits form and prograde in the predominant direction of net shore-drift (EVANS, 1942). Their development is cyclic, alternating between growth of a subaqueous sediment platform and a period of spit growth on the upper surface of the platform, emergent above the level of mean high water (Figure 4)(MEISTRELL, 1972).

Using aerial photographs (scale:1"=200') taken in 1970 by the Seattle District, U.S. Army Corps of Engineers, spits were examined and individual areas of the spit and platform were calculated using a digitizing board. Nautical charts and topographic maps with well defined features and bathymetric contours were used in conjunction with the aerial photographs to obtain elevations for spits and platforms. Field surveys confirmed subaerial spit elevations above mean high water. From these data spit volumes were calculated. Aerial photographs, of the same scale, taken in 1985 or 1986 were analyzed in the same manner to determine changes in the total volume of each spit. From the difference in volumes and the time interval between photographs, an average volume-per-year rate was calculated.

Dredging Volumes

Maintenance-dredging records are good sources of information for determining net shore-drift rates at navigation channels. These channels generally have a specific depth, length, and width that must be maintained

Figure 4. Semiahmoo Spit and spit platform.

Figure 5. Navigation channel at Keystone Harbor.

for safe navigation (Figure 5). Records of dates and amount of sediment removed can be compiled to calculate net shore-drift rates.

At the entrance channel to the marina at Birch Bay Village (Figure 2) this method was used in conjunction with sediment accumulation updrift of an obstruction, where sediment bypassed the west jetty and subsequent dredging of the channel became necessary.

DISCUSSION

Maritime air masses, originating over the North Pacific Ocean, dominate the weather patterns of the Strait of Juan de Fuca and Puget Sound region, creating a temperate, marine climatic regime typical of west coasts in similar latitudes elsewhere in the world (PACIFIC NORTHWEST RIVER BASINS COMMISSION, 1970).

The Cascade Mountains to the east, Vancouver Island to the north, and the Olympic Mountains to the west all have a moderating effect on the winds reaching the Puget Sound region. Continental air masses from Canada seldom reach Puget Sound due to the blocking effect of the Cascade Mountains. Winds from the west and northwest are redirected by the Olympic Mountains and Vancouver Island respectively (Figure 1).

Corridors through which air masses can reach the region are the Strait of Georgia, east of Vancouver Island; the Strait of Juan de Fuca, north of the Olympics and south of Vancouver Island; and the Chehalis Gap, south of the Olympic Mountains. Based on physiography and the resulting wind patterns, Puget Sound and the Strait of Juan de Fuca can be divided, for the purpose of this study, into four regions: southern, which includes King, Mason, Pierce, and Thurston Counties; west-central, which includes Clallam County; east-central, which contains Island, Jefferson, Kitsap, San Juan, Skagit, and Snohomish Counties; and northern which includes Whatcom County (Figure 1). Each region falls under the influence of different wind patterns, directly affecting net shore-drift.

At this point, the distinction between prevailing waves and predominant waves must be made. Prevailing waves are the most frequently occuring waves. Predominant waves, on the other hand, are those having the greatest effect on the shore. The predominant waves are responsible for net shore-drift (JACOBSEN AND SCHWARTZ, 1981).

Fetch Distance

Schou (1952) found that in protected coastal areas, the direction of net shore-drift is most often determined by the direction of maximum fetch.

The waterways of southern Puget Sound are oriented in a general southwest-northeast trend. However, the coastline of the southern region is very irregular; with many headlands, coves, bays, and islands. Fetch distances and directions are variable because of these irregularities. Prevailing air masses move northward through the Chehalis River Valley into the southern region (BLANKENSHIP, 1983).

Fetch distances observed in the southern region were, with the exception of the Des Moines City Marina, all less than 10 km (Table 1). The mean annual net shore-drift rate for 11 sites in the southern region, excluding Des Moines, is 400 $m^3 yr^{-1}$ (Table 1). The relatively small drift rates are related to shorter fetch distances.

In contrast to southern Puget Sound, the central region waterways are generally oriented east-west. The main body of water is the Strait of

TABLE 1. Site Location Parameters

REGION	SITE (COUNTY)	WAVE APPROACH	FETCH DISTANCE (km)	CELL LENGTH (km)	RATE (m^3 yr^{-1})
Southern Region	1. Twanoh Park Boatramp (Mason)	SW	6.9	8.1	200
	2. Vaughn Bay Spit Pierce	S	8.6	3.9	2,000
	3. Steamboat Island Spit (Thurston)	SW	5.4	4.0	300
	4. Cooper Point Spit (Thurston)	S	10.0	7.7	800
	5. Zittel's Marina (Thurston)	N	4.8	0.5	100
	6. South Foss Tug Jetty (Pierce)	S	1.5	0.6	80
	7. North Foss Tug Jetty (Pierce)	S	1.5	0.3	100
	8. Carr Inlet Naval Range (Pierce)	SW	6.4	2.8	600
	9. Nearns Point Spit (Pierce)	SW	6.4	0.7	90
	10. NW Fox Island Bridge (Pierce)	SW	7.6	1.5	30
	11. SE Fox Island Bridge (Pierce)	SE	7.6	2.7	50
	*12. Des Moines City Marina (King)	SW	17.7	2.9	5,000
	Mean		6.1	3.0	400
West-Central Region	13. Neah Bay Breakwater (Clallam)	E	4.0	4.0	900
	14. Ediz Hook (Clallam)	W	51.5	11.8	9,000
	15. Dungeness Spit (Clallam)	W	200+	26.0	14,000
	16. Travis Spit (Clallam)	NE	30.0	5.6	2,000
	Mean		30.0+	11.9	6,500
East-Central Region	17. Port Townsend Marina (Jefferson)	SE	8.6	6.0	1,000
	18. Pope and Talbot Mill Jetty (Kitsap)	SW	8.0	26.0	80
	19. Kingston Ferry Terminal (Kitsap)	SE	12.5	1.2	2,000
	20. Keystone Harbor (Island)	SW	13.7	9.6	5,000

REGION	SITE (COUNTY)	WAVE APPROACH	FETCH DISTANCE (km)	CELL LENGTH (km)	RATE ($m^3 yr^{-1}$)
	21.Mariner's Cove (Island)	SW	14.3	1.5	200
	22.Skyline Marina (Skagit)	SW	48.3	10.0	800
	Mean		17.6	9.1	1,500
Northern Region	23.Sandy Point Spit (Whatcom)	NW	145.0	13.3	2,000
	24.Birch Bay Village (Whatcom)	W	40.0	2.9	600
	25.Semiahmoo Spit (Whatcom)	W	40.0	6.5	8,000
	26.Point Roberts Marina (Whatcom)	SE	48.0	3.3	4,000
	Mean		69.8	6.5	3,500

* excluded from mean calculations

Juan de Fuca, through which wind and waves approach from the west.

The central region is subdivided into a west-central and east-central region. The west-central region includes four sites along the southern coast of the Strait of Juan de Fuca. Drift rates at Ediz Hook and Dungeness Spit, 9,000 and 14,000 $m^3 yr^{-1}$, respectively, represent the largest rates in the study area. Both sites are within drift cells having fetch distances in excess of 50 km, among the largest in the Puget Sound area.

The east-central region includes six sites located east of the Strait of Juan de Fuca. Four have fetch distances in excess of 12.5 km and the mean annual net shore-drift rate for this region is 1,500 $m^3 yr^{-1}$ (Table 1).

The northern region is dominated by air masses moving in from the west and northwest through the Strait of Georgia (Figure 1). The four sites in this region all have fetch distances greater than 40 km. Consistent with relatively long fetches, these sites have a relatively large mean annual net shore-drift rate of 3,500 $m^3 yr^{-1}$; corresponding once again, to an increase in fetch distance.

Regression analysis also supports the fetch distance-rate relationship. If there is no relationship between fetch distance and drift rate, computation using regression equations of a critical value (r), with a confidence level of 95%, should have a value of 0.33 or less. Data on fetch distance taken from Table 1 was used to arrive at a value for (r). The critical (r) value was 0.69; thus the null hypothesis was rejected and an increase fetch distance-increase drift rate relationship was inferred.

Available Sediment

The rate of net shore-drift is intimately related to the amount of sediment made available to the littoral zone. The marine coast of Puget Sound and the Strait of Juan de Fuca have a preponderance of easily-eroded glacial deposits. However, human intervention along the shore has interfered with the natural supply of sediment from the bluffs to the beaches. Evaluation of available sediment requires a close look at coastal stratigraphic units, with special consideration for the number and type of shore defense structures in a given area.

Shore defense structures are becoming a part of nearly every coastal property owner's landscape in Puget Sound. As development continues, natural sediment supplies are restricted or eliminated. As a result, net shore-drift rates are drastically reduced.

In the southern region of Puget Sound, along the northwest shore of Hale Passage (sites 10 & 11), the smallest net shore-drift rates in the study were recorded (30 and 50 m^3 yr^{-1}). There are easily erodable, 5-8-m-high bluffs fronting the shore (HARP, 1983) and fetch distances of 7.5 km. Similar conditions exist at Vaughn Bay Spit (site 2), with regard to fetch distance, cell length, and bluff morphology; however, the annual drift rate is two orders of magnitude greater than those along Fox Island. The difference lies in the extent of shore defense structures. While the coast updrift of Vaughn Bay Spit has relatively few bulkheads and groins, the shore along a 4 km stretch on either side of the Fox Island Bridge is completely bulkheaded to protect waterfront property.

Drift Cell Length

The length of a drift cell plays a role in the observed rate of net shore-drift. Although each cell is constrained by its own geographic orientation with regard to wind, waves, and sediment supply; mean drift rates show an overall increase with increased drift cell length (Table 1). This is most evident in less developed areas where there is simply more shore exposed to wave action in longer drift cells; and, therefore, the potential for erosion and transport is greater.

Data on cell length from Table 1 was also analyzed using regression. If the null hypothesis is assumed to be correct (no relation between cell length and drift rate) the critical value (r) should once again be less than 0.33, to be within a 95% confidence interval for the data set. Analysis yielded an (r) value of 0.53. Although not as high as the critical value for fetch distance, this, nontheless, appears to indicate that there is a relationship between the length of a drift cell and the rate of net shore-drift.

Drift cells varied in length from 0.3 km to 26.0 km. Four groups were delineated, based on drift cell length: Group 1, <=2 km; Group 2, <=4 km; Group 3, <=10 km; and Group 4, >10 km. Of the twenty-six sites, seven were within drift cells of 2 km or less. The mean drift rate in cells of this length was 400 $m^3 yr^{-1}$. Within drift cells 2-4 km long, there were eight sites, these had a mean drift rate of 1,500 $m^3 yr^{-1}$. Seven sites were within drift cells 4-10 km long, and the mean rate for these sites was 3,000 $m^3 yr^{-1}$. In drift cells exceeding 10 km there were four sites, these show a mean drift rate of 6,000 $m^3 yr^{-1}$.

This data supports the trend of increased drift rates associated with increased drift cell length, as was suggested by the critical value test.

SUMMARY

Net shore-drift rates in Puget Sound and the Strait of Juan de Fuca vary considerably. The range in rates is due to interaction of the following: fetch distance, available sediment, and drift cell length.

Relatively large segments of undefended coastline, under the combined influence of westerly waves, large fetch distances, and relatively long drift cells, result in transport of the largest volumes of sediment recorded in this study; eastward, along the south coast of the Strait of Juan de Fuca (west-central region). Northern Puget Sound exhibits the second highest mean annual transport volume. This is due in part to fetch distances in excess of 40 km, combined with predominant, northwesterly wind and waves entering Puget Sound through the Strait of Georgia. The east-central region is not directly subjected to westerly waves like those sites along the south coast of the Strait of Juan de Fuca. However, the mean fetch distance for sites in this area is 17.6 km, and the overall drift rates are an order of magnitude greater than those is southern Puget Sound. Southern Puget Sound, with waterways oriented along a southwest-northeast trend, is affected primarily by southerly waves and relatively small fetches to the south, southwest, and southeast. Smaller volumes of sediment are transported in southern Puget Sound due mainly to limited fetch exposures arising from the many islands, bays, and headlands in the region.

Due to contrasting shore-drift rates, development in the southern portion of Puget Sound is less likely to cause a major interruption of sediment transport than development in the two central and the northern regions.

The coast of Puget Sound and the Strait of Juan de Fuca are rapidly developing areas. Comprehensive sediment transport studies such as this, assist planning and licensing agencies in the State of Washington assess the character and potential of the shore for industrial and residential expansion.

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APPENDIX

Note: Values are reported to the following precision:

VOLUMES

less than 100 m^3	to nearest 10 m^3
less than 1,000 m^3	to nearest 100 m^3
over 1,000 m^3	to nearest 500 m^3

AREAS

less than 1,000 m^2	to nearest 10 m^2
over 1,000 m^2	to nearest 100 m^2

LENGTHS

less than 10 m	to nearest 0.1 m
less than 100 m	to nearest 1 m
over 100 m	to nearest 10 m

SITE 1: Twanoh State Park Boat-Ramp, Hood Canal, Mason County, Washington

LOCATION: 15 km southwest of Belfair, Washington, along the southeast portion of the Hood Canal.

OBSERVATIONS: The boat-ramp at Twanoh State Park is the terminus of a drift cell originating 8.1 km to the southwest. Virtually the entire length of the beach in this area is fronted by some form of shore defense structure. These structures, while protecting valuble waterfront property, limit the sediment supply available to the littoral zone. Sediment that reaches the beach is transported northeastward toward the drift cell terminus (Blankenship, 1983).

The southwest side of the boat-ramp has a large accumulation of fine to coarse sand, well rounded pebbles and oyster shell fragments. This deposit has marked the end of the drift cell since the boat-ramp was built in 1964. The prograding beach extends updrift 78 m from the boat-ramp to the far end of the prograded wedge. The height of the current beach crest is 5.2 m, and the beach measures 47 m from the back of the old beach to the seaward tip of the boat-ramp.

Since 1964, approximately 4,500 m^3 of sediment have accumulated updrift of the Twanoh Park boat-ramp. From these figures the annual net shore-drift rate at the park is estimated to be 200 $m^3 yr^{-1}$.

NET SHORE-DRIFT DIRECTION AND RATE: Net shore-drift at Twanoh State Park is southwest to northeast, and the rate is 200 $m^3 yr^{-1}$.

SITE 2: Vaughn Bay Spit, Vaughn, Pierce County, Washington

LOCATION: Northeastern Case Inlet, partially enclosing the bay 1 km southwest of Vaughn, Washington.

OBSERVATIONS: The spit, prograding northward across the mouth of Vaughn Bay, is the terminus of a drift cell originating 4 km to the south, at the north end of Dutcher Cove (Harp, 1983).

Predominant southwesterly waves transport sediment northward from vertical glacial bluffs and a wide wave-cut platform (Harp, 1983). The spit is approximately 600 m long from proximal to distal end; and a narrow 50-meter-wide channel remains open north of the spit, due primarily to tidal action.

Comparisons of 1970 and 1986 aerial photographs, indicate Vaughn Bay Spit increased in total area by 7,600 m^2. The sub-aerial portion increased by 1,900 m^2 and the spit platform added 5,600 m^2. Over the past 16 years the depth to the base of the platform from MLLW has remained approximately 3.2 m, and the elevation difference between the berm crest and MLLW is unchanged at 4.2 m.

The growth of the spit has resulted in a volumetric increase of 32,000 m^3 between 1970 and 1986. Assuming a fairly constant accumulation rate, the net shore-drift rate at Vaughn Bay is 2,000 m^3 yr^{-1}.

NET SHORE DRIFT DIRECTION AND RATE: Net shore-drift at Vaughn Bay Spit is from south to north, and the rate is 2,000 m^3 yr^{-1}.

SITE 3: Steamboat Island Spit, Steamboat Island, Thurston County, Washington

LOCATION: Northeastern end of Totten Inlet, 14.5 km north of Olympia, Washington.

OBSERVATIONS: The spit, building to the northwest from western Steamboat Island, marks the terminus of a drift cell originating 4.0 km to the south. The net shore-drift within this cell is from south to north, caused by the approach of prevailing and predominant waves over a fetch to the west-southwest (Hatfield, 1983).

Comparisons of 1970 and 1986 aerial photographs of Steamboat Island Spit show the spit increased in sub-aerial area by 480 m^2, and in platform area by 590 m^2. The vertical dimensions from berm crest to MLLW, and from MLLW to the base of the spit platform are approximately 5.0 m and 2.8 m, respectively.

The growth experienced by the spit resulted in an increase in total volume of 5,500 m^3 between 1970 and 1986. Assuming accretion to be fairly constant, the annual net shore-drift rate is approximately 300 $m^3 yr^{-1}$.

NET SHORE-DRIFT DIRECTION AND RATE: Net shore-drift on western Steamboat Island is from south to north, and the rate is 300 $m^3 yr^{-1}$.

SITE 4: Cooper Point Spit, north-central Thurston County, Washington

LOCATION: Northern end of the penninsula separating Eld Inlet from Budd Inlet, 9 km north of Olympia, Washington.

OBSERVATIONS: Cooper Point is a 250-meter-long spit which has formed due to the net shore-drift of sediment northward along the eastern and western shores of a north-trending penninsula. The spit derives its sediment from glacial bluffs exposed to predominant southerly waves along eastern Eld and western Budd Inlets (Hatfield, 1983).

1970 and 1986 aerial photographs show Cooper Point increased in total area by 4,400 m^2. This increase was entirely due to the growth of the spit platform. Over the 16 years separating the photographs, the depth to the base of the platform from MLLW has remained approximately 3.4 m. There is also a consistent difference in elevation between MLLW and the berm crest of 5.0 m.

From these dimensions, Cooper Point is estimated to have increased in total volume by 13,000 m^3 between 1970 and 1986. Assuming fairly constant sediment accumulation, the net shore-drift rate is approximately 800 m^3 yr^{-1}.

NET SHORE-DRIFT DIRECTION AND RATE: Net shore-drift at Cooper Point is from south to north, and the rate is 800 m^3 yr^{-1}.

SITE 5: Zittel's Marina, northwestern Nisqually Reach, Thurston County, Washington

LOCATION: North end of Baird Cove, 13 km north of Olympia, Washington.

OBSERVATIONS: Net shore-drift is from north to south along this portion of northern Nisqually Reach. Sediment is supplied to the littoral zone from a wave-cut platform, cut across glacial outwash, 300 m north of Baird Cove. At the northern end of Baird Cove a large concrete bulkhead has been built out over the foreshore. This bulkhead is the foundation for a boathouse, restaurant and marina office. The drift cell terminates at the northern side of the bulkhead (Hatfield, 1983). A medium to fine-grained sandy wedge of sediment is presently accumulating there.

The prograding beach extends seaward 30 m to the outer edge of the foundation. The elevation difference from the lower foreshore to the beach crest is 3.6 m, and the point where the beach begins to prograde is 89 m updrift (north) of the bulkhead.

The bulkhead-foundation was built in 1961 (Mike Zittel, Zittel's Marina, personal communication, 1986). Prior to that, the terminus of the drift cell was a spit 0.5 km to the south, on the west side of Baird Cove (Hatfield, 1983).

The volume of the prograding beach was approximately 2,500 m^3 during the summer of 1986. Assuming fairly constant sediment accumulation, a first approximation of the net shore-drift rate would be 100 $m^3 yr^{-1}$.

NET SHORE-DRIFT DIRECTION AND RATE: Net shore-drift at Zittel's Marina (northwestern Nisqually Reach) is from north to south, and the rate is 100 $m^3 yr^{-1}$.

SITE 6 & 7: Foss Tug Jetty, Dupont, Pierce County, Washington

LOCATION: Weyerhauser Corp. property, 2 km north of the Nisqually River Delta in southwestern Pierce County.

OBSERVATIONS: The Foss Tug jetty acts as the terminus for two drift cells, converging on one another from the north and south. The regional drift pattern is northward with the exception being the cell north of the jetty. This reversal is due to predominant southwesterly waves refracting around the jetty (Harp, 1983).

On the north and south sides of the jetty, sediment (sand-to-pebble-size) wedges are accumulating. This has resulted in the formation of a cusp-like coastal feature with the jetty located in the center. Dimensions of both wedges were measured, to the north and south of the jetty. The northern wedge begins to prograde 150 m north of the jetty. It extends 39 m seaward from the back of the old beach, and has a maximum landward thickness of 3.1 m. The total volume of the northern prograding beach is 4,500 m^3. The southern wedge begins to prograde at a point 140 m south of the jetty. It extends symmetrically 39 m seaward, and has an accreted landward thickness of 2.8 m. The total volume of this prograding wedge is 4,000 m^3. The jetty was constructed in 1940 (Harp, 1983), the wedges have accumulated since that time. If accretion is taken to be fairly constant, the net shore-drift rate north of the jetty is 100 $m^3 yr^{-1}$, and 80 $m^3 yr^{-1}$ to the south.

NET SHORE-DRIFT DIRECTION AND RATE: Net shore-drift at the Dupont, Foss Tug Jetty is convergent from the north and south. The rate, north of the jetty is 100 $m^3 yr^{-1}$, and 80 $m^3 yr^{-1}$ to the south.

SITE 8: Carr Inlet Naval Accoustic Range, Fox Island, Pierce County, Washington

LOCATION: 8 km west of Tacoma, Washington, on the northwest side of Fox Island.

OBSERVATIONS: The Carr Inlet Naval Accoustic Range is a monitoring station for wave patterns and sounds emitted from a wide variety of Naval ships. The waves generated by these vessels are inordinately larger than the normal wind generated waves in the area. This would seem to have an effect on the rate of net shore-drift to a certain degree, but was not a focus in this study.

The net shore-drift along northwestern Fox Island is to the southeast. Wave induced erosion of the coastal bluffs supplies a large volume of sediment to this drift cell (Harp, 1983). At the Naval testing center, 1 km northwest of the drift cell terminus, a large wedge of sand-to-cobble-sized sediment has accreted on the northwest side of a bulkhead and row of wood pilings. These structures form a pier which extends out over the foreshore. The sediment wedge has a thickness of 5.1 m from the top of the present beach to the lower foreshore. It has prograded 54 m seaward from the back of the old beach, and begins to accumulate at a point 140 m north of the pier. The total volume of accumulated sediment is approximately 9,500 m^3.

The pier was built in 1971 (Michael Kaaland, Carr Inlet Accoustic Range, personal communication, 1986), at which time this beach began to prograde. Assuming a uniform accumulation rate, this indicates an annual net shore-drift rate of 600 $m^3 yr^{-1}$.

NET SHORE-DRIFT DIRECTION AND RATE: Net shore-drift at the Carr Inlet Naval Accoustic Range (west-central Fox Island) is from northwest to southeast, and the annual drift rate is 600 $m^3 yr^{-1}$.

SITE 9: Nearns Point, Fox Island, Pierce County, Washington

LOCATION: Northwestern end of Fox Island, 9.7 km west of Tacoma, Washington.

OBSERVATIONS: Nearns Point is a northward-prograding recurved spit. It is the terminus for a drift cell originating approximately 1 km south of Nearns Point (Harp, 1983). Predominant southwesterly waves erode a wide wave-cut platform and 15-meter-high bluff on northwestern Fox Island, thereby supplying sediment to the littoral zone (Harp, 1983).

Aerial photographs show Nearns Point increased in total area by 370 m^2 between 1970 and 1986. This growth occurred exclusively in the spit platform. Over the past 16 years, the depth to the base of the platform from MLLW has remained 5.5 m, while the difference in elevation between the berm crest and MLLW is 4.9 m. Based on these dimensions, the spit at Nearns Point has increased its total volume by 1,500 m^3 between 1970 and 1986. An annual net shore-drift rate of 90 $m^3 yr^{-1}$ accounts for this volumetric increase.

NET SHORE-DRIFT DIRECTION AND RATE: Net shore-drift at Nearns Point, (northwestern Fox Island), is from southwest to northeast, and the rate is 90 $m^3 yr^{-1}$.

SITE 10 & 11: Fox Island Bridge, Fox Island, Pierce County, Washington

LOCATION: 6.5 km southwest of Gig Harbor, Washington, north-central Pierce County.

OBSERVATIONS: The bridge that spans Hale Passage, and connects Fox Island with the central portion of Pierce County, is the terminus for two converging drift cells.

On the mainland side of the bridge, drift cells from the northwest and southeast converge on their respective sides of the bridge abutment (Harp, 1983).

The drift cell southeast of the bridge originates along a partially eroded headland near East Cromwell, Washington. The proximal 700 m have been modified by seawalls, eliminating the source for much of the sediment that was once supplied to the littoral zone (Harp, 1983). At the terminus, the foreshore has prograded seaward 27 m from the back of the original beach. This prograding beach is composed of mixed pebbles and cobbles. The elevation of the lower foreshore is 3.1 m below the crest of the present beach and the wedge of sediment begins prograding at a point 60 m updrift (southeast) of the bridge. The total volume of the current accumulation is 1,500 m^3.

The drift cell northwest of the bridge originates south of Arletta, Washington (Harp, 1983). A large portion of the shore along northwestern Hale Passage has been modified with shore defense structures, thereby limiting sediment supply to the foreshore. Within this cell sediment is transported to the southeast, with a prograding coarse sand and pebble beach accumulating northwest of the bridge abutment. The beach begins to prograde 48 m updrift (northwest) of the bridge, and extends 24 m seaward from the back of the original beach. The thickness of the present beach crest is 3.3 m. The total volume of this sediment wedge is estimated to be 1,000 m^3.

The Fox Island Bridge was built in 1954 (Don Peterson, Pierce County Public Works Dept., personal communication, 1986). Subsequently these beaches began to prograde.

The annual net shore-drift rate southeast of the Fox Island Bridge averages 50 $m^3 yr^{-1}$, while the drift rate northwest of the bridge averages 30 $m^3 yr^{-1}$.

NET SHORE-DRIFT DIRECTION AND RATE: Net shore-drift in southeastern Hale Passage is from southeast to northwest, and the drift rate is 50 $m^3 yr^{-1}$. The net shore-drift in north-western Hale Passage is from northwest to southeast, and the drift rate is 30 $m^3 yr^{-1}$.

SITE 12: Des Moines City Marina, Des Moines, King County, Washington

LOCATION: Des Moines, Washington, 6.4 km south of the Seattle-Tacoma International Airport.

OBSERVATIONS: The breakwater at the Des Moines marina is the terminus for a drift cell originating 100 m south of Saltwater State Park. The net shore-drift along this cell is from south to north (Chrzastowski, 1982). Prior to construction of the breakwater in 1969 (Jesse Cadena, Des Moines City Marina, personal communication, 1986) the drift cell was continuous northward to Three Tree Point (Chrzastowski, 1982).

A large volume of sediment is supplied to the littoral zone of southern King County by eroding glacial bluffs. In response to the termination of littoral drift at the breakwater, a large prograding beach has formed south of the marina. This beach begins to prograde at a point 310 m updrift (south) of the breakwater, and extends 200 m seaward, to the tip of the obstruction. The thickness of the present beach measures 5.4 m from the lower foreshore to the beach crest. The current volume of the prograding beach is approximately 83,500 m^3 of coarse sand-to-pebble-sized sediment.

Assuming fairly constant sediment accumulation over the past 17 years, the annual net shore-drift at the Des Moines Marina is 5,000 $m^3 yr^{-1}$.

NET SHORE-DRIFT DIRECTION AND RATE: Net shore-drift at the Des Moines City Marina is from south to north, and the drift rate is 5,000 $m^3 yr^{-1}$.

SITE 13: Neah Bay Breakwater, Neah Bay (Makah Indian Reservation), Clallam County, Washington

LOCATION: 6.5 km southeast of Cape Flattery in the extreme northwest portion of the Olympic Peninsula, Washington.

OBSERVATIONS: The breakwater joining Waadah Island to the mainland, 0.6 km northwest of the Indian village at Neah Bay, is approximately 2.4 km long. The breakwater protects the town from the predominant waves approaching from the northwest. The orientation of the island-breakwater structure, normal to these waves, causes them to refract and enter the bay from the east. These are the waves which are responsible for the westerly net shore-drift of sediment within Neah Bay (Bubnick, 1986).

The Seattle District, U.S. Army Corps of Engineers, completed construction of the breakwater in 1944 (U.S. Army Corp of Engineers, 1949). Since that time, mainly coarse-to-fine sand eroded from the Neah Bay shore has been accumulating at the western end of the bay, south of the breakwater. The local villagers have, from time to time, mined sand from the upland areas around the town and deposited it along the beach face to stabilize the shore (Bubnick, 1986). The amount of sediment added to the littoral zone is thought to be minor, but is not known. It was not accounted for in this study.

To calculate net shore-drift, I measured the dimensions of the sediment wedge accumulating south of the breakwater, at the west end of Neah Bay. The prograding sand wedge extends 367 m south of the breakwater, along the western shore of Neah Bay. It has prograded from the back of the old beach 152 m to the east, and presently is 2.6 m thick directly south of the breakwater. The volume of the prograding sandy wedge is 36,000 m^3. Assuming the accretion rate within Neah Bay is fairly constant, an annual east to west, net shore-drift rate of 900 $m^3 yr^{-1}$ would be responsible for the accumulated sediment.

NET SHORE-DRIFT DIRECTION AND RATE: Net shore-drift is east to west within Neah Bay, and the rate is 900 $m^3 yr^{-1}$.

SITE 14: Ediz Hook, Port Angeles, Clallam County, Washington

LOCATION: Port Angeles, in the north-central portion of the Olympic Peninsula, Washington.

OBSERVATIONS: Ediz Hook is a spit composed of gravel and sand, which extends along the south shore of the Strait of Juan de Fuca. The spit is 5.5 km long and forms a natural breakwater for Port Angeles Harbor.

Ediz Hook initially derived its sediment from glacial bluffs and the Elwah River Delta, which are both a short distance west of the spit. The construction of both water-line protective works along the base of the bluffs since the 1930's, and dams on the lower Elwah River have seriously depleted the quantity of material available to maintain the spit. The reduction in available sediment has caused the neck of the spit to erode. It is now more susceptable to breaching and overtopping by wave action.

Crown Zellerbach Corporation and the U.S. Coast Guard have facilities on Ediz Hook. Thus, stability of the spit is an important issue.

In 1978 the Seattle District, U.S. Army Corp of Engineers studied the littoral transport rate of sediment along Ediz Hook for design of a beach nourishment program. Comparing nearshore surveys from 1948-1975, and offshore surveys from 1926-1970, the Corps computed an average erosion rate along the northern shore of the spit of 9,000 $m^3 yr^{-1}$ (U.S. Army Corp of Engineers, 1978). This erosion rate figure is used in this report.

The Seattle District, U.S. Army Corp of Engineers, currently employs a beach protection program to maintain the integrity of the spit. The program consists of three parts: revetment, rock blanket and beach nourishment. The revetment and rock blanket are primarily designed to prevent damage to the roadway and utilities that serve the spit. The beach nourishment program maintains the nearshore beach profile.

Nourishment involves placement of approximately 76,500 m^3 of sand- to-cobble-size sediment at the proximal end of Ediz Hook every five years. Natural shore-drift processes then redistribute the sediment, maintaining the nearshore beach profile (U.S. Army Corp of Engineers, 1981).

NET SHORE-DRIFT DIRECTION AND RATE: Net shore-drift at Ediz Hook is from west to east, and the rate is 9,000 m^3 yr^{-1}.

SITE 15: Dungeness Spit, Dungeness, Clallam County, Washington

LOCATION: 17.7 km east of Port Angeles, on the northeast coast of the Olympic Penninsula, Washington.

OBSERVATIONS: Dungeness Spit and the surrounding shore area form one of the most well-developed spit complexes in the world. Much of the spit has been designated a National Wildlife Refuge, which has left the region mostly undeveloped.

Sediment from glacial bluffs to the west is transported eastward by the predominant west to east wave regime in the Strait of Juan de Fuca. Based on plane-table and alidade mapping of various spit segments, and comparison of old and recent maps (Schwartz et al., 1987), there has been very little change in the western half of Dungeness Spit in the past 130 years. However, the bulbous, distal portion of the spit has prograded 575 m to the northeast between 1855 and 1985 (Schwartz et al., 1987), with a volumetric growth of 1,850,000 m^3. Volume measurements are based on the portion of the spit above the platform, which is 10 m below MLLW (mean lower low water). Any sediment contributing to the growth of the platform below that depth is not considered.

If Dungeness Spit has undergone fairly constant growth over the past 130 years, an annual net shore-drift rate of 14,000 $m^3 yr^{-1}$ accounts for the volumetric increase.

NET SHORE-DRIFT DIRECTION AND RATE: Net shore-drift at Dungeness Spit is primarily west to east, with a few reversals inside the complex due to wave refraction. The rate at the distal end of Dungeness Spit is approximately 14,000 $m^3 yr^{-1}$.

SITE 16: Travis Spit, Sequim Bay, Clallam County, Washington

LOCATION: Northwestern portion of the Miller Peninsula, Clallam County. Forms the northern boundary of Sequim Bay.

OBSERVATIONS: Travis Spit is a 1.2-km-long spit which has grown westward across the mouth of Sequim Bay. It marks the terminus of a drift cell originating 4 km to the east, at Rocky Point (Bubnick, 1986). Net shore-drift is east to west at Travis Spit. This is opposite the prevailing eastward trend found along the south coast of the Strait of Juan de Fuca because the spit lies in the wave shadow of the upland, south of Dungeness Spit to the west (Bubnick, 1986). In a wave shadow, refracted waves resulting from a headland or promontory, approach from the direction opposite the unrefracted waves. This causes a reversal in the direction of sediment transport.

Comparisons of 1970 and 1985 aerial photographs of Travis Spit show an increase in size of 17,800 m^2. The fact that the spit did not lengthen but rather volume increase was due to platform growth is evidence for the cyclic nature of spit growth (Meistrell, 1972). The depth to the base of the platform from MLLW has remained approximately 3.7 m over the 15 year interval between the photographs. Field measurements also confirm a consistent 3.0 m difference in elevation between MLLW and the berm crest of the spit.

Using the dimensions of Travis Spit, spit volume increased by 32,500 m^3 between 1970 and 1985. The annual net shore-drift rate is estimated to be 2,000 $m^3 yr^{-1}$.

NET SHORE-DRIFT DIRECTION AND RATE: Net shore-drift at Travis Spit is east to west, and the rate is 2,000 $m^3 yr^{-1}$.

SITE 17: Port Townsend Marina, Port Townsend, Jefferson County, Washington

LOCATION: Port Townsend, Washington, 2 km southwest of the Keystone-Port Townsend Ferry terminal, on the northeastern portion of the Quimper Peninsula.

OBSERVATIONS: The marina at Port Townsend is sheltered from Admiralty Bay by a large, L-shaped rubblemound breakwater. The coastline in the Port Townsend area trends northeast-southwest. The entrance channel to the breakwater faces northeast.

South of the breakwater, 20 to 30-meter-high glacial bluffs supply sediment to the littoral zone. Approximately 350 m south of the marina, an old railroad trestle extends northward out over the water. The trestle is supported by wood pilings, which do not inhibit the northward transport of sediment.

The breakwater is built over the foreshore, interrupting northward sediment transport. As a result, a prograding sandy beach has formed and extends 310 m updrift from the southern side of the breakwater. This wedge projects 150 m seaward from the back of the old beach and is 2.3 m thick.

The breakwater was built as part of an expansion project of an old boat basin. Construction by the Seattle District, U.S. Army Corps of Engineers was completed in 1964 (U.S. Army Corp of Engineers, 1984). Approximately 26,000 m^3 of material have accumulated to form this prograding beach in the last 22 years. The net shore-drift rate is estimated to be 1,000 $m^3 yr^{-1}$.

NET SHORE-DRIFT DIRECTION AND RATE: Net shore-drift is from south to north, and the rate is 1,000 $m^3 yr^{-1}$.

SITE 18: Pope and Talbot Sawmill Jetty, Port Gamble, Kitsap County, Washington

LOCATION: 2.2 km east of the Hood Canal Bridge, at the northwest end of Port Gamble.

OBSERVATIONS: The rubblemound jetty west of the Pope and Talbot Sawmill is the terminus for a drift cell originating 6 km south of Bangor, Washington, along the northeastern shore of the Hood Canal. The net shore-drift in the southern portion of the cell is south to north. The drift direction is west to east over the last 2 km, due to a change in coastline trend to east-west near Port Gamble (Taggart, 1984).

A small prograding sandy beach has formed west of the jetty. This structure projects out into deep water, effectively halting all net shore-drift toward the east. The jetty was built in 1900 by the Pope and Talbot Corporation to shelter a loading area for ships and barges at the northwest entrance to Port Gamble (Dan Harper, Pope and Talbot Corporation, personal communication, 1986).

The beach extends seaward 116 m from the landward end of the jetty, and 85 m updrift along the shore. The top of the present beach is 2.7 m above the level of the lower foreshore. The total volume of prograded sediment is 6,500 m^3. Assuming a fairly constant accumulation rate since 1900, the annual net shore-drift rate is 80 m^3 yr^{-1}.

NET SHORE-DRIFT DIRECTION AND RATE: Net shore-drift is from west to east, and the rate is 80 m^3 yr^{-1}.

SITE 19: Kingston Ferry Terminal Parking Lot, Kingston, Kitsap County, Washington

LOCATION: Kingston, Washington, at the northern end of Appletree Cove.

OBSERVATIONS: The Kingston Ferry terminal and parking lot are built out over the foreshore just north of Appletree Cove. The parking lot is defended along its northern and eastern perimeter by rip-rap. Rip-rap has interrupted the southerly transport of sediment in this drift cell, whose origin is 0.8 km northwest of Kingston (Taggart, 1984). As a result, a large prograded beach has accumulated on the updrift (north) side of the parking lot. The beach is composed of sand and gravel, derived from nearly vertical bluffs of unconsolidated glacial sediments. These bluffs line the shore directly north of the parking lot. The prograded beach measures 120 m from its most seaward point to the back of the old beach. It stretches 400 m updrift from the parking lot, with an elevation difference of 3.4 m from the lower foreshore to the top of the current beach profile. The volumetric total of this prograded beach is 40,000 m^3.

The parking lot was built for the Washington State Department of Transportation in 1967 (Carol Andrews, Dept. of Transportation, personal communication, 1986). The beach has been prograding updrift of the parking lot for the past 19 years. The net shore-drift rate is therefore 2,000 $m^3 yr^{-1}$.

NET SHORE-DRIFT DIRECTION AND RATE: Net shore-drift is from north to south, and the rate is 2,000 cubic meters per year.

SITE 20: Keystone Harbor, West Central Whidbey Island, Island County, Washington

LOCATION: West side of Whidbey Island, 15 km south of Oak Harbor, Washington; between Lake Crockett on Whidbey Island and Admiralty Bay on Puget Sound.

OBSERVATIONS: Keystone Harbor is man-made and was constructed by the Seattle District, U.S. Army Corps of Engineers in 1948 (U.S. Army Corps of Engineers, 1976). It provides a harbor of refuge, a boat ramp, and a terminal for the Washington Ferry, which runs between Whidbey Island and Port Townsend. The harbor is connected to Admiralty Bay by a channel; 6 m deep at MLLW and 60 m wide. The east side of the channel has a rip-rap breakwater which protects the harbor entrance.

In the days preceding the construction of the harbor, the beach to the east of the breakwater was nourished by the net shore-drift of sediment from the west (Admiralty Head). Construction of the breakwater, entrance channel and harbor have interrupted this natural drift process. This has caused two main problems: (1) the accumulation of sediment drifting into the navigation channel, and (2) erosion of the beach downdrift (east) of the breakwater.

The Seattle District, U.S. Army Corp of Engineers has maintained a maintenance dredging and beach renourishment program here since 1950. Under this plan it has been neccessary to dredge the entrance channel every 5-7 years to maintain a navigable passage. Dredged volumes removed from 1961 to 1980 (U.S. Army Corps of Engineers, 1976; Eric Nelson, personal communication, 1986), are as follows:

accumulation period	volumes dredged
1956-1961	20,600 m^3
1961-1967	29,800 m^3
1967-1971	20,600 m^3
1971-1976	21,400 m^3
1976-1980	16,800 m^3
total	109,200 m^3

The entrance channel is scheduled for dredging in 1987 (Eric Nelson, personal communication, 1986).

Of the 109,200 m^3 of sediment that have been dredged in the 24 years between 1956 and 1980, approximately 102,500 m^3 have been deposited on the beach east of the breakwater, to prevent landward outflanking and gradual deterioration. This beach nourishment has been successful in keeping the shore east of the breakwater in equilibrium (U.S. Army Corps of Engineers, 1980).

Based on the amount of sediment dredged from the channel, the annual rate of net shore-drift infilling the channel is 5,000 $m^3\ yr^{-1}$.

NET SHORE-DRIFT DIRECTION AND RATE: Net shore-drift is from west to east at Keystone Harbor, and the rate is 5,000 $m^3\ yr^{-1}$.

SITE 21: Mariner's Cove, northeast Whidbey Island, Island County, Washington

LOCATION: Strawberry Point on northeastern Whidbey Island, 9.5 km east of Oak Harbor, Washington.

OBSERVATIONS: Mariner's Cove is a private beach-front community situated on southwestern Skagit Bay. The homes in this development are built around a dredged inlet, which allows small private boats to be moored near the owner's residence. The entrance channel joining the inlet to Skagit Bay has been defended on its north and south sides by two rubblemound jetties.

Sand-to-cobble-sized sediment is supplied to the foreshore by undefended glacial bluffs, 1 km south of the entrance channel. The net shore-drift along this portion of northeastern Whidbey Island is from south to north. The channel and jetties interrupt the natural northward transport of sediment in the area, resulting in deposition of a sediment wedge to the south and erosion of foreshore sediments north of the entrance channel.

The channel was dredged and the jetties built in 1966. The sediment wedge south of the entrance channel has prograded 45 m seaward from the back of the original beach, and begins to accumulate at a point 160 m updrift (south) of the south jetty. The present beach has attained a thickness from lower foreshore to beach crest of 2.4 m adjacent to the south jetty. Based on these dimensions, the total volume of the prograding beach is currently 4,500 m^3.

An average net shore-drift rate of 200 $m^3 yr^{-1}$, over the past 20 years, accounts for the volume of sediment accumulated updrift of the Mariner's Cove entrance channel.

NET SHORE-DRIFT DIRECTION AND RATE: Net shore-drift at Mariner's Cove (Strawberry Point) is from south to north, and the rate is 200 $m^3 yr^{-1}$.

SITE 22: Skyline Marina, Anacortes, Skagit County, Washington

LOCATION: 3 km west of Anacortes, Washington, adjacent to the eastern boundary of Washington Park.

OBSERVATIONS: Skyline Marina is a well established small boat basin, built directly behind a spit. An entrance channel to the marina has been dredged through the proximal end of the spit. The channel is protected on its east and west sides by two rubblemound jetties, which project 70 m out into Burroughs Bay.

The net shore-drift is from east to west along the shore fronting the marina (Keuler, 1979). The major source of sediment for this area are 10-meter-high coastal bluffs, located 0.5 km east of the jetties. These bluffs are composed of unconsolidated glacial sediments, which are easily eroded due to direct exposure to waves within Burroughs Bay.

In response to the east to west movement of littoral zone sediments a prograded wedge of coarse-fine sand, pebbles and cobble has accumulated on the updrift (east) side of the entrance channel. The wedge extends seaward 73 m from the back of the old beach, and 180 m to a point updrift of the east jetty. The beach profile currently has an elevation difference of 1.5 m.

The jetties were built in 1980 (George Wasaluski, Skyline Marina, personal communication, 1986). Since that time, approximately 5,000 m^3 of sediment have accumulated updrift of the east jetty. The annual rate of net shore-drift, based on these figures, is 800 $m^3 yr^{-1}$.

NET SHORE-DRIFT DIRECTION AND RATE: Net shore-drift at Skyline Marina is east to west, and the rate is 800 $m^3 yr^{-1}$.

SITE 23: Sandy Point Spit, Whatcom County, Washington

LOCATION: 16 km northwest of Bellingham, Washington, at the northwest córner of Lummi Bay.

OBSERVATIONS: Sandy Point, by analogy with nearby Semiahmoo Spit, is thought to have begun development somewhat after 4,000 years ago, and had grown to a reasonable-sized landform by 2,000 years ago (Schwartz, 1983). The 145 km fetch along Georgia Strait, combined with northwest winds, cause predominant waves to strike the shore from the northwest. This initiates net shore-drift of sediment to the south, and has resulted in the formation of Sandy Point. Sediment is initially supplied to the littoral zone from the Cherry Point-Point Whitehorn area. Beach sediment grades from cobbles at Point Whitehorn to mixed sand and gravel at Sandy Point (Jacobsen, 1980).

In 1983, Dr. Maurice L. Schwartz, working under contract with the Seattle District, U.S. Army Corp of Engineers, studied the sediment transport rate at Sandy Point. Two methods were used to determine the lower foreshore-nearshore bottom transport of sediment: (1) age and volume of Sandy Point Spit and (2) shoaling of the marina channel at the southwest side of the spit.

By measuring several maps based on surveys taken over the last 100 years, the area of Sandy Point was found to remain fairly constant. This is generally attributed to the small scale, and generalizing of surface shape on the older maps, along with human modification of the surface in recent years. The area of Sandy Point was determined to be approximately 1,036,000 m^2 (Schwartz, 1983). The thickness of Sandy Point was determined from the Seattle District, U.S. Army Corps of Engineers project topo survey map of March 1983, and borehole data. A first approximation of the spit thickness is 5.5 m.

From the figures above, the total volume of Sandy Point is estimated to be 5,684,000 m^3. The table below shows the average annual net shore-drift rate for Sandy Point based on various times of origin (Schwartz, 1983):

Years before present	Rate (m^3 yr^{-1})
2000	2,842
2500	2,274
3000	1,895
3500	1,624
4000	1,421
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average	2,011

In 1983 the inlet channel was approximately 30 m wide, 180 m long and 1.5 m deep at MLLW. For a rectangular cross-sectional model, the volume for the channel would be 8,000 m^3. The channel has a subaqueous side angle of repose of 25 degrees, however, resulting in a total volume for the channel of approximately 4,000 m^3 (Schwartz, 1983).

Mr. Dan Walker furnished a 1962 map of the marina area (scale 1"=100') as it was when he purchased land in 1963. From this map the inlet was determined to be 107 m wide, 180 m long and 3.6 m deep at MLLW. The volume of that channel would be 70,500 m^3 with a rectangular cross-section, and 35,000 m^3, considering the angle of repose of the sides (Schwartz, 1983).

The volumetric difference in the 1962-1983 rectangular cross-sectional model is 62,500 m^3. The volumetric difference in the 1962-1983 modified, angle of repose cross-section is 31,000 m^3. Dividing these differences in volume by 21 years, gives an annual net shore-drift rate of 3,000 and 1,500 m^3, respectively. Averaging the two, an annual drift rate of 2,250 $m^3 yr^{-1}$ is obtained.

The average value obtained from the shoaling of the channel inlet (2,250 $m^3 yr^{-1}$) and that obtained from age-volume data (2,011 $m^3 yr^{-1}$) are in close agreement. Averaging the final rates from the two methods, results in an annual net shore-drift rate of 2,000 $m^3 yr^{-1}$ for Sandy Point.

NET SHORE-DRIFT DIRECTION AND RATE: Net shore-drift at Sandy Point is north to south, and the rate is 2,000 $m^3 yr^{-1}$.

SITE 24: Birch Bay Village Marina, Birch Bay, Whatcom County, Washington

LOCATION: 7.5 km south of Blaine, Washington, at the northwest corner of Birch Bay.

OBSERVATIONS: The Birch Bay Village Marina entrance channel is the terminus for a drift cell originating 3 km to the west at Birch Point (Jacobsen, 1980). Undefended glacial bluffs supply sediment to the littoral zone west of Birch Bay.

The entrance channel to the marina is protected by rubblemound jetties on the west and east. The west jetty is almost a total barrier to the eastward movement of littoral sediment. A large prograding beach has formed west of the channel jetty in response to this obstruction. The beach extends 72 m seaward from the back of the original beach, and begins to accumulate at a point 110 m updrift (west) of the west jetty. The thickness is 4.4 m from the top of the beach to the lower foreshore, and the total volume for the prograding beach is presently estimated to be 8,500 m^3. East of the channel the shoreline is off-set landward, showing the effects of sediment depletion.

Sediment does bypass the west jetty, and it has been necessary to dredge the channel. Since the construction of the jetties in 1967 the channel has been dredged four times (Elliot Fleming, Birch Bay Village Marina, personal communication, 1986). Approximately 800 m^3 of material were removed from the channel in 1981 and also in 1986 (Roland Culbertson, Birch Bay Village Marina, personal communication, 1986). Records of earlier maintenance dredging volumes and dates are unavailable. Considering the time interval and the number of pre-1981 dredging projects, the assumption was made that a similar volume of material had been removed from the channel during the two previous dredging operations.

The total volume of sediment dredged from the entrance channel is estimated to be 3,000 m^3. This volume when added to the volume of the prograded beach is 11,500 m^3, and represents the total volume accumulated at the marina since 1967. A first approximation of the annual net shore-drift rate is 600 $m^3\ yr^{-1}$.

NET SHORE-DRIFT DIRECTION AND RATE: Net shore-drift at the Birch Bay Village Marina is west to east, and the drift rate is 600 $m^3\ yr^{-1}$.

SITE 25: Semiahmoo Spit, Blaine, Whatcom County, Washington

LOCATION: 2 km southwest of Blaine, Washington, and forms the western boundary of Drayton Harbor.

OBSERVATIONS: Semiahmoo Spit is a northeasterly trending spit that is the terminus of a 6.5 km drift cell originating to the southwest at Birch Point (Jacobsen, 1980). The spit is composed primarily of fine-to-coarse sand, with grain size increasing to the southwest.

In determining the net shore-drift at Semiahmoo Spit, historical and recent maps were used. A U.S. Coast Survey Map of Semi-ah-moo Bay in 1857 yielded base volumetric calculations (U.S. Coast Survey, 1857). The spit had an area of 1,563,200 m^2 and a total volume of 3,764,000 m^3 in 1857. The total volume includes the spit from proximal to distal end and the platform down to 2 m below MLLW. By 1952, the spit area had increased to approximately 1,885,900 m^2 and the total volume, with the same depth and length constraints, increased to 4,544,000 m^3 (U.S.G.S., 1952). This is an increase in volume of 780,000 m^3 over the 95 years separating the two maps. The increase can be accounted for by an annual net shore-drift rate of 8,000 m^3 yr^{-1}.

NET SHORE-DRIFT DIRECTION AND RATE: Net shore-drift is southwest to northeast along Semiahmoo Spit, and the rate is 8,000 m^3 yr^{-1}.

SITE 26: Point Roberts Marina, Point Roberts, Whatcom County, Washington

LOCATION: South shore of Point Roberts, 24 km west of Blaine, Washington.

OBSERVATIONS: The entrance channel to the 1000-berth marina at Point Roberts is protected on the west, east and southeast sides by three rubblemound breakwaters. A small riprap groin also connects the east breakwater to the offshore southeast breakwater. The groin is not more than 2 m high, and is only visible at extremely low tides. The low height is to allow small fish to migrate past the channel without going into deeper, predator-laden water (Layton, 1979). The groin and east jetty obstruct the westward net shore-drift of sediment (Jacobsen, 1980). In response to this interruption in the natural shore-drift pattern, sediment accumulates in a prograding wedge updrift (east) of the entrance channel. Erosion west of the entrance channel results from sediment deprivation.

Prior to construction of the marina, net shore-drift studies were conducted. These studies indicated a net westerly transport of sediment with an approximate volume of 4,000 $m^3 yr^{-1}$ (Layton, 1979). Construction of the marina was completed in 1978, and a sediment bypass operation was included as a part of the marina maintenance plan (Layton, 1979).

In the bypass operation, sediment trapped updrift of the east groin and breakwater is transported by dump-truck to a point 0.4 km west of the entrance channel, where it is re-introduced into the natural beach system. The bypass operation has been successful in moving over 23,000 m^3 of sediment since 1978 (Layton, 1986), and appears to be satisfactorily replenishing the loss of sediment created by the construction of the Point Roberts Marina. This would amount to a rate of 3,500 $m^3 yr^{-1}$,over the 7 year period between 1978 and 1986.

Based on initial sediment transport studies and the beach nourishment program, the average net shore-drift rate is 4,000 m^3 yr^{-1}.

NET SHORE-DRIFT DIRECTION AND RATE: Net shore-drift is east to west at the Point Roberts Marina, and the annual drift-rate is 4,000 m^3 yr^{-1}.

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