Shoaling of Port of Astoria, Oregon, by Sediment from Mt. St. Helens Eruption

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Larry S. Slotta

Carlos R. Cobos

Roger S. Mustain

Water Resources Research Institute

Oregon State University

Corvallis, Oregon

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Civil Engineering Department, Oregon State University

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ABSTRACT

Sedimentation rates suddenly increased in the Lower Columbia River immediately following the May 18, 1980 eruption of Mt. St. Helens. Research conducted at the Port of Astoria during 1981-1982 permitted determination of the shoaling mechanisms and confirmed that some of the sediment was of recent Mt. St. Helens origin.

Three types of models were used to study the circulation and shoaling characteristics of the Port of Astoria: a physical model, numerical circulation model, and a numerical sedimentation model. The physical model provided insight to the overall circulation patterns and tidal exchanges of water. The numerical circulation model gave additional information on residence times and flushing rates of water in the port slips. It also provided input information for use with the numerical sedimentation model. This model gave reasonable estimates of sedimentation rates at the Port. A paucity of accurate field data presently limits the applicability of theoretical models to qualitative rather than quantitative interpretation.

Field research allowed a more quantitative investigation of the shoaling conditions in the lower Columbia River at Astoria. Rates of sediment deposition in the harbor slips were measured using sedimentation buckets. Core samples of bed material were obtained for various physical analyses. Water currents and circulation were measured using drogues and current meters. Water samples were collected to characterize suspended sediment concentrations. Typical suspended sediment sizes and bed material sizes were 0.01-0.03 mm, indicating well-graded silt.

Three distinct tests (clay mineralogy, heavy minerals and microprobe) indicated that the Columbia River is the primary source of the suspended sediment causing shoaling in Astoria Harbor. However, under certain conditions Youngs Bay sediment may also enter the Astoria Harbor. The microprobe analysis provided the most definitive answer regarding effects produced at the Port of Astoria by the Mt. St. Helens eruption, indicating that part of the sediment sampled from the port slips contained non-juvenile glass from Mt. St. Helens.

The sedimentation mechanism in the Astoria area is described. The Columbia River (rather than Youngs Bay) is identified as the main source of the sediment causing chronic shoaling problems at the Port of Astoria. This accounted for the abrupt increase in sedimentation that occurred in the harbor slips due to the Mt. St. Helens eruption.

The elevated sedimentation rate caused by the eruption was observed to decrease slightly with time after the eruption. This decreased rate should be proportional to the decrease in the amount of upriver channel storage of sediment from Mt. St. Helens. The present (early 1983) sedimentation rate is still higher than before the eruption. Further reductions in sedimentation rate will occur over several years before reaching the pre-eruption level, assuming that no further eruptions and major sediment disturbances occur.

FOREWORD

The Water Resources Research Institute, located on the Oregon State University campus, serves the State of Oregon. The Institute fosters, encourages and facilitates water resources research and education involving all aspects of the quality and quantity of water available for beneficial use. The Institute administers and coordinates statewide and regional programs of multidisciplinary research in water and related land resources. The Institute provides a necessary communications and coordination link between the agencies of local, state and federal government, as well as the private sector, and the broad research community at universities in the state on matters of water-related research. The Institute also coordinates the inter-disciplinary program of graduate education in water resources at Oregon State University.

It is Institute policy to make available the results of significant water-related research conducted in Oregon's universities and colleges. The Institute neither endorses nor rejects the findings of the authors of such research. It does recommend careful consideration of the accumulated facts by those concerned with the solution of water-related problems.

ACKNOWLEDGEMENTS

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We thank the staff of the U.S. Army Corps of Engineers, Portland and Seattle Districts, especially Pamela Moore and Mary Vargas, for providing important information related to the project. The Port of Astoria authorities are thanked for their continual cooperation and help in facilitating the field studies and providing local information.

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1. INTRODUCTION

The Problem

Astoria is located on the Columbia River estuary. Situated at the tip of a peninsula between the Columbia River and Youngs Bay, Astoria is 78 miles (125 kilometers) from Mt. St. Helens by direct distance, as shown in Figure 1. The Port of Astoria has had continuous shoaling problems over the years. However, in 1980 a sudden increase in the sedimentation rate was experienced in the Port of Astoria harbor slips and in numerous other lower Columbia River ports. The resulting dredging required to maintain the harbor slips in a usable condition exceded the capacity of the Port's existing dredging equipment. This increased sedimentation was immediately attributed to the Mt. St. Helens eruption of May 18, 1980. Verifying whether or not that eruption was in fact the direct and immediate cause of increased sedimentation at the Columbia River ports was the main challenge of this study. Another significant concern was whether the severe sedimentation would prove to be a relatively short-term problem or could lead to chronic additional dredging.

The question of whether or not the increased sedimentation was produced by the Mt. St. Helens eruption also resurfaced an older question on whether or not the sediment that accumulates in the Astoria Harbor slips was from Youngs Bay or Columbia River sources. The Youngs Bay vs. Columbia River sedimentation question had not yet been satisfactorily resolved and hence did not shed immediate light on the shoaling problem following the Mt. St. Helens eruption, other then the obvious inference that the eruption was responsible for the shoaling.

Youngs Bay was previously identified as a possible contributor to the sedimentation problem in the Port of Astoria slips (Higley et al., 1976; Krone, 1971). Circulation studies had indicated current patterns in the vicinity that could influence the transport of sediments. One current pattern was reported to extend out from Youngs Bay past the site entrance under certain tidal conditions (Slotta et al.,1975).

Research Objectives

The goal of this research was to determine the origin of the sediment found in the Port of Astoria slips. The research goal was pursued under two objectives: (1) to determine whether or not the May 1980 Mt. St. Helens eruption produced the sudden increase in lower Columbia River sedimentation rates; (2) to determine if the aggravated problems due to the sedimentation rate increase were of short duration or were instead likely to be prolonged for several years, mainly due to upriver and estuary storage of the recent eruption-derived sediments.

Setting and Site Description

The Toutle River drains the northwest slopes of Mt. St. Helens, including the debris-flow area. The Toutle River discharges into the Cowlitz River at river mile (RM) 25 (km 40). The Cowlitz, in turn, joins the Columbia River at RM 68 (km 109).

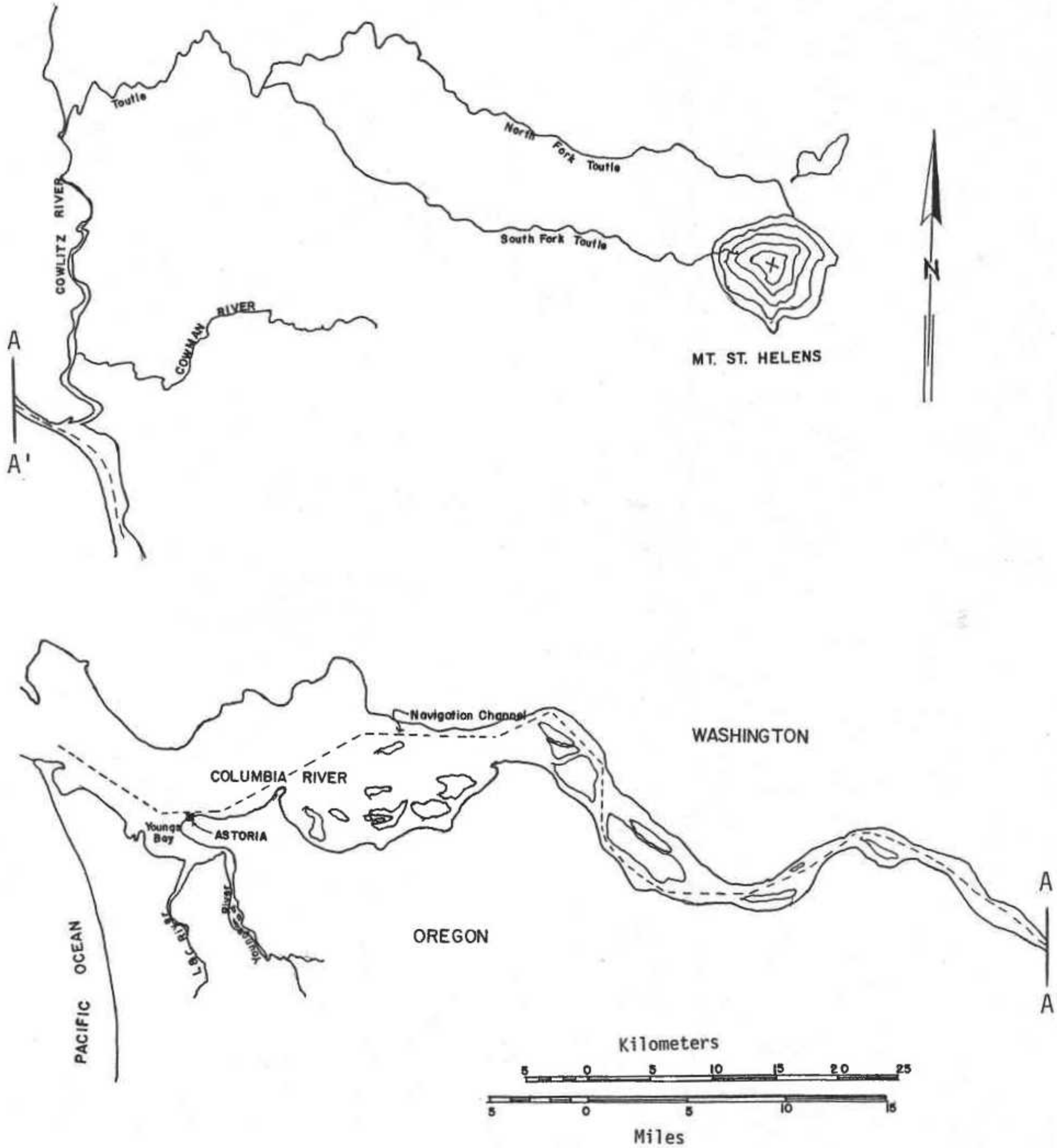


FIGURE 1. MT. ST. HELENS, THE COLUMBIA RIVER ESTUARY AND ASTORIA

The Port of Astoria is located at RM 13 (km 21) on the south bank of the Columbia River estuary (see Figures 1 and 2). The limits of the estuary are not exactly defined. Hubbell et al. (1971) considered the upriver limit to be at Longview, Washington, near RM 68; others (Roy et al., 1982) farther upriver, and still others (Gelfenbaum, 1981), no farther upriver than Harrington Point, near RM 24. However, all agreed that the estuary limit is farther upriver than the Port of Astoria.

Several estimates of the mean water discharge and the mean suspended load for the Columbia River near Astoria are available in the literature. A mean discharge of 256,000 cfs (7,260 m^3/s) and a suspended sediment load of 1.03×10^6 tons per year are reported by Holeman (1968). The accepted average suspended sediment load reported by others has been taken as 10^7 metric tons/year (Gelfenbaum, 1981; Hubbell et al., 1971). River discharge varies seasonally due to winter precipitation and spring-summer snowmelt. The natural runoff pattern is greatly altered due to reservoir operation. Lowest discharge generally occurs in late summer and early autumn.

The Columbia River estuary is considered a partially-mixed estuary for low river flows and a well-mixed estuary for high discharges (Dyer, 1979). The mean tidal range of the lower Columbia River is 6.4 ft. (2 m). A maximum variation of 11.4 ft. (3.5 m) reportedly occurs, with respect to Local MLLW, at the 100-year flood stage at Astoria, (Seaman et al., 1972). The limit of sea water intrusion is about 23 miles (37 km). Tidal flow reversals occur as far as 53 miles (85 km) upstream of the mouth and tidal fluctuations are observed as far upstream as Bonneville Dam, 140 miles (225 km) from the mouth (Hamilton, 1973).

The Port of Astoria slip layout is shown in Figure 2. Both slips are open to the Columbia River at their north end. The designed depth in the slips is 35 ft. (11 m). The navigation channel on the river is 55 ft. (17 m) deep and passes at a distance of 600 feet (180 m) from the entrance to the slips.

The piers have concrete decks supported by wood pilings. Beneath each deck is a rubble breakwater which extends along the length of the pier, although the breakwater of pier 3 is incomplete. Facilities such as warehouses, shops, office, cranes and railroad tracks are located above the deck.

Timber is the principal cargo handled at the Port of Astoria. Slip 1 has greater commercial use than slip 2 and, therefore, is more frequently dredged. Silt curtains have been recently added on the landward section of slip 2 to retain dredged material that must be stored there in periods of low flows rather than be released into the Columbia River.

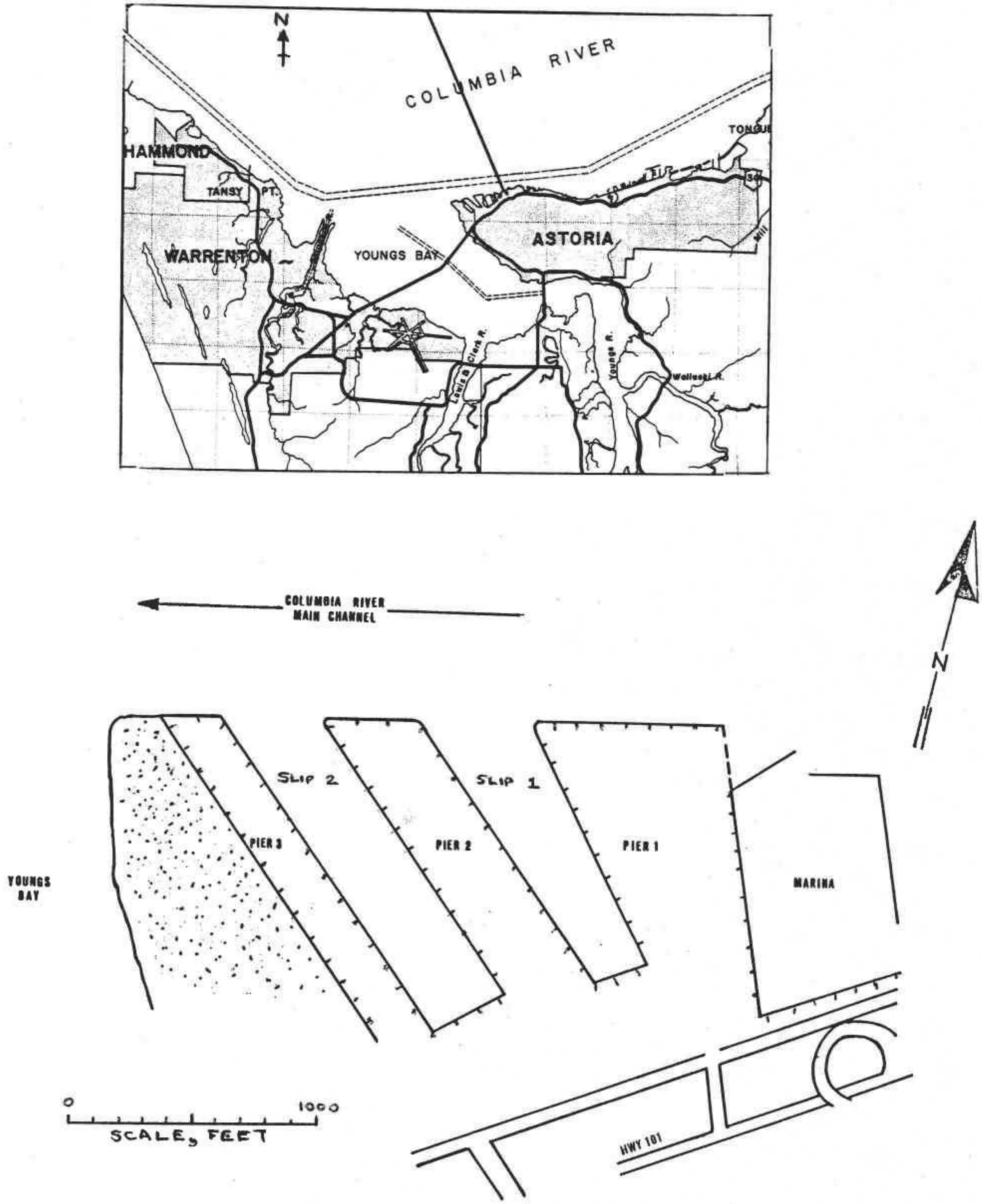


FIGURE 2. PORT OF ASTORIA PIER AND SLIP LAYOUT

2. LABORATORY AND COMPUTER STUDIES OF WATER CIRCULATION AT PORT OF ASTORIA

Scope and Approach

The circulation and shoaling characteristics of the harbor slips at the Port of Astoria were investigated by means of three types of models: a physical model, a numerical circulation model, and a numerical sedimentation model. Each model simulates various aspects of the hydraulic and/or sedimentary processes at the Port. The small-scale physical model was used to give insight to the overall flow and circulation patterns and tidal exchanges for water. The one-dimensional numerical circulation model was then used to obtain information on velocities, residence times and flushing rates for water in the port slips. This model also provided input information for use with the sedimentation model. The single-cell numerical sedimentation model was used to make estimates of sedimentation rates in the harbor slips. Collectively, the models give needed qualitative understanding of the shoaling mechanisms that can be used to plan and conduct field research. Field research, in turn, can be used to validate the model results.

Physical Model and Results

A physical hydraulic model was used for preliminary investigation of the hydrodynamics and flushing in the Port area. The model was of small size and not designed or intended to provide precise quantitative information regarding velocities, flow rates, diffusivities, etc. Rather, the model was intended to provide a clear overview of the possible hydraulic exchanges occurring within the harbor slips. The information thus gained could then serve as a "point of departure" for further studies, either field or theoretical.

Numerous variables affect the circulation in an estuary. Fortunately, the system to be modeled at the Port of Astoria is a comparatively simple one in which several of these variables can be assumed negligible. Figure 3 shows the area included in the model. Slips 1 and 2 were each treated as a small embayment closed on the landward side, and open on the seaward side to the Columbia River. Consequently, no fresh water inflow is present, with the result that essentially no stratification due to temperature and salinity variation occurs. The comparatively small lengths of the estuaries under consideration do not provide sufficient fetch for significant wind-induced motion to develop; wind-induced phenomena can therefore be assumed negligible except at the water surface.

The horizontal and vertical scales of the model were 1:1200 and 1:120, respectively, as determined by the size of the available modeling tank, which was 4 ft (1.2 m) square and constructed of clear plexiglass. The tidal period for the model was about 6.8 minutes for a prototype tidal period of approximately 12.4 hours.

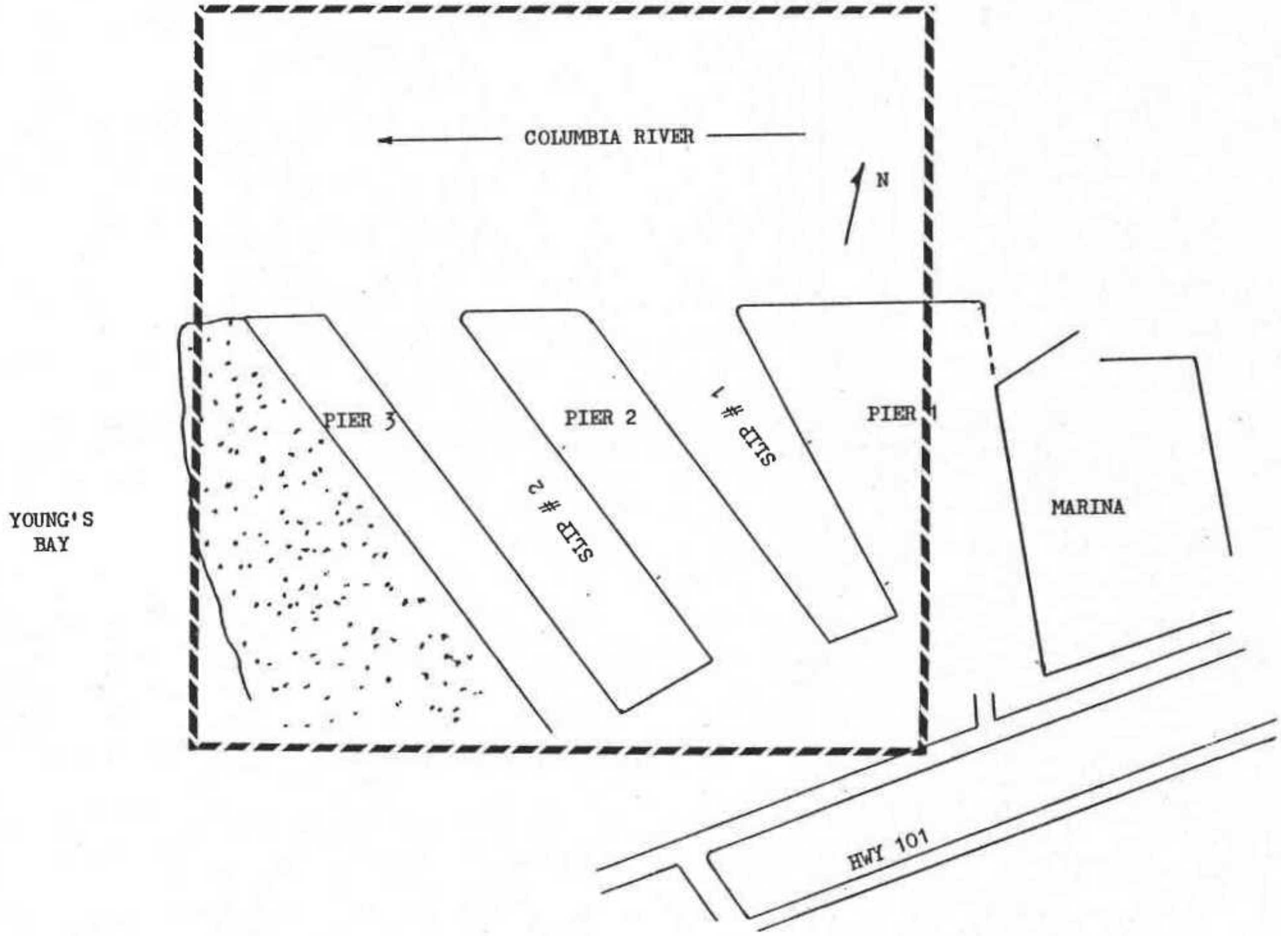


FIGURE 3. PHYSICAL MODEL, PLAN VIEW

The model was constructed of plastic. Lights were then installed under the model with a reflector so that the areas representing water was clearly illuminated. Land areas were covered above the high tide level to prevent light from showing through. A movie camera was fixed above the model to record the movement of dye tracers of current patterns.

The tidal flow pattern was simulated by use of two pumping systems. One, representing the flow of the Columbia River, consisted of a pump which provided a constant uni-directional (downstream) flow in the model. The second, representing the periodic tidal flow, consisted of a pump and valves which could be used to generate upstream flow (incoming tide) and reversed to generate downstream flow (outgoing tide). The model tide amplitude was established corresponding to the maximum tide range experienced at Astoria. Approximately forty different tests were made. Slug and trickle injections of dye were made at frequent intervals along the length of each slip, in the river channel upstream to represent Columbia River suspended sediment, and just outside the mouth of each slip to represent the effect of disposing of dredge spoils at such locations.

To investigate the prevention of sedimentation, the model was also modified by the addition of impervious wall sections to represent possible structures (e.g. silt curtains, sheet piling) which might feasibly be constructed at the Port to improve hydrodynamic patterns as they affect sedimentation. It was surprisingly difficult to so modify the hydrodynamics without resorting to impractical configurations.

The results from the model were highly illuminating and satisfactory. Details are given in Mustain (1982) and only summarized here. Figure 4 shows the results of model run which clearly illustrated the interaction between the slips. Dye was released continuously in slip 2. Figure 4(a) gives the motion of the dye on the ebb tide. The dye dispersed in slip 2 and flowed into the Columbia River, whence it proceeded downstream. Figure 4(b) illustrates the changes in flow patterns which occurred during flood tide. As the flow in the Columbia River reversed, the dye was carried upstream to and past the mouth of slip 1. A portion of this dye drifted into slip 1 and remained there, even on the next ebb tide. The implication of this behavior for the Port of Astoria is that the generation of large volumes of suspended sediment in one slip (e.g. disposal of dredge spoils in slip 2) can result in increased sedimentation in the other slip. This is of concern at the Port of Astoria, since disposal of dredge spoils into the Columbia River is only permitted during periods of high flow. Consequently, it may be necessary at times to adopt the seemingly contradictory policy of disposing of dredge spoils in one slip to keep the other slip navigable.

The film records were transferred to videotape for presentation to officials at the Port of Astoria. The simplicity and flexibility of the model were particularly attactive features. Test runs could easily be made to simulate virtually any desired conditions in the field, both existing and proposed; the film results were easily comprehensible to anyone, whether familiar or not with hydraulic modeling.

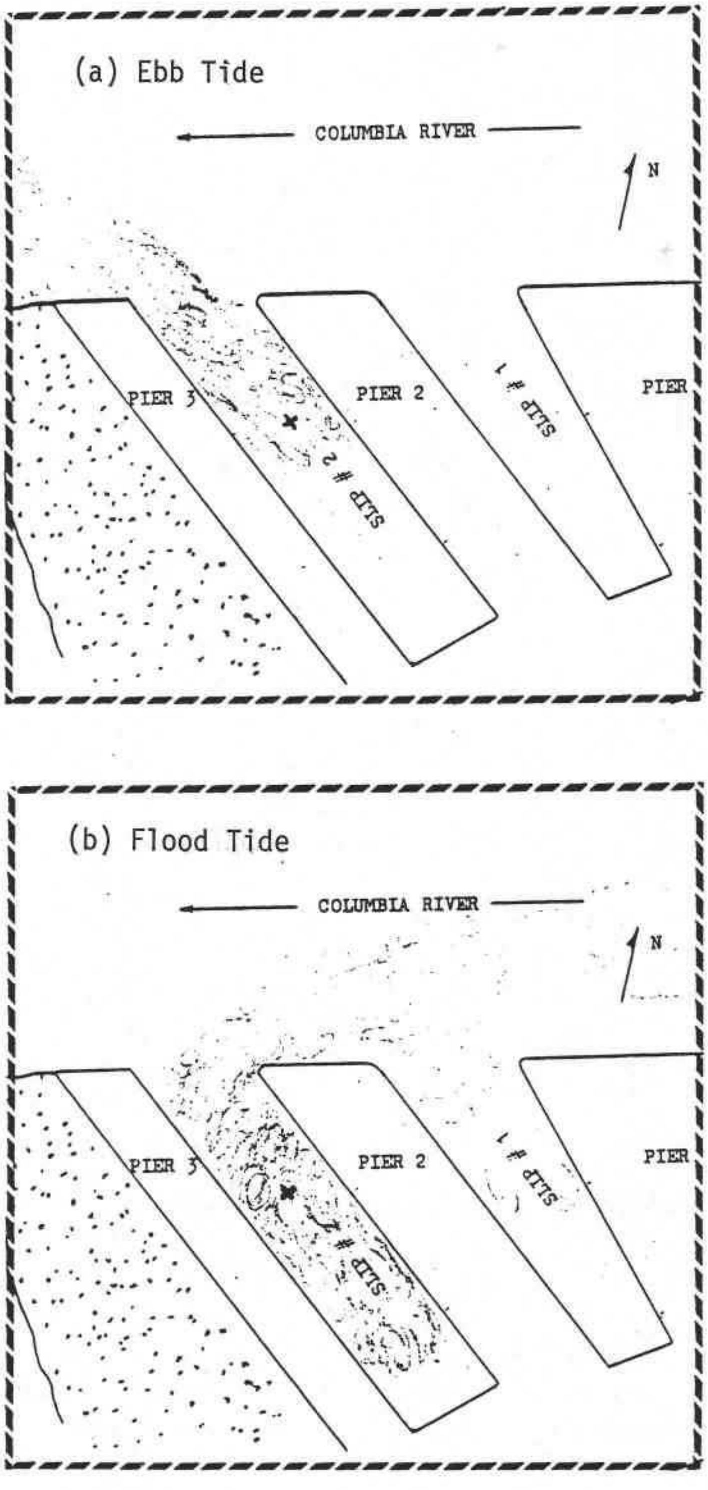


FIGURE 4. DYE MOVEMENT IN PHYSICAL MODEL

The model results compared favorably with aerial photographs of subsequent dye releases in the field. Correspondence between the model and prototype was excellent for a dye release on the incoming tide. Correspondence was less satisfactory for the field dye release made on the outgoing tide, probably due to a stiff breeze which was blowing against the outgoing tide.

In summary, the model was a useful tool in gaining an understanding of the hydraulic exchange of the prototype system. Such a model might be particularly useful as a management tool in performing preliminary investigations into the possible impacts of proposed actions which may affect the prototype.

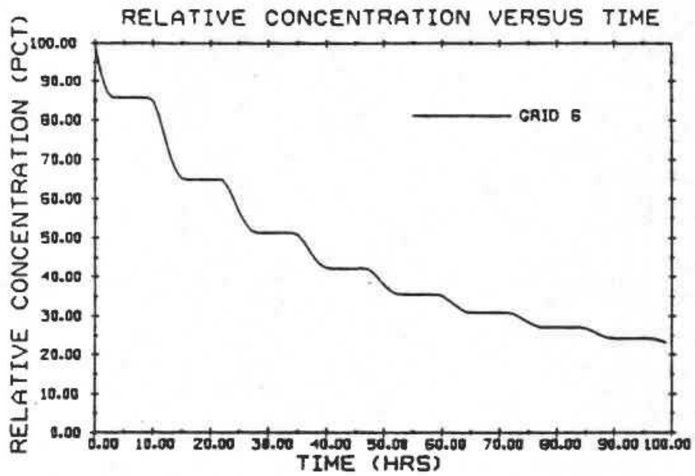
Numerical Circulation Model and Results

A simple one-dimensional numerical model was developed by McDougal (1980) for the analysis of flushing in relatively narrow estuaries open to the tide at one end. If certain simplifying assumptions can be satisfied, the only variables which vary over space are flow rates and concentrations of dissolved or suspended constituents. The simplifying assumptions are approximately met for the Port of Astoria at slip 1. The slip was divided into several grid cells for analysis. Details of the applied model are given in Mustain (1982).

Figure 5 illustrates the model results for three runs in which initial (normalized) concentrations (C) of 100 units were established in the landward (highest numbered) grids of the models. Figures 5(a) and 5(b) show the relative concentration versus time in grid 6 of a six-grid model with tidal amplitudes (a) of 2.0 ft (.61 m) and 5.0 ft (1.72 m), respectively. Figure 5(c) shows the relative concentration versus time in grid 9 of a nine-grid model for a tidal amplitude of 5.0 ft (1.72 m).

The rate of flushing predicted by the three models of Figure 5 varies, ranging from 78 to 92 percent. Given the same number of grids in the model (i.e. for Figures 5(a) and 5(b)) the higher tidal amplitude results in a greater predicted flushing rate. This is reasonable, since greater tidal amplitudes result in larger exchanges of water between adjacent cells in the model. A more subtle result is that, given the same tidal amplitude (i.e. Figures 5(b) and 5(c)), the model with the greater number of cells predicts lower flushing rates. This "numerical retardation" effect is important when numerical models are employed: as the number of grids in the model increases, the volume exchanged between the grids decreases, which results in an apparently lower rate of hydraulic exchange. Determining the optimum number of grids to be used in the model is an important aspect of model calibration.

Figure 6(a) illustrates concentration versus time for grids located near the midpoint of the slip (grid 4 or 5) and at the mouth of the slip (grid 2) with tidal amplitude equal to 5.0 ft (1.72 m), initial concentration of 100 units in cell 6, and a six-cell model. The resultant concentrations on grids 2 and 4 begin at zero, rise to a peak, then decrease at a declining rate,

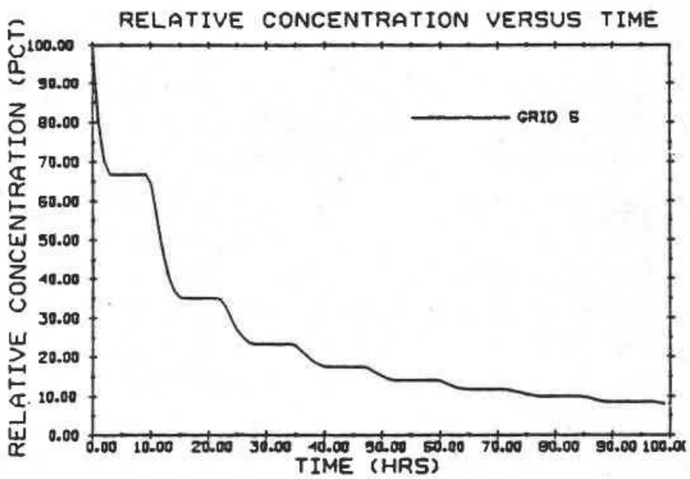


(a)

$a = 2.0$ ft

$C_{0,6} = 100$

$S = 0$

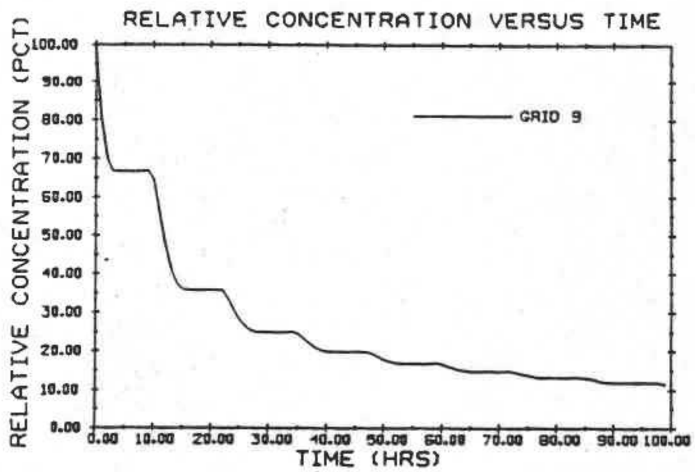


(b)

$a = 5.0$ ft

$C_{0,6} = 100$

$S = 0$



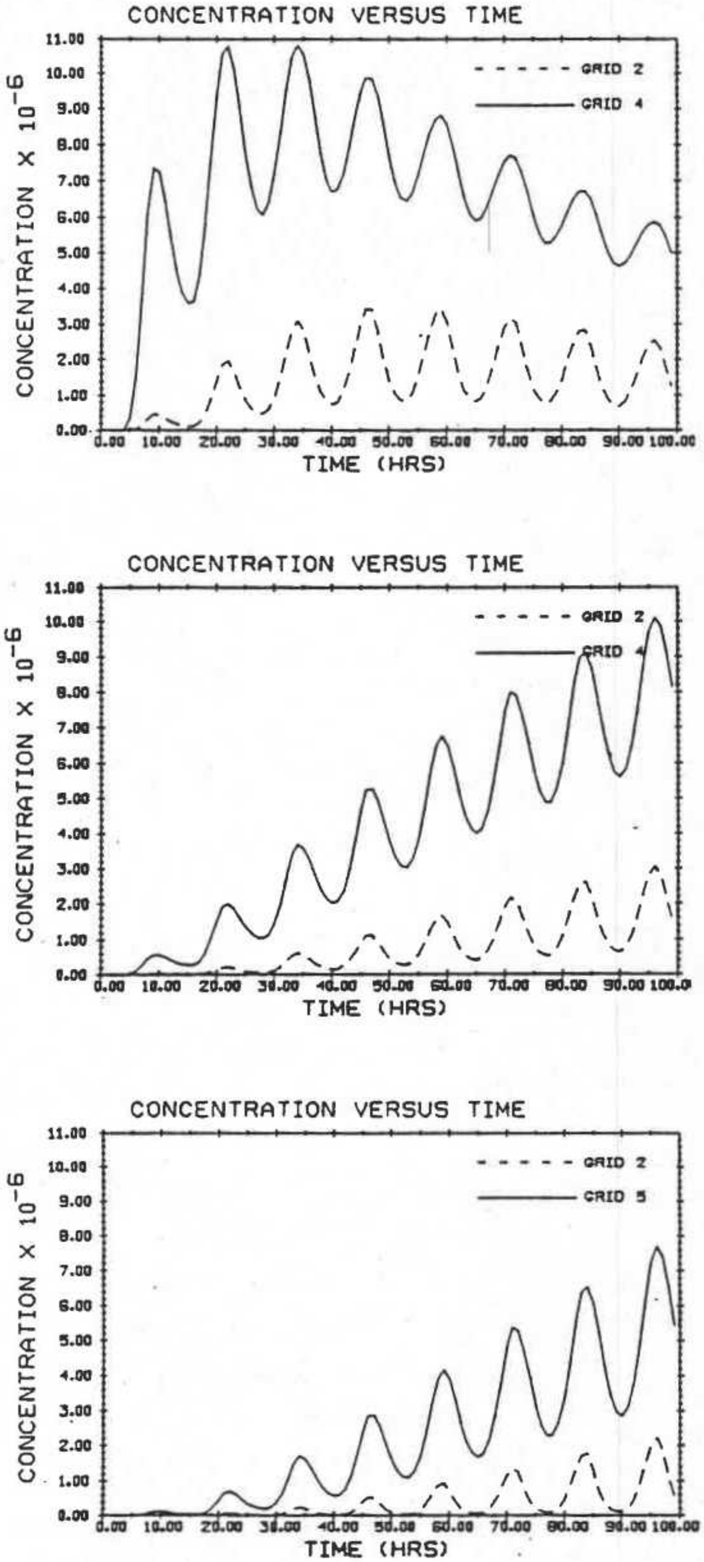
(c)

$a = 5.0$ ft

$C_{0,9} = 100$

$S = 0$

FIGURE 5. RELATIVE CONCENTRATION VS TIME



(a)

a .= 5.0 ft

$C_{0,6}$= 100

S = 0

(b)

a = 5.0 ft

C_0= 0

S_6= 1

(c)

a = 5.0 ft

C_0= 0

S_9= 1

FIGURE 6. CONCENTRATION VS TIME

which would eventually become asymptotic to C = 0. The concentration in grid 4 reaches its maximum in about half the time that grid 2 requires. Also, the maximum concentration in grid 4 is about three times the maximum attained in grid 2.

Figure 6(b) shows concentration versus time for no initial concentration anywhere in the slip but with a constant input of one unit per hour into grid 6 of a six-grid model. The resultant concentrations in this case begin at zero and increase at a decreasing rate. Eventually, the concentrations would level out as the system attained its steady-state.

Figure 6(c) shows concentration versus time for an initial condition of zero concentration throughout the slip and a constant input of one unit per hour in cell 9 of a nine-cell model. The resultant concentration plots are similar to those in Figure 6(b), but again the effect of numerical retardation is evident. Both models will eventually reach the same steady-state concentrations. Due to numerical retardation, however, the nine-grid model will approach the steady-state more slowly.

The model results give an indication of the hydraulic exchange which occurs between slip 1 and the Columbia River. The predicted flushing rates (80-90 percent over four days) indicate that the slip exchanges sufficient water to avoid stagnation. Another inference which may be drawn is that sufficient suspended-sediment-laden water from the river enters the slip to provide the source of the shoaling which occurs there. Further, the numerical circulation model's estimated residual concentrations may be used as an initial estimate in planning field work. Finally, the numerical circulation model estimates the flow rates into and out of each cell over time. From these flow rates, the average velocity of the water flowing in the slip may be approximated, which will be important when considering the sedimentation within the slip.

Based on the model results, a field study was planned to calibrate the model. It was intended to release Rhodamine WT into the landward end of slip 1 and monitor the concentration over time in the slip using a fluorometer. Unfortunately, due to a combination of factors including equipment problems and a heavy workload at the Port, useable quantitative data was not obtained from the field dye tracer experiment. Thus, the model remains uncalibrated. While it may provide useful insights into the qualitative aspects of the circulation patterns at the Port, further field data are needed to calibrate the model before it can be considered quantitatively reliable at Astoria.

Numerical Sedimentation Model and Results

The source of the sediment that accumulates in the Port of Astoria is the suspended load in the Columbia River which enters the slips during each incoming tide (regardless of whether the sediment originates upstream in the

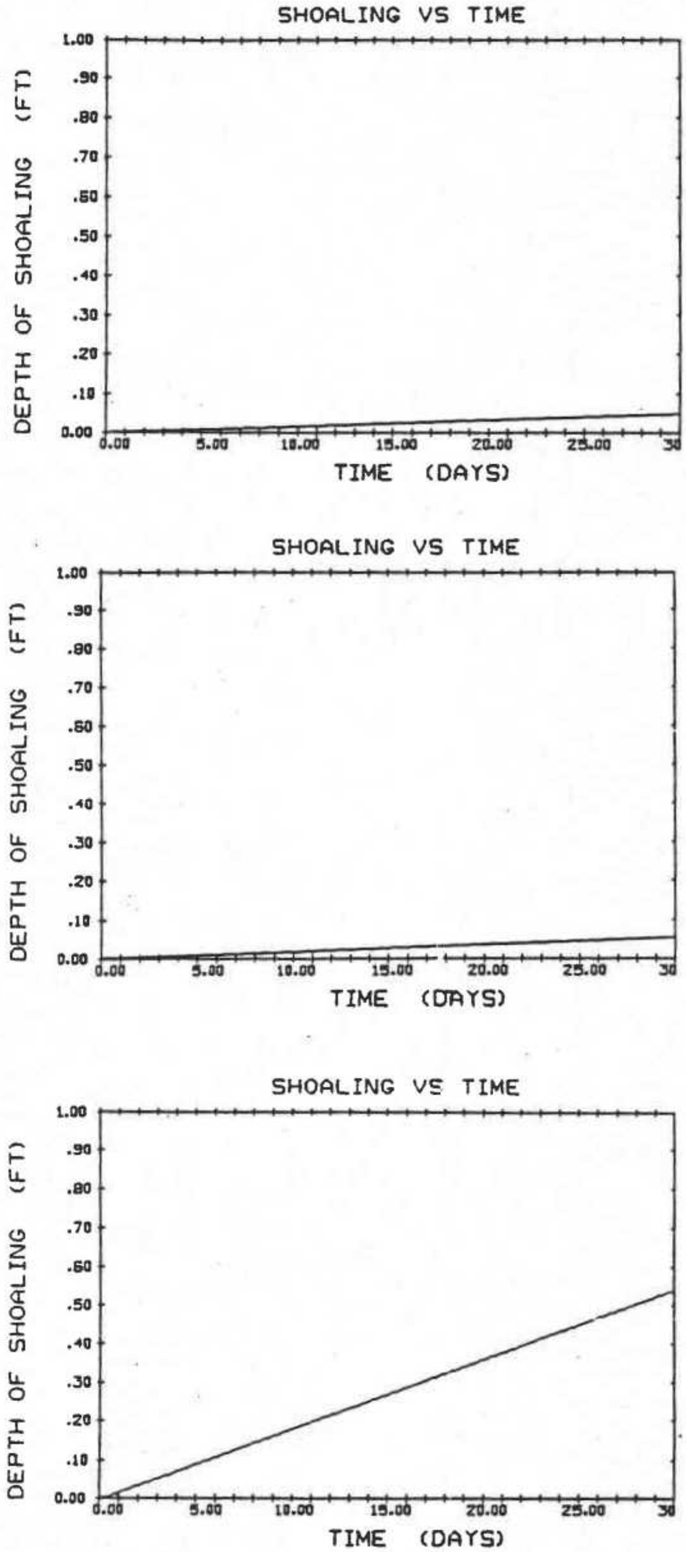
Columbia or in Youngs Bay). As a result of lower current velocities in the slips, compared to current velocities in the channel, a certain proportion of the suspended sediment settles out of the water onto the floor of the slip and is left behind when the water flows out of the slip on ebb tide. Also as a result of low current velocities at the slips, bedload transport of sediment may be assumed to be negligible.

A numerical sedimentation model was used in an attempt to estimate the rate of accumulation of sediment in the slips. Everts (1981), by making several simlifying assumptions, developed a mathematical model for the prediction of sedimentation rates in semienclosed harbors. Based on the available data and field observations, these assumptions appear to be reasonable for the Port of Astoria. Therefore, a single-cell, finite element model has been developed for estimating sedimentation rates at the Port of Astoria. The model is quite general in nature. The river sediment concentration, which serves as a boundary condition, may vary freely with time, the sediment distribution over depth in the harbor may take on any desired form, and the plan area of the harbor may vary with depth. Furthermore, the equations for the model may be applied to separate size fractions of sediment, each having its own settling velocity and concentration distribution. The total sediment disposition in this case would simply be the sum of the deposits for each size fraction. (Use of size fractions is particularly appropriate if there exists a wide range of sizes among the sediment grains, since this may result in widely varying settling velocities and concentration profiles.) Details of the model are given in Mustain (1982).

The numerical sedimentation model was applied to slip 1 at the Port of Astoria. The sediment characteristics (concentration, grain size, specific gravity, and porosity) were estimated based on field data obtained during the period March 24 through June 24, 1982. The sediment settling velocities were estimated as a function of the grain diameter using the methods presented in Bogardi (1974). As the data regarding sediment grain-size were rather limited, a single size fraction, based on the median grain diameter, was used in the model. Considering the relatively small grain size present (D_{50} = 0.015 mm) the verticle distribution of sediment concentration was assumed constant.

Figure 7 illustrates the results obtained from three model runs with different input parameters. Case (a) used the best available data from the field studies. The model gave an estimated sedimentation rate of about 0.05 ft/month (0.0015 m/month), equivalent to about 0.6 ft/year (0.18 m/year). This appears to be approximately an order of magnitude too low when compared with actual sedimentation rates experienced at the Port of Astoria.

Two input variables are particularly important in determining the model's behavior: sediment concentrations in the Columbia River and settling velocities of the sediment. Unfortunately, both of these variables can only be very roughly estimated from the available data. Although accurate values for these variables cannot presently be arrived at, their effect on the model



(a)

(b)

(c)

FIGURE 7. DEPTH OF SHOALING VS TIME

can be analyzed by arbitrarily varying the inputs and observing the model response. Runs (b) and (c) were made for this purpose. For run (b) the settling velocity was doubled but all other input variables were left as in run (a). As shown in Figure 7(b), the doubling of the settling velocity had only a very slight effect on the predicted rate of shoaling. For run (c), the concentration in the Columbia River was increased by a factor of ten but all other parameters were left as in run (b). As shown in Figure 7(c), this resulted in almost an order of magnitude of increase in the predicted shoaling rate. This predicted shoaling rate was equivalent to about 6.0 ft (1.8 m) annually, which appears to be consistent with the actual historical rate of sedimentation estimated by Port officials.

Clearly then, the model is more sensitive to changes in the input concentrations than to changes in the settling velocities of the sediment particles. This result does not appear incompatible with the prototype, where the rate of sedimentation has been observed to vary with the rate of flow of the Columbia River (and hence, with the suspended sediment concentrations in the river). During winter and spring freshets, for example, the flow rate, river suspended sediment concentration, and sedimentation rate at the Port of Astoria have all been observed to increase. Further data are needed concerning the suspended sediment concentrations in water entering the slip for further validation and/or refinement of this model. One aspect that should be addressed is the variation over time of these concentrations. Further data on settling velocites would also be useful. However, due to the relative insensitivity of the model to differences in settling velocities, this information is less critical than are the suspended sediment concentrations.

3. FIELD RESEARCH AT PORT OF ASTORIA

Objectives and Approach

The main objectives of the field research program were to determine the magnitude of and mechanisms behind the siltation problem at the Port of Astoria and, from the results, to try to explain the change in the 1980-81 sedimentation rate. The harbor slips at the Port and at the adjacent small boat marina were studied. Funding limitations prevented in-depth study of other ports along the Columbia River estuary, beyond an abbreviated study during 1982.

The field program consisted of six major physical interpretive efforts: (1) examination of sedimentation buckets placed on the estuary bottom; (2) examination of core samples of the estuary bottom; (3) circulation studies using current meters and drogues; (4) examination of water samples collected at various depths and locations; (5) a side-scan sonar study; and (6) a dye study which incorporated aerial photographs. The field work schedule is summarized in Table 1. The detailed procedures and results of the dye study and aerial photography are given in Mustain (1982). Detailed procedures and results of the other field studies are given in Cobos (1983).

Sedimentation Buckets And Suspended Sediment Characteristics

In an attempt to measure sedimentation resulting from the suspended load only, five-gallon buckets were weighted and sunk to the estuary bottom. It was believed that these buckets would exclude the effects of any bed load transport, since the lip of the bucket would rest an inch (> 2 cm) above the estuary bottom, assuming no embedment in the bottom sediments, and bed load transport was considered to be confined to a height above the bed of about two times the diameter of the bed sediment particles (assumed to be 1 cm). Thus, the collection of suspended sediment in the buckets would give a rough indication of both the rate of sedimentation and the composition of the sediment settling out from the suspended load.

Sedimentation buckets were placed at the stations indicated on Figure 8. It was decided to place the buckets next to the piers since the probability of recovering buckets located elsewhere was low, due both to the difficulty of relocation and the likelihood of disturbance either by the dredging activities or by log loading and sinker-log recovery operations. Buckets were placed on February 20 and March 6, 1982 and were selectively retrieved on March 6 and March 24, 1982. Several buckets could not be successfully recovered.

The retrieved buckets were returned to Oregon State University for laboratory analyses. These included grain size distributions, specific gravity and volatile solids content. The results of these analyses are summarized in Table 2. Analysis procedures and grain size distributions are

TABLE 1. FIELD WORK SCHEDULE

Date in 1982	Activity
February 19, 20	Placed sedimentation buckets
March 6	Pulled and replaced buckets
March 24	Pulled buckets
March 24	Collected water samples
March 25	Suspended sediment samples Circulation Study (drogues) Pulled buckets
March 26	Collected water samples
March 27	Collected water samples
April 2	Collected water samples
April 10	Collected water samples
May 2	Collected water samples
June 22	Anderra current meter work Marsh-McBirney current meter work
June 23	Core samples
June 24	Anderra current meter with transmissometer Water samples Velocity profiles
August 11	Velocity profiles Suspended sediment profiles Bulk samples
August 18	Rhodamine dye circulation study
August 19	Long cores

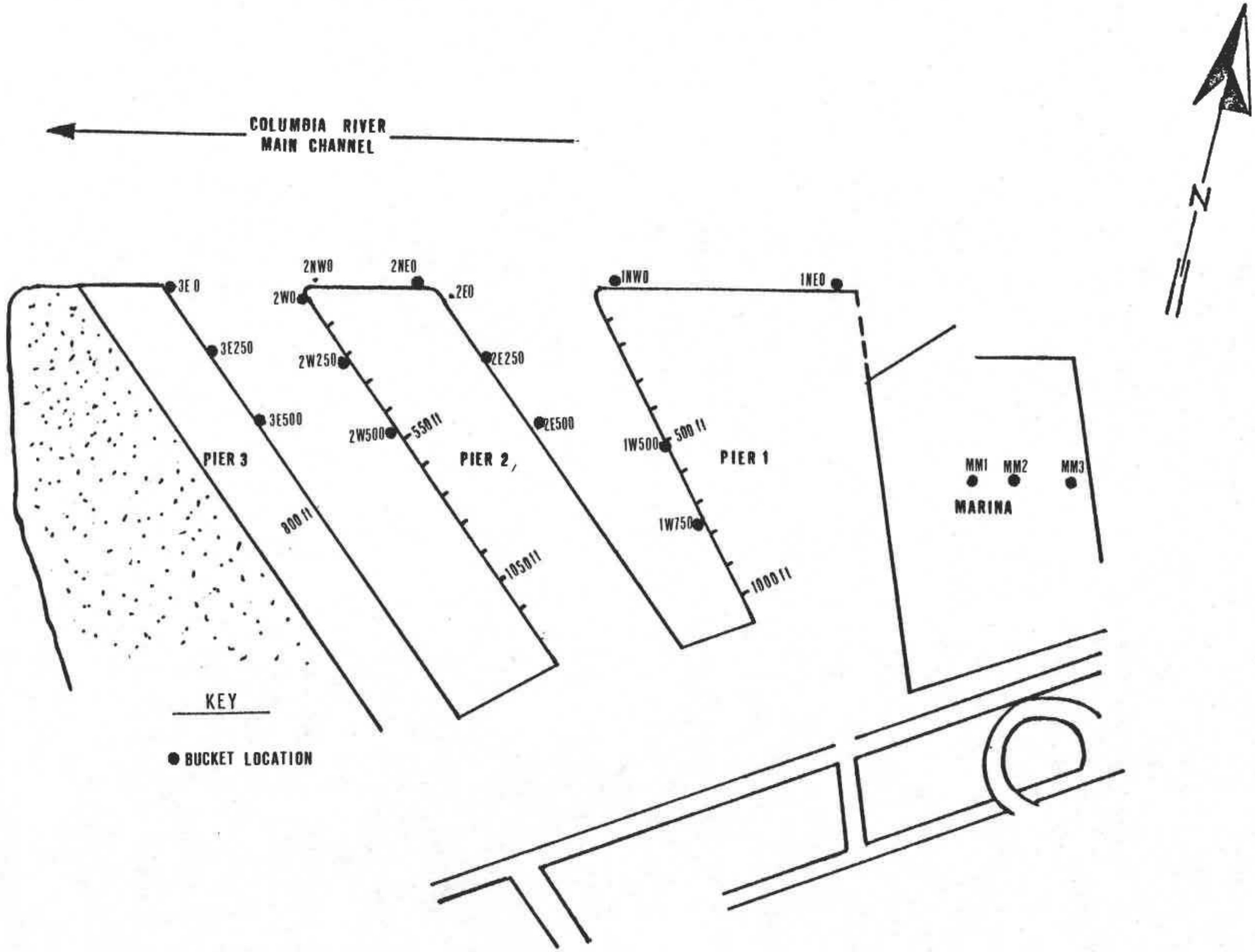


FIGURE 8. LOCATIONS OF SAMPLING BUCKETS TO MEASURE SEDIMENTATION OF SUSPENDED LOAD.

TABLE 2. ANALYSIS RESULTS FOR SEDIMENTATION BUCKET SAMPLES.

Sample Identification	Date Placed	Date Removed	Days In-Situ	Depth of Deposition	Depth Per Day	% Volatile Solids	Specific Gravity	Grain Size Characteristics			
								D_{10} (mm)	D_{50} (mm)	D_{60} (mm)	D_{60}/D_{10}
3E250-2	6 Mar	24 Mar	18	5.7cm	3.2mm	4.65	2.60	0.0008	0.020	0.027	33.8
3E500	20 Feb	6 Mar	14	1.6	1.1	2.84	2.61	0.0012	0.012	0.016	13.3
3E500-2	6 Mar	24 Mar	18	3.8	2.1	3.26	2.59	0.00075	0.012	0.016	21.3
2NWO-2	6 Mar	24 Mar	18	7.6	4.2	4.71	2.62	0.0010	0.030	0.040	40.0
2WO-2	6 Mar	24 Mar	18	10.2	5.7	5.93	2.63	0.00075	0.014	0.020	26.7
2NEO-2	6 Mar	24 Mar	18	10.2	5.7	5.39	2.60	0.0008	0.026	0.034	42.5
2EO	20 Feb	6 Mar	14	1.6	1.1	3.40	2.61	0.0012	0.021	0.027	22.5
2EO-2	6 Mar	24 Mar	18	9.5	5.3	4.03	2.56	0.0009	0.018	0.024	26.7
2E250	20 Feb	24 Mar	32	6.4	2.0	3.70	2.58	0.0010	0.016	0.021	21.0
2E500	20 Feb	24 Mar	32	11.1	3.5	4.86	2.57	0.0004	0.010	0.050	35.0
INEO-2	6 Mar	24 Mar	18	2.5	1.4	3.11	2.61	0.0011	0.030	0.038	34.5
INWO-2	6 Mar	24 Mar	18	8.9	4.9	4.2	2.57	0.0010	0.028	0.033	33.0
IW500	20 Feb	6 Mar	14	10.2	7.3	3.9	2.58	0.0009	0.010	0.040	44.4
IW750	20 Feb	6 Mar	14	1.3	0.9	2.5	2.61	0.0011	0.0095	0.011	10.0
IW750-2	6 Mar	24 Mar	18	6.0	3.3	4.6	2.61	0.0006	0.010	0.014	23.3
MMI	20 Feb	24 Mar	32	1.3	0.4	3.4	2.56	0.0009	0.010	0.014	15.6
MM2	20 Feb	26 Mar	14	1.3	0.9	4.0	2.48	0.0010	0.0095	0.011	11.0
MM3	20 Feb	24 Mar	32	1.6	0.5	4.0	2.54	0.0012	0.013	0.018	15.0

*bucket disturbed during dredging activities given in Cobos (1983). Any layering of deposits that may have occurred within each bucket sample was not considered, since the samples were severely disturbed by resuspension during transport between Astoria and Corvallis.

It is difficult to make any conclusions on the rate of sedimentation from the limited data shown in Table 2. The apparent sedimentation rates vary between 0.4 and 7.3 mm per day. Rates of sedimentation appear to be higher in the harbor slips than at the adjacent marina; within the slips the sedimentation rates are higher towards the channel end. However, considerably more data would be required to verify these observations.

The specific gravity of the bucket sediment samples was found to range from 2.5 to 2.6. Volatile solids contents range from 2 to 6 percent. Both of these are in the range expected for estuary sediments and compare well with samples obtained previously in the area (Crane et al.,1981).

The grain size distributions for these samples indicated well-graded silty soils for almost all locations. The median grain size, D_{50}, ranged from 0.0095 to 0.03 mm. Results are shown in Figure 9. The coefficient of uniformity, $Cu=D_{60}/D_{10}$, ranged from 10 to 44. The same trends as indicated by the deposition rates show up coarser material at the channel end of the slips than at the landward end. This is to be expected, since the flow energy level is higher adjacent to the shipping channel than in the quiescent water at the landward end of the slip; a decrease in flow velocity results in a corresponding decrease in the sediment size remaining in suspension. Median grain size is smaller in the marina than in the port slips, again due to lower flow velocities. The coefficient of uniformity also exhibits the same trends, indicating a larger range of grain size present in areas of higher energy.

It is of interest to compare these bucket sediment results with core data obtained by Crane in March 1981. Considering just the top three inches of each core and neglecting those samples taken in areas recently dredged, the median grain sizes for Crane's samples follow the same patterns as for those obtained in this study. The D_{50} values obtained by Crane are all slightly larger than those obtained in this study. This may be due to some degree of bedload transport that moved the coarse material into the study area -- transport which theoretically would not add material to the sedimentation buckets. However, no evidence is available to either substantiate or disprove this hypothesis. Crane's grain size distributions are also more uniform for the surface layer, with the uniformity coefficient varying between 10 and 25.

Core Samples and Bottom Sediment Characteristics

To gain information on depositional layering, core samples of the estuary bottom were taken on June 23, 1982. The sampling stations are indicated on Figure 10. The cores were taken using a 25-pound gravity coring device attached to a wire line. The corer was dropped over the stern of the research vessel and recovered using an electric winch. The core tubes were

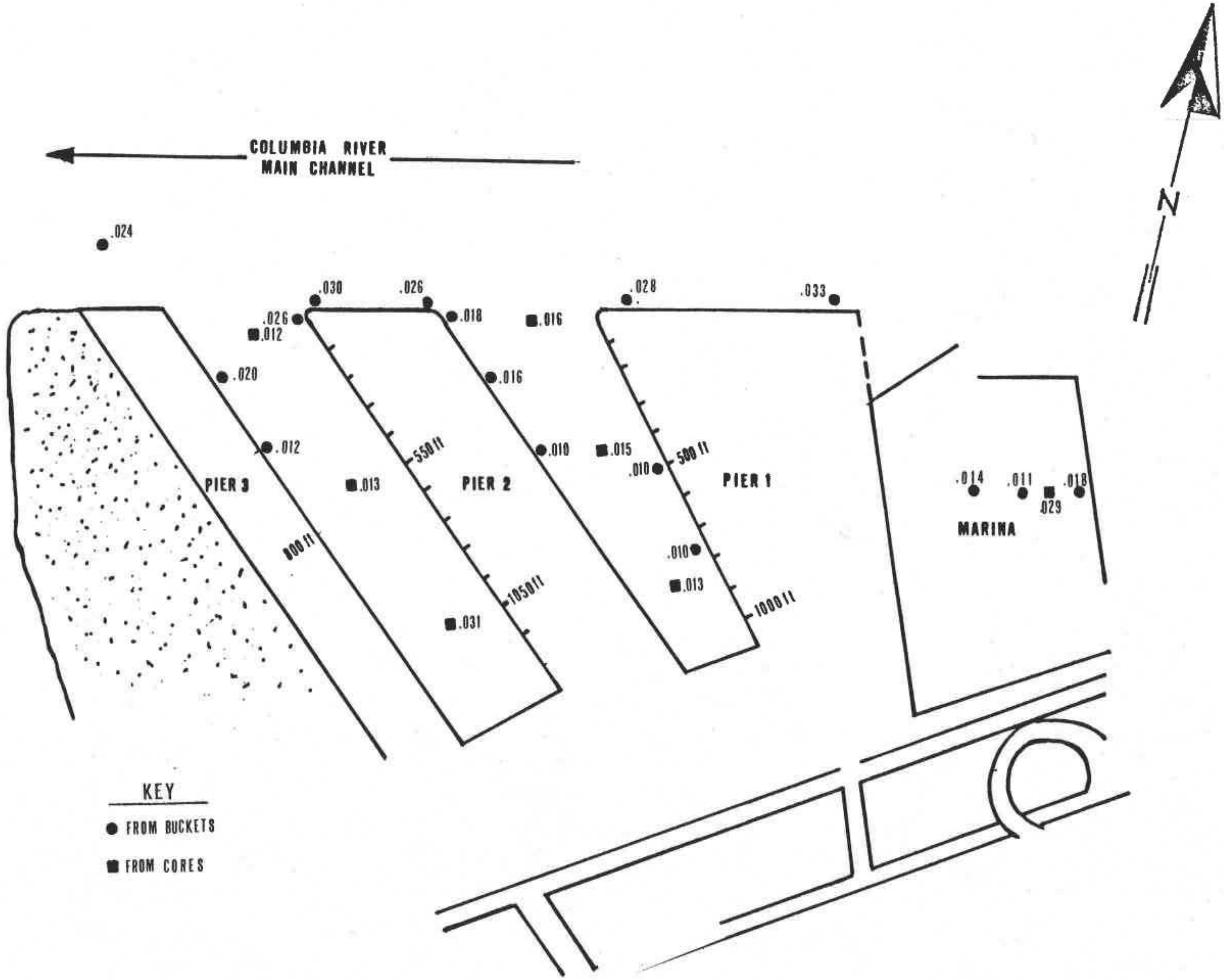


FIGURE 9. MEDIAN GRAIN SIZE DIAMETERS FOR BOTTOM SEDIMENT, D_{50}, mm.

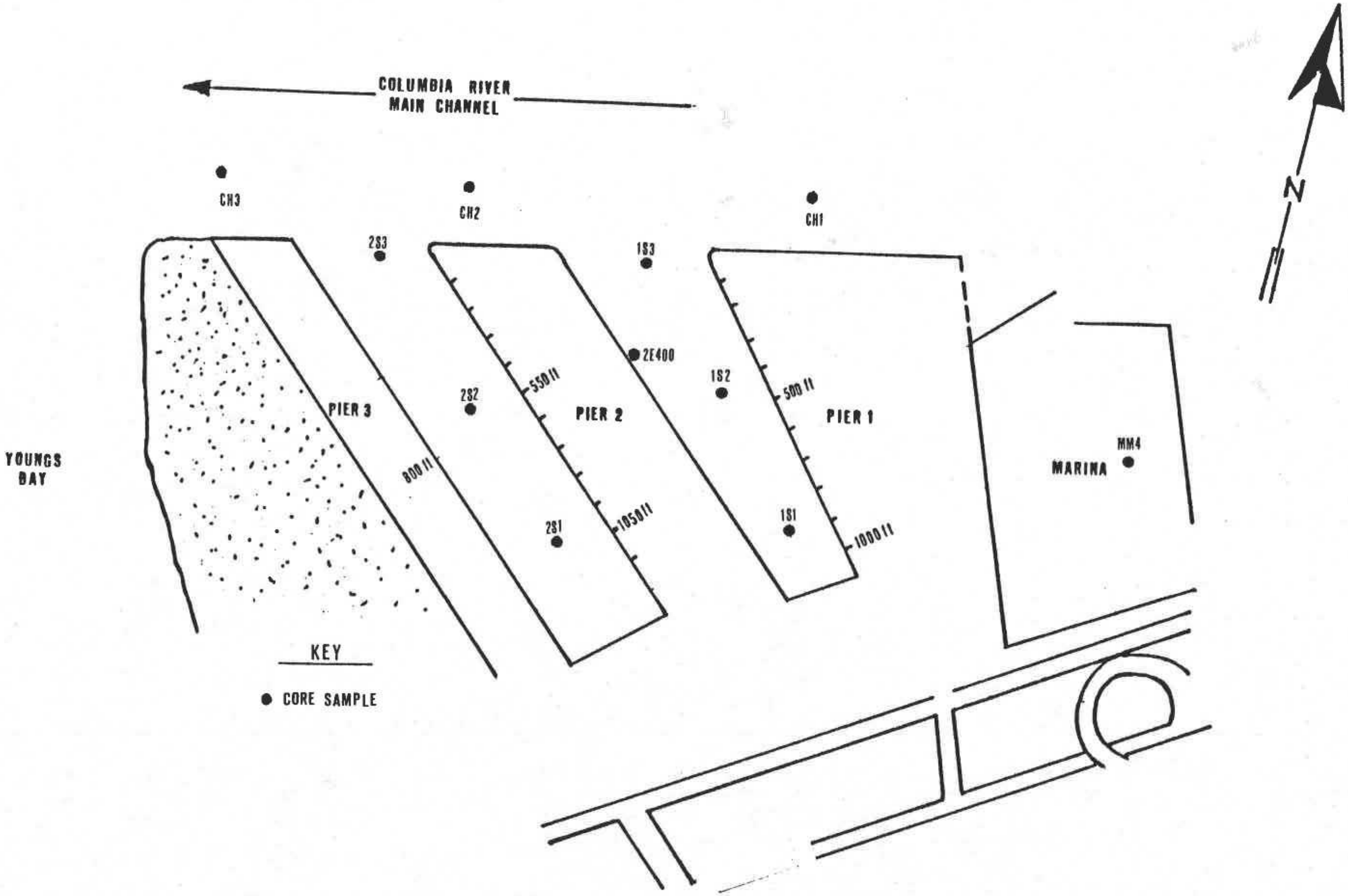


FIGURE 10. LOCATIONS FOR CORE SAMPLING OF ESTUARY BOTTOM.

about 2-1/2 inches in diameter. The core samples were retained within the tubes by means of a "core-catcher" at the lower end; this closed as soon as the coring device stopped its downward motion. Unfortunately, this system did not function well in the soft sediments encountered at Astoria. In some cases it was very difficult to retain the sample within the core tube as it was raised from the water. Other samples were lost when the core catcher was raised for reuse on the next core sample. As a result, the cores obtained on June 23 were generally quite disturbed and were too short to indicate any depositional layering effects. However, they did provide a rough indication of the nature of the surface sediments.

More cores were taken with much better success on August 19, 1982. The sampling method was altered to allow scuba divers to use a submerged, manually driven piston-type coring device. These cores, were of high quality. Their sampling positions are described later in this chapter.

The cores were returned to Corvallis for analysis for specific gravity, volatile solids and grain size distributions according to analytical methods already described. Results are summarized in Table 3. Grain size distribution curves are given in Cobos (1983). The samples were also analyzed for heavy minerals and clay mineralogy and were used in microprobe tests.

Specific gravities of the core samples ranged from 2.54 to 2.62 mg/l. Volatile solids content ranges from 3 to 5 percent. These are well within expected ranges and are similar to those values obtained for sedimentation bucket samples. Grain size distributions indicate well-graded silty sediments. Median grain size, D_{50}, ranged from 0.010 mm to 0.031 mm. Results are shown in Figure 9. The coefficient of uniformity, Cu, ranged from 4 to 43. The grain size distributions for the core samples are very similar to those obtained from the sedimentation buckets, although spatial variations are less pronounced. A single anomaly is exhibited by core 2S1, which had a coarser median grain size and a more uniform grain size distribution curve than expected. However, this is probably associated with the concurrent dredging activity taking place in the sediment source area for this core sample. Although this sample was not taken from a recently dredged location, the dredge was at that time operating nearby on the west side of pier 2 and dredge spoils were being discharged near the shore end of pier 3. Contamination of this sample by dredge spoils is likely.

Water Circulation and Water Current Studies

Water circulation patterns within the slips at the Port of Astoria were studied by three methods. These included following the paths of drogues which move with adjacent water masses, examining the records from stationary current meters placed on the estuary floor, and using hand-held current meters to obtain velocity profiles at different locations and tidal stages within the slips. Also, the circulation patterns were analyzed based on a physical model and dye study, as already discussed.

TABLE 3. ESTUARY BOTTOM SEDIMENT CHARACTERISTICS FROM CORE SAMPLES.

Sample Identification	Description	Length of Core (cm)	% Volatile Solids	Specific Gravity	Grain Size Characteristics			
					D_{10} (mm)	D_{50} (mm)	D_{60} (mm)	D_{60}/D_{10}
1S1	Very dark clay, little visible organics taken in about 15 ft. of water.	8.9	3.63	2.6	0.0011	0.014	0.018	16.4
1S1	Very dark clay, little visible organic matter taken in about 25 ft. of water.	9.5	4.32	2.54	0.0011	0.013	0.017	15.5
1S2	0.6 cm brown layer on surface; rest of core is grey-black clay with no visible organic matter. Taken in 17 ft. of water.	31.8						
	1S2 a 0-8 cm		3.15	2.61	0.0010	0.015	0.020	20.0
	1S2 b 8-16 cm							
	1S2 c 16-24 cm							
	1S2 d 24-32 cm		3.78	2.54	0.0008	0.010	0.014	17.5
1S3	Grey-black clay with no visible matter. Taken in about 17 ft. of water.	12.7						
	1S3 a 0.0- 6.3 cm		3.72	2.56	0.0010	0.016	0.020	20.0
	1S3 b 6.3-12.7 cm							
2S1	Dark sandy clay, no visible organic matter taken in about 10 ft. of water.	10.2	4.58	2.58	0.008	0.031	0.036	4.5
2S2	Top layer is black clay; bottom is grey-black clay. No visible organic matter. Taken in about 27 ft. of water.	15.9						
	2S2 a 0-8 cm		4.60	2.55	0.0011	0.012	0.015	13.6
	2S2 b 8-16 cm							
2S3	Grey-black clay with little visible organic matter. Taken in about 27 ft. of water.	13.0						
	2S3 a 0-6.5 cm							
	2S3 b 6.5-13 cm		4.03	2.58	0.0014	0.013	0.018	12.9
CH3	Dark grey-black sandy clay containing some organic material. Taken in about 12 ft. of water.	5	3.51	2.61	0.0009	0.024	0.039	43.3
CH3	Grey-black clay with black clay surface layer. No visible organic matter. Taken in about 15 ft. of water.	23						
	a 0-7 cm		4.39	2.62	0.0012	0.025	0.033	27.5
	b 7-15 cm							
	c 15-23 cm							
MM4	Grey-black sandy clay containing no visible organic matter. Taken in about 20 ft. of water.	15						
	a 0-7 cm		3.11					
	b 8-15 cm			2.6	0.0020	0.029	0.040	20.0

Table 3 Cont. ESTUARY BOTTOM SEDIMENT CHARACTERISTICS FROM CORE SAMPLES.

Sample Identification	Description	Length of Core (cm)	% Volatile Solids	Specific Gravity	Grain Size Characteristics D_{10} (mm)	D_{50} (mm)	D_{60} (mm)	D_{60}/D_{10}
2E400	*Black clay with very little visible organic material. Taken by diver in an estimated 35 ft. of water.	30						
	a 0-8 cm		4.18	2.58	0.0010	0.016	0.022	22.0
	b 8-15 cm							
	c 15-23 cm							
	d 23-30 cm		4.84	2.53	0.0012	0.013	0.017	14.2

*This core was well mixed due to sampling method.

The paths of drogues over a time interval give a picture of the circulation patterns from a Langrangian point of view. Drogue movement studies were conducted on March 25, 1982 between the east side of Pier 3 and the west side of Pier 2. The drogues consisted of meterological balloons which were filled with water to a diameter of roughly one foot (0.30 m) and weighted with lead fishing weights to sink to the desired depth. Each drogue's position was indicated by a small surface flag connected to the drogue by fishing line. Drogue positions were calculated by the intersecting ray method, with angles determined by two surveyors transits set up on opposite sides of the slip. The study was conducted on an ebb tide; later attempts to repeat this study on a flood tide were hampered by adverse weather conditions.

Five drogues were positioned at various locations in slip 2 on March 25. Their depths ranged from 5 to 30 feet. Most of these drogues had a slow movement towards the channel end of the slip. However, effects of the piers on currents appeared to have been significant, since the drogues tended to migrate towards and become caught in the pilings on either side of the slip. Three of the drogues were later repositioned in the center of the slip, the remaining two having been lost into the Columbia River channel. No evidence was obtained for either shearing stratified flow or a particular gyre system within the harbor slips. The movement of the drogues is shown in Figure 11. Local winds may have had a substantial effect on the movement of the surface flags.

Two Anderra meters and one Marsh-McBirney current meter were used in a circulation study during June 22-24, 1982. Their locations are shown in Figure 12. The Anderra meters were placed in slip 1 near the bed and left in place for approximately 20 hours. The first Anderra meter was placed in shallow water at the shore end of the slip at approximately 11:25 a.m. on June 22, and removed at approximately 10:30 a.m. on June 23. The second Anderra meter was placed approximately two-thirds the length of the slip from the land end, roughly in the center of the slip. It was placed at 3:50 p.m. on June 22 and removed at 10:43 a.m. on June 23. The first meter took readings of water temperature, current speed and direction at approximately 75-second intervals. Current speed was measured by a rotor-type device and current direction by the alignment of a freely rotating vane. Readings were recorded digitally on a magnetic tape within the meter.

The Marsh-McBirney current meter has a threshold velocity of about 0.03 feet/second. Water moving in a magnetic field produces a voltage that is linearly proportional to the water velocity. The Marsh-McBirney current meter was placed on the middle of slip 1 on June 23. The output data showed a definite periodicity of the signal, which was disconcerting and difficult to explain (perhaps electrical discharges from the cathodic protection devices in the ships were driving the meter). These data were therefore questionable because of this periodicity.

Ship activity in slip 1 was very limited during this part of the study. A log ship was berthed at the east side of Pier 2 when the first Anderra

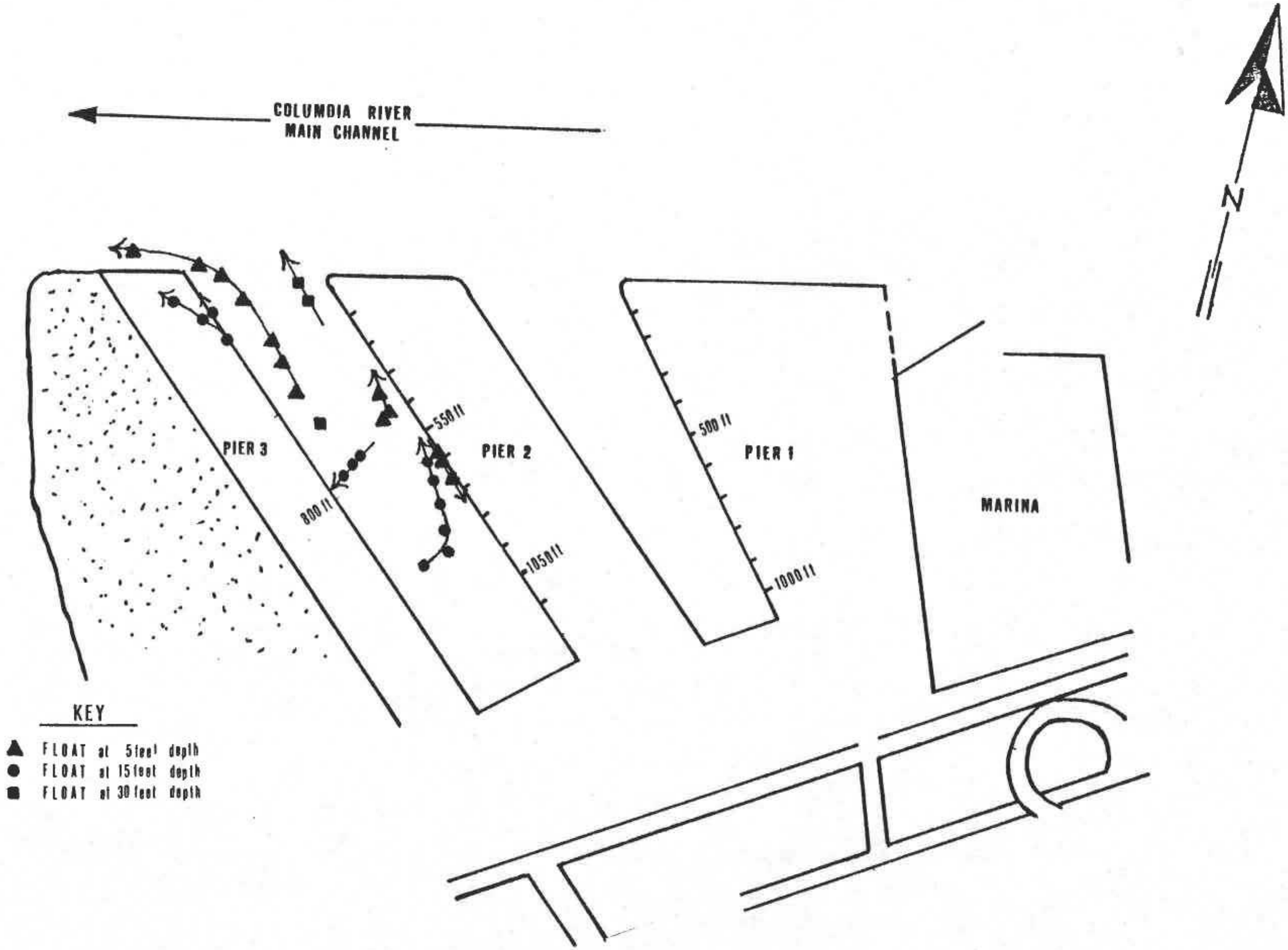


FIGURE 11. PATHS OF DROGUES DURING EBB TIDE MARCH 25, 1982.

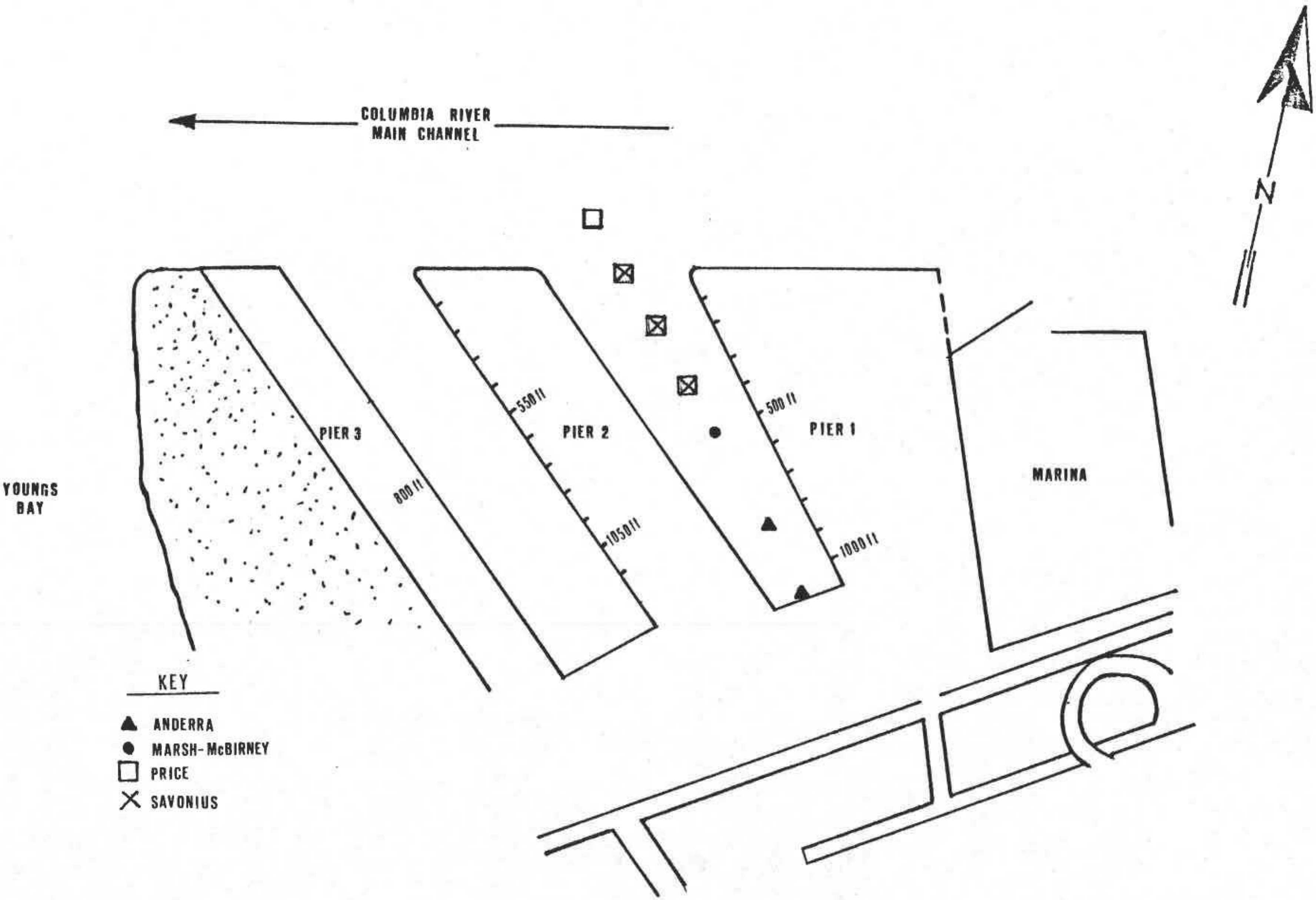


FIGURE 12. CURRENT METER LOCATIONS.

meter was placed in position on June 22. This ship departed at approximately 2:00 p.m. on June 22 and a log raft was moved into its place. Aside from this activity, the slip was empty of ship movement until approximately 8:00 p.m. on June 23. Thus, the currents measured on the meters during this time period should be those due to waves, wind, tidal and river flows only, with the possible exception of currents caused by large ships in the Columbia River navigation channel passing by the slip entrance.

The currents recorded by the first Anderra meter were very low, generally less than 10 cm/sec and often below the threshold meter value of 1.50 cm/s. The currents recorded by the second Anderra meter were generally even lower than those recorded by the first meter. Hence, the resulting data were dominated by the threshold velocity of the meters and the merit of interpreting the data became questionable.

Vertical profiles of the velocity field within slip I were taken on June 24 and August 11, 1982. The profiles on June 24 were taken using a Price current meter, for which the revolutions of a cup-type wheel are counted in a given time interval. This meter gives only current speed, not direction. Three profiles were taken in shallow water near the third Anderra meter placement and one profile was taken just outside the mouth of slip 1 in the Columbia River channel. Results are given in Table 4. The current speeds are somewhat quesionable due to the inaccuracy of the meter at low velocities. Generally, speeds were very low at the shallow water position, as expected. A tendency towards higher speeds at the surface was evident, although this trend may have been caused by nearby boat movement. The profile taken at the mouth of the slip indicated higher velocities due to the Columbia River flow. Stratified flow, if present, was not detectable since the Price meter did not have the capability of measuring current direction.

Vertical velocity profiles were again taken within slip 1 on August 11, 1982 at the positions indicated on Figure 12. Results are shown in Table 5. A Savonius rotor-type current meter equipped with a directional vane device was used. Instantaneous readings of current speed and direction were taken using on-deck meters. However, variations were often of the order of 200 percent in speed and 180 degrees in direction. Although the boat was anchored at both its bow and stern, movement of the boat probably influenced the results. Attempts were made to synchronize readings with the boat swing; however, this proved to be impractical. Thus, these values can only be used as a rough indication of the order of magnitude for current velocities. There was also an abrupt "jump" in the record of the Savonius meter due to boat activity.

Water Samples and Water Quality Characteristics

Water sampling was carried out between March and August, 1982, to examine spatial and temporal variations in suspended sediment concentrations and associated parameters in the water column. A Nansen bottle was used to collect water samples at the desired depths. These water samples were also returned to Corvallis for suspended sediment analysis, using procedures

TABLE 4. VELOCITY PROFILES ON JUNE 24, 1982.

High Tide	3:53 a.m.	9.2 ft.
Low Tide	10:56 a.m.	-1.6 ft.
High Tide	5:23 p.m.	7.6 ft.

Profile #1 - 9:45 a.m. - Ebb

Depth Below Surface (ft)	Current Speed(fps)
2	0.45
4	0.25
6	0.15
8	0.10
10(bottom)	0.10

Profile #2 - 11:00 a.m. - Slack

Depth Below Surface (ft)	Current Speed(fps)
2	0.30
4	0.20
6	0.10
8	0.15
10(bottom)	0.15

Profile #3 - 1:00 p.m. - Flood

Depth Below Surface (ft)	Current Speed(fps)
1	0.45
4	0
6	0
8	0.35
10	0
12(bottom	0.05

Profile #4 - 3:30 p.m. - Flood

Depth Below Surface (ft)	Current Speed(fps)
4	1.2
9	2.5
13	2.6
17	2.6
22	2.6
26	2.75
35	2.6

TABLE 5. VELOCITY PROFILES ON AUGUST 11, 1982.

High Tide 6:31 a.m. 6.3 ft.
Low Tide 12.27 p.m. 1.1 ft.
High Tide 6:55 p.m. 7.9 ft.

Profile Number	Time	Depth Below Surface(ft.)	Current Speed(fps)	*Direction
#1	10:30 a.m	5	0.17	270°
		10	0.25	**(massive flucuations)
		15	0.33	180°
		20	0.25	115°
		25	0.33	**
#2	11:45 a.m.	5	0.17	135°
		10	0.25	135°
		15	0.22	**
		18	0.17	250°
#3	12:15 p.m.	5	0.17	90°
		10	0 (flucuations up to 0.8fps)	
		15	0	
		20	0	
		25	0	
#4	1:25 p.m.	5	0.17	110°
		10	0	
		15	0.17	90°
		20	0	
		25	0.25	0°
#5	2:00 p.m.	5	0.5	45°
		10	0.5	0°
		15	0.25	300°
		20	0.25	180°

*Direction is with respect to magnetic north.
**High Fluctuations

outlined in Cobos (1983). An in-situ temperature and salinity meter was also used during the water sampling program.

Samples were collected at various locations during the months of March through May. Samples were also collected on June 24 to study variations in suspended sediments over a tidal cycle. Additional data for suspended sediment profiles were collected on August 11. Sampling locations are shown in Figure 13 and results of analysis are given in Table 6. Some of the results are shown in Figure 14.

Data from March 24 indicate an average water temperature of 8.3^{0}C, with values ranging from 7.5 to 10^{0}C. The surface water appeared to be slightly warmer than deeper water in many locations. Temperatures were slightly higher on April 10; average temperature was 9.0^{0}C and values ranged from 8.5 to 10^{0}C. Seasonal warming of the water was more pronounced by May 2nd, when the average temperature was 11.6^{0}C. Neither the April nor May data indicate any stratification of temperature with depth.

Salinities ranged from 0 to 15 percent. Distinct variations of salinity with depth were observed on March 24, 26, 27 and May 2, but were not evident in the April data. Stratified flow is to be expected in the Columbia River channel, with lighter, fresher water on the surface and denser, more-saline water at depth. This stratification is evident from the data collected at stations "CH1" and "CH2", which were just outside the Port itself. Deeper samples consistently had higher salinities than those at the surface. Stratification appears to extend into the slips at the Port; however, more data are required to substantiate this.

The change of salinity with time cannot be analysed on the basis of data taken at different times in different places, although such data show that the salinity is usually higher in the channel than in the slips (Gelfenbaum, 1981). Gelfenbaum measured the variation of salinity with respect to time near Tongue Point, upstream of Astoria, and found values to vary from 6 to 25 percent.

The volatile solids present in samples ranged from 3 to 42 percent, with the bottom samples containing more volatile matter. The March 24 samples appeared to have less volatile solids--from 3 to 14 percent. Results at other times ranged between 8 and 42 percent. Higher percentages of volatiles are present during ebb period. The values obtained in this study appear to be higher, relative to other data (unpublished data from Corps of Engineers; Moore, 1982).

Suspended sediment concentrations ranged between 20 and 170 mg/l. One sample having approximately 300 mg/l of sediment was probably taken too close to the bottom, and included some bedload. The data obtained on March 24 show a general trend towards higher concentrations of suspended sediments with increasing depth, but data are again insufficient to make firm conclusions. The data do indicate decreasing suspended sediment concentrations from March to May.

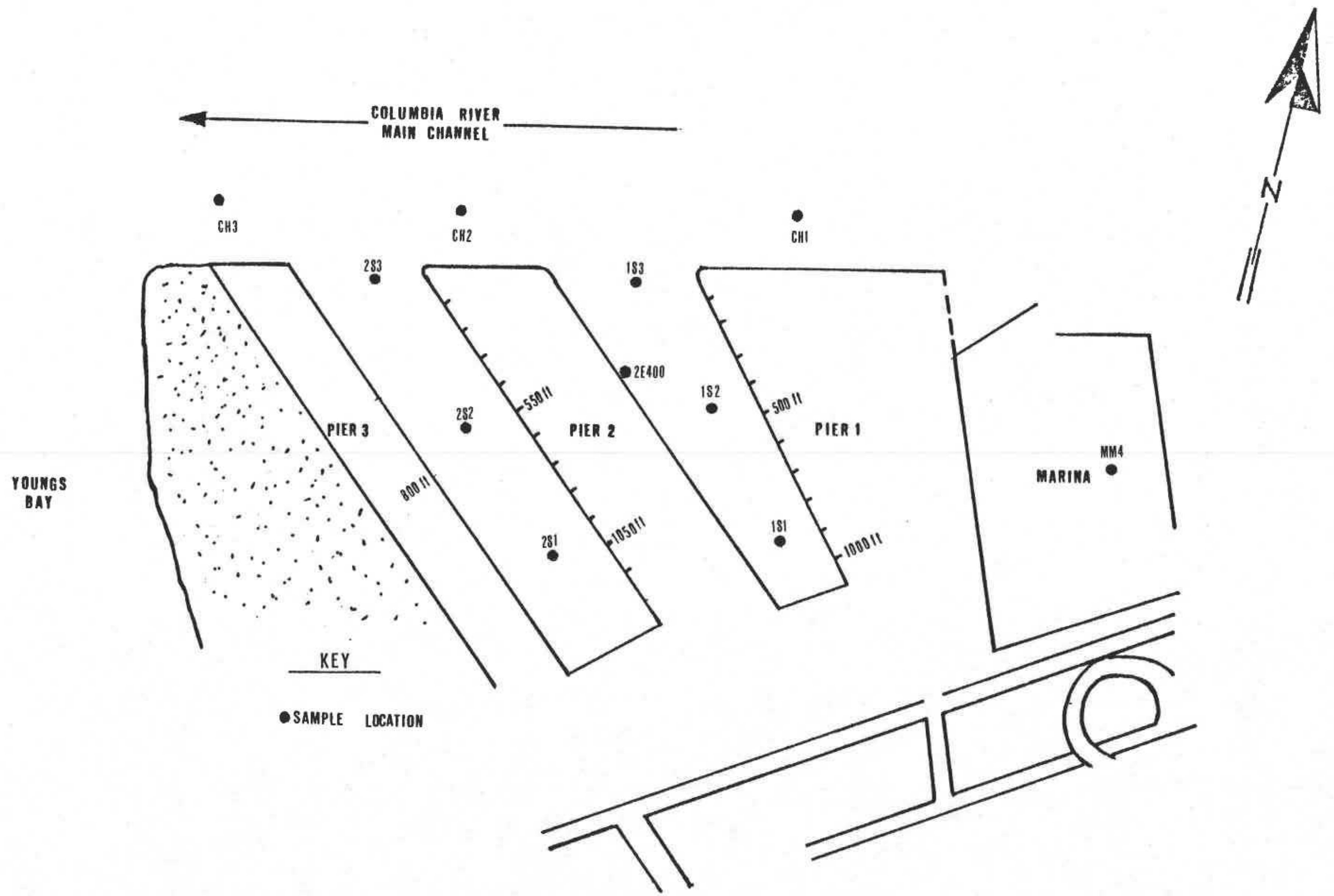


FIGURE 13. WATER QUALITY SAMPLING LOCATIONS.

TABLE 6. SUMMARY OF WATER SAMPLE DATA.

Date: 24 March 1982
High Tide: 12:47 p.m. 8.2 ft.
Low Tide: 7:16 p.m. 0.1 ft.; 6.57 a.m. 1.4 ft.

Sample Location	Depth(ft) Total Depth(ft)	Time	Temp. (°C.)	Salinity (°/oo)	Vol. Suspended Solids (mg/l)	Non-Volatile Solids(mg/l)
MML	5/	8:30 a.m.	8	0.3	2* = 3%	64* = 97%
MM2	5/	8:55 a.m.	8	1.0	6* = 14%	37* = 86%
MM4	10/	9:07 a.m.	7	0	12* = 12%	85* = 88%
2S1	9/18	10:02 a.m.	15	0	4* = 8%	45* = 92%
2S2	12/24	10:10 a.m.	10	0	8 = 11%	66 = 89%
2S3A	10/30	10:15 a.m.	8	0	6* = 10%	53* = 90%
2S3B	20/30	10:20 a.m.	8	1.0*	8* = 8%	92* = 92%
1S3A	10/34	10:40 a.m.	8	1.0	7* = 12%	53* = 88%
1S3B	25/34	10:40 a.m.	8	2.0*	8* = 9%	86* = 91%
1S2A	10/26	11:10 a.m.	8	1.0	9* = 14%	57* = 86%
1S2B	20/26	11:15 a.m.	8	2.5*	8 = 8%	97 = 92%
1S1A	5/23	11:20 a.m.	8	0.5	8* = 11%	62* = 97%
1S1B	20/23	11:25 a.m.	8	2.5*	2* = 3%	58* = 89%
CH1A	10/53	11:50 a.m.	9	2.0	2* = 3%	67* = 97%
CH1B	40/53	11:45 a.m.	8	3.0*	2 = 2%	83 = 93%
CH2A	10/53	12:05 p.m.	10	3.0	4 = 8%	47 = 92%
CH2B	40/53	12:10 p.m.	8.5	11.0	8 = 5%	163 = 95%
CH2A	10/40	3:55 p.m.	8	1.5	3 = 3%	87 = 97%
CH2B	10/46	4:05 p.m.	8	8.0	6 = 6%	100 = 94%
2S2	10/21	4:10 p.m.	8.5	2.5	3 = 8%	35 = 92%
1S2A	10/22	4:20 p.m.	8.5	2.5	3 = 6%	45 = 94%
1S2B	20/22	4:25 p.m.	8	4.5	2 = 4%	53 = 96%

* probably in error(too low) Average Temp. = 8.3

Date: 10 April 1982
High Tide: 3:01 p.m. 7.4 ft.
Low Tide: 9:01 a.m. 0.0 ft.

Sample Location	Depth (ft) Total Depth (ft)	Time	Temp (°C.)	Salinity (°/oo)	Vol. Suspended Solids(mg/l)	Non-Volatile Solids(mg/l)
MM4	5/18	10:23 a.m.	10	0.5	8 = 25%	24 = 75%
MM4	10/18	10:24 a.m.	9	0.5	9 = 31%	20 = 69%
MM4	15/18	10:25 a.m.	9	1.0	16 = 26%	46 = 74%
CH2	15/45	11:05 a.m.	9	0	--- ---	--- ---
CH2	35/45	11:04 a.m.	9	0	20 17%	101 = 83%
2S2	7/21	11:13 a.m.	9	0	13 24%	41 = 76%
2S2	15/21	11:12 a.m.	9	0.5	--- ---	--- ---

Average Temp. = 9.0

TABLE 6 Cont.

Date: 2 May 1982
High Tide: 9:57 a.m. 7.2 ft.
Low Tide: 4:32 p.m. 0.4 ft.

Sample Location	Depth(ft) Total Depth(ft)	Time	Temp. (°C.)	Salinity (°/oo)	Vol. Suspended Solids(mg/l)	Non-Volatile Solids(mg/l)
MM4	5/23	11:26 a.m.	11.5	0	8 = 31%	18 = 69%
MM4	15/23	11:27 a.m.	11.5	1.5	12 = 18%	56 = 82%
MM2	5/12	11:37 a.m.	11.5	0.5	18 = 33%	36 = 67%
MM2	10/12	11:38 a.m.	12.0	1.0	7 = 17%	34 = 83%
CH1	20/50	11:52 a.m.	11.0	9.0	9 = 39%	14 = 61%
CH1	40/50	11:52 a.m.	11.0	15.0	4 = 20%	16 = 80%
IS2	10/28	12:14 p.m.	11.8	2.0	16 = 42%	22 = 58%
1S2	20/28	12:13 p.m.	11.2	9.5	10 = 42%	14 = 58%
CH2	10/48	12:24 p.m.	11.5	3.0	12 = 29%	30 = 71%
CH2	20/48	12:21 p.m.	11.9	8.0	11 = 35%	20 = 65%
2S2	5/20	12:34 p.m.	11.7	1.0	7 = 35%	13 = 65%
2S2	15/20	12:33 p.m.	11.5	4.5	16 = 39%	25 = 61%

Date: 26 March 1982
High Tide: 2:15 p.m. 8.1 ft.
Low Tide: 8:27 p.m. 0.6 ft.

Sample Location	Depth(ft) Total Depth(ft)	Time	Temp. (°C.)	Salinity (°/oo)	Vol.Suspended Solids(mg/l)	Non-Volatile Solids(mg/l)
2W500	10/35	1:45 p.m.			23 = 26%	67 = 74%
2W500	30/35	1:45 p.m.			23 = 8%	281 = 92%

Date: 27 March 1982
High Tide: 3:02 p.m. 7.9 ft.
Low Tide: 9:02 p.m. 1.1 ft.

Sample Location	Depth(ft) Total Depth(ft)	Time	Temp. (°C.)	Salinity (°/oo)	Vol.Suspended Solids(mg/l)	Non-Volatile Solids(mg/l)
2W500	10/	4:30 p.m.			16 = 17%	78 = 83%
2W500	30/	4:30 p.m.			6 = 8%	68 = 92%
2NO	10/	4:45 p.m.			21 = 21%	79 = 79%
2NO	30/	4:45 p.m.			18 = 19%	76 = 81%

Date: 2 April 1982
High Tide: 9:36 p.m. 6.7 ft.
Low Tide: 2:59 p.m. 0.0 ft.

Sample Location	Depth(ft) Total Depth(ft)	Time	Temp. (°C.)	Salinity (°/oo)	Vol.Suspended Solids(mg/l)	Non-Volatile Solids(mg/l)
2W500	10/	1:45 p.m.			7 = 21%	27 = 79%
2W500	30/	1:45 p.m.			4 = 10%	37 = 90%
2NO	10/	2:00 p.m.			--- ---	--- ---
2NO	25/	2:00 p.m.			16 = 26%	46 = 74%

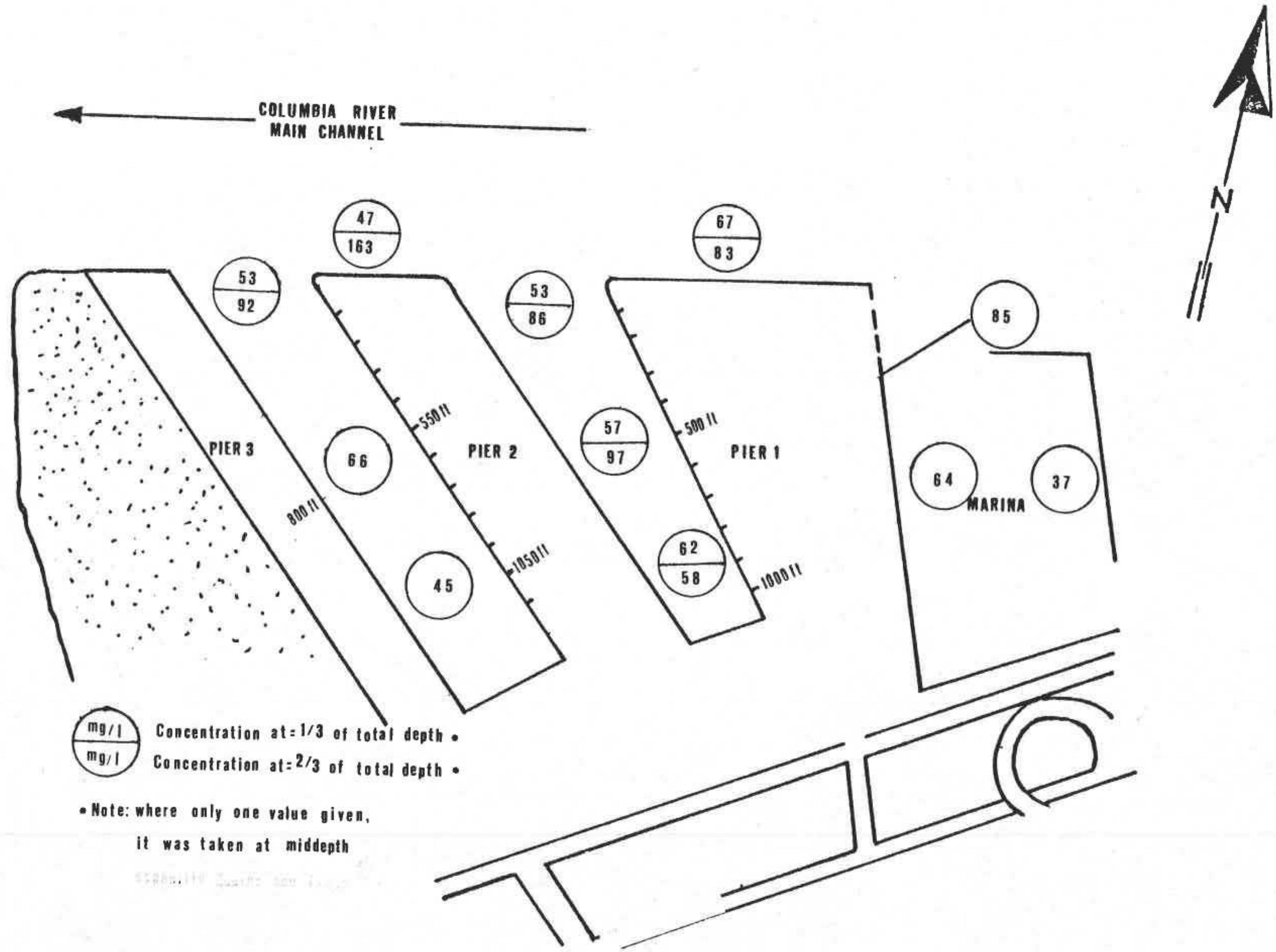


FIGURE 14. NON-VOLATILE SUSPENDED SEDIMENT CONCENTRATION (FLOOD TIDE MARCH 24, 1982).

Variations in suspended sediment concentration with time at a fixed location were examined on June 24. Data are plotted with the tidal cycle in Figure 15. No correlation can be discerned between tidal stage and suspended sediment concentration. The sediment concentration is basically constant with the exception of two samples which have concentrations roughly three times those of the other samples. This can be directly attributed to tugboat activity in the immediate vicinity of the sampling area at that time; the resulting increased suspension of sediments was visible to the naked eye as a change in water color. Thus, resuspension of bottom sediments by boat movement is an important factor, at least in shallow water.

Profiles of suspended sediment concentration were taken on August 11. The data are summarized in Table 7. Profiles were taken over the center "hump" in the slip and in a recently dredged berth area. Two of the profiles, both taken on ebbing tides, are given in Figure 16 and clearly show an increase in concentration of suspended sediment with depth. The other three profiles, taken on slack or flooding tides, did not show the same increase. Two of these three profiles were taken in deeper water. It was not found whether tidal stage or local topography influenced the suspended sediment concentration profiles, since available data were limited. The variations in suspended concentrations were found to be within the experimental error range, especially considering the unsteady nature of suspended sediment transport processes.

Side-Scan Sonar Observations

Side-scan sonar can provide insight into the behavior of an estuarine system. Two basic acoustic approaches are used to distinguish topographic features of the sea floor and objects on or above the sea floor. The conventional method is echo sounding, which uses a vertical-axis acoustic beam. The alternate method, called side-looking or side-scanning sonar, requires an acoustic beam whose main axis is slightly below horizontal. The beam is very narrow in the horizontal plane, yet sufficiently broad in the vertical plane to obtain echoes from points on the bottom ranging from directly below the transducer to points 500 meters or more abeam of the transducer (EGG, 1974). The combination of the beam shape and the very short length of the acoustic pulse gives side-scan sonar the capability to resolve small topographic irregularities and identify small objects on or above the sea floor. As the transducer is towed behind a boat at an appropriate depth, the reflected echoes are graphically recorded in a form which approaches a topographic or plan view map. Those projections above the bottom which are good reflectors are represented by a darkening of the record. Depressions, on the other hand, are represented by a lightening of the record. Further details are given in Cobos (1983).

Side-scan sonar records obtained at the Port of Astoria are shown in Figures 17 and 18. The records show the location of some submerged logs, some recent dredge cuts and other interpretative information. The dredge hull is a clear example of the mirror effect, whereby the water surface acts as a mirror to give erroneous information.

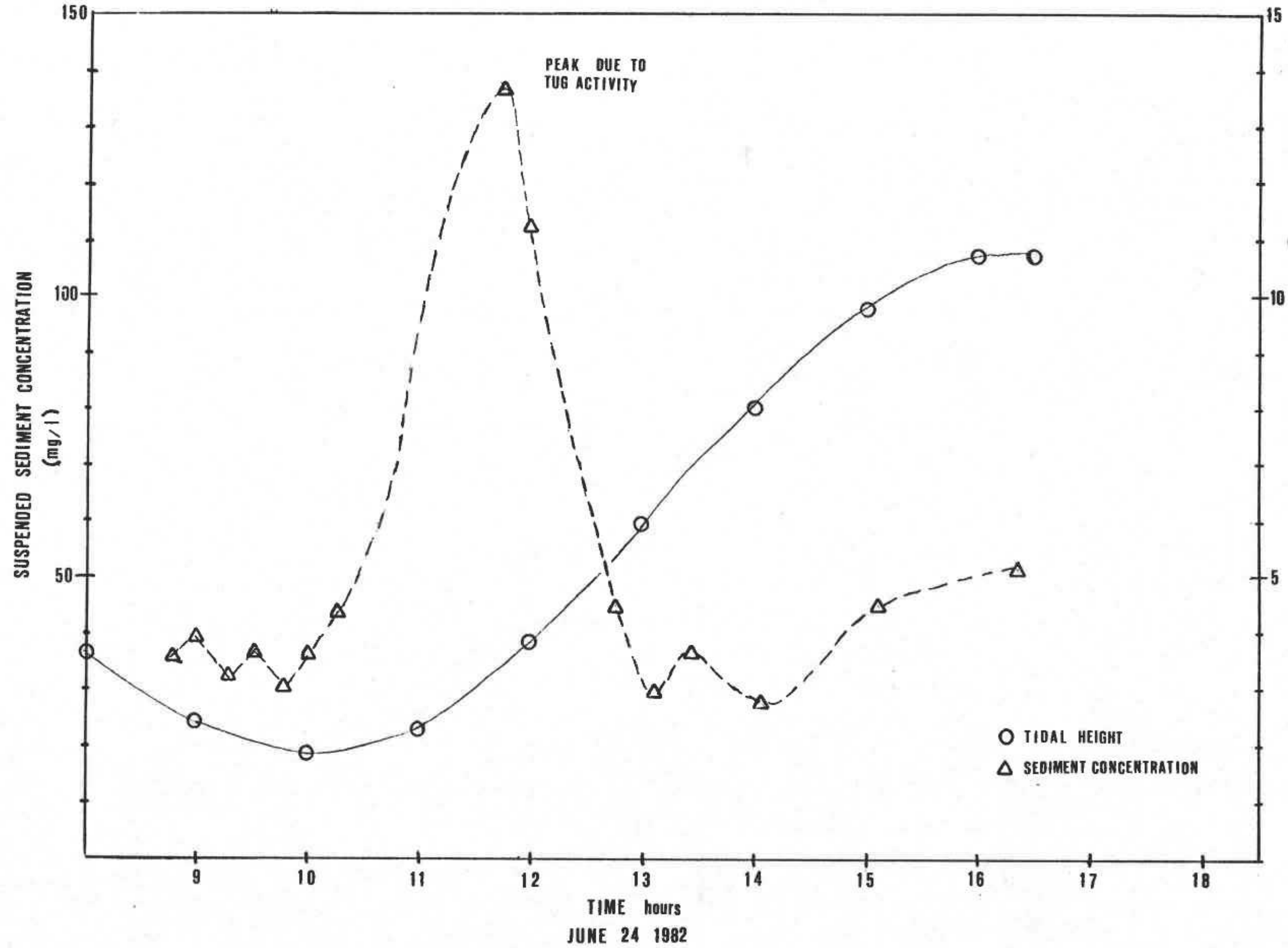


FIGURE 15. VARIATION OF SUSPENDED SEDIMENT CONCENTRATION AND TIDAL HEIGHT WITH TIME.

TABLE 7. SUSPENDED SEDIMENT CONCENTRATION PROFILES.

High Tide 6:31 a.m. 6.3 ft.
Low Tide 12:37 p.m. 1.1 ft.
High Tide 6:55 p.m. 7.9 ft.

Profile#	Time	Depth(ft.)	Bottle#	Volatile Susp.Seds. mg/l	Non-Volatile Susp.Seds. mg/l
1	10:20 a.m.	5	159	4.0	10.0
	(Ebb Tide)	10	198	5.0	17.0
		15*	231	9.0	17.0
		20	146	0	35.0
	10:40 a.m.	25	165	12.0	51.0
2	11:40 a.m.	5	41	5	16.0
	(Late Ebb	10	519	6	14.0
	Tide)	15	7	3	29.0
	11:49 a.m.	18	220	4	35.0
3	12:08 p.m	5	50	4	21.0
	(Near Slack	10	47	3	22.0
	Tide)	15	222	5	15.0
		20	153	4	13.0
	12:20 p.m.	25	273	7	32.0
4	1:20 p.m.	5	189	4	19.0
		10*	71	6	1.0
		15	109	5	9.0
		20	133	3	13.0
	1:30 p.m.	25*	244	7	16.0
5	1:58 p.m.	5	11	5	15.0
		10*	230	0	33.0
		15	164	4	10.0
	2:10 p.m.	20*	54	9	37.0

*bulk water samples

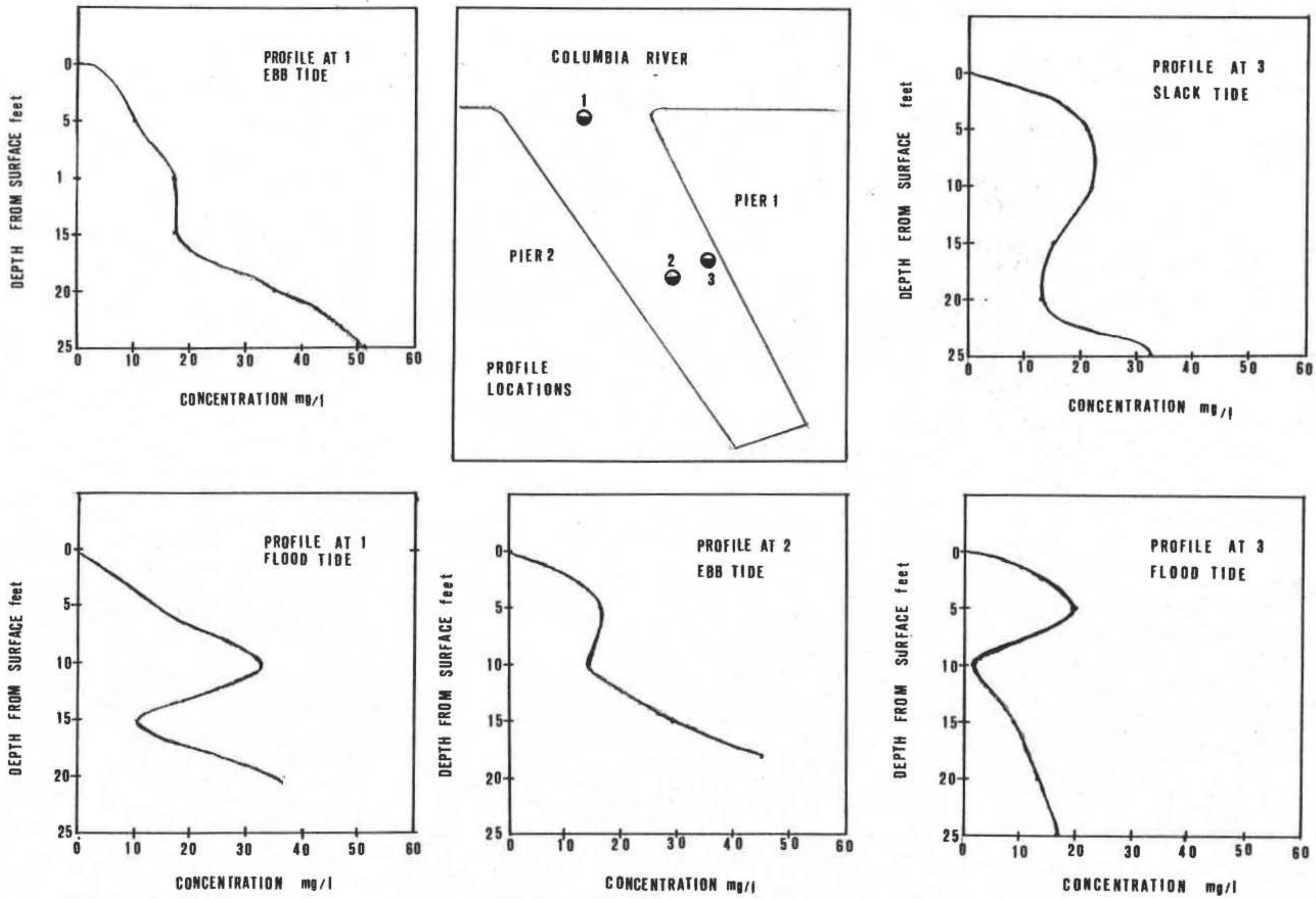


FIGURE 16. SUSPENDED SEDIMENT PROFILES AUGUST 11, 1982.

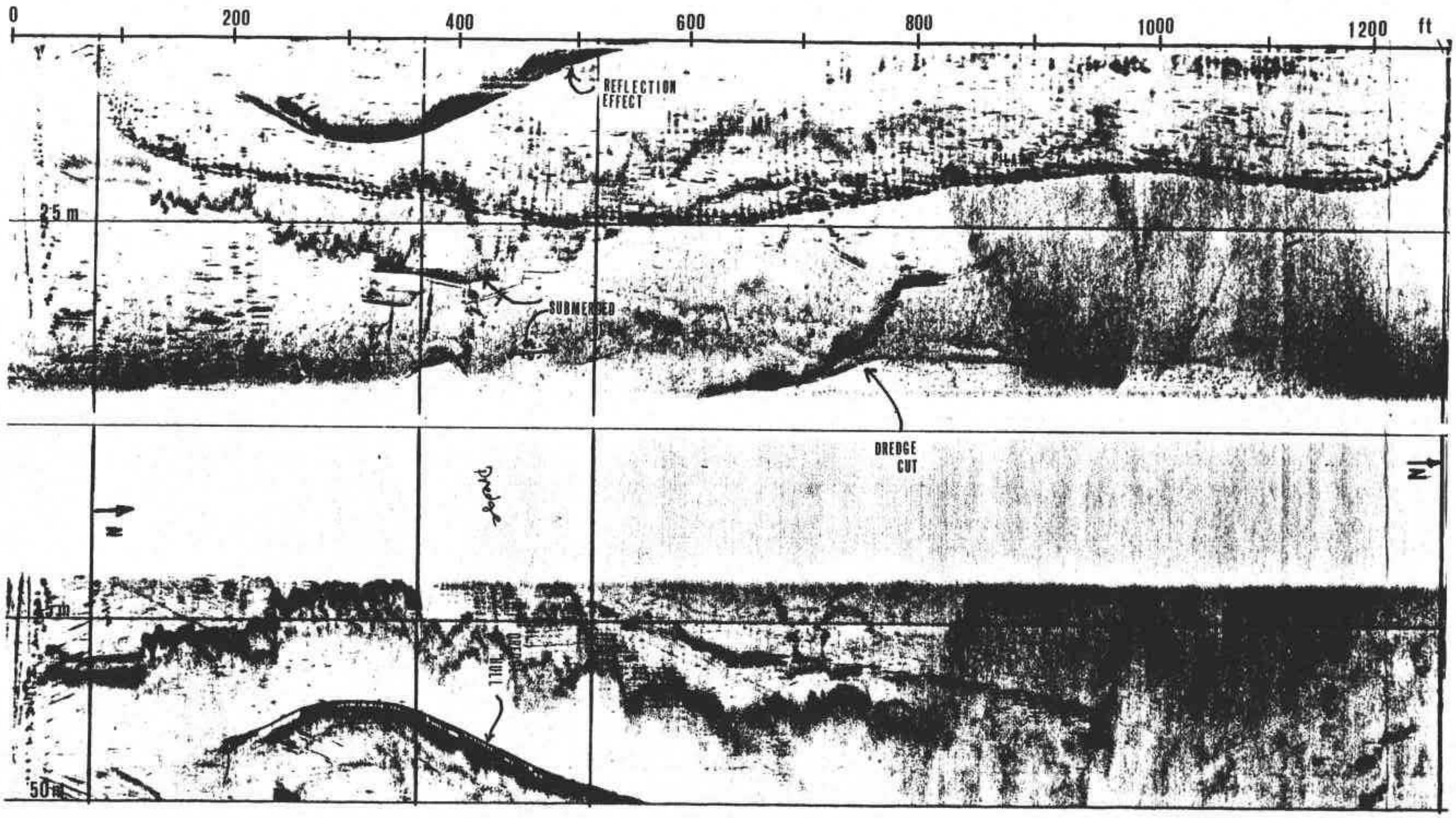


FIGURE 17. SIDE-SCAN SONAR RECORD, PORT OF ASTORIA, SLIP 1.

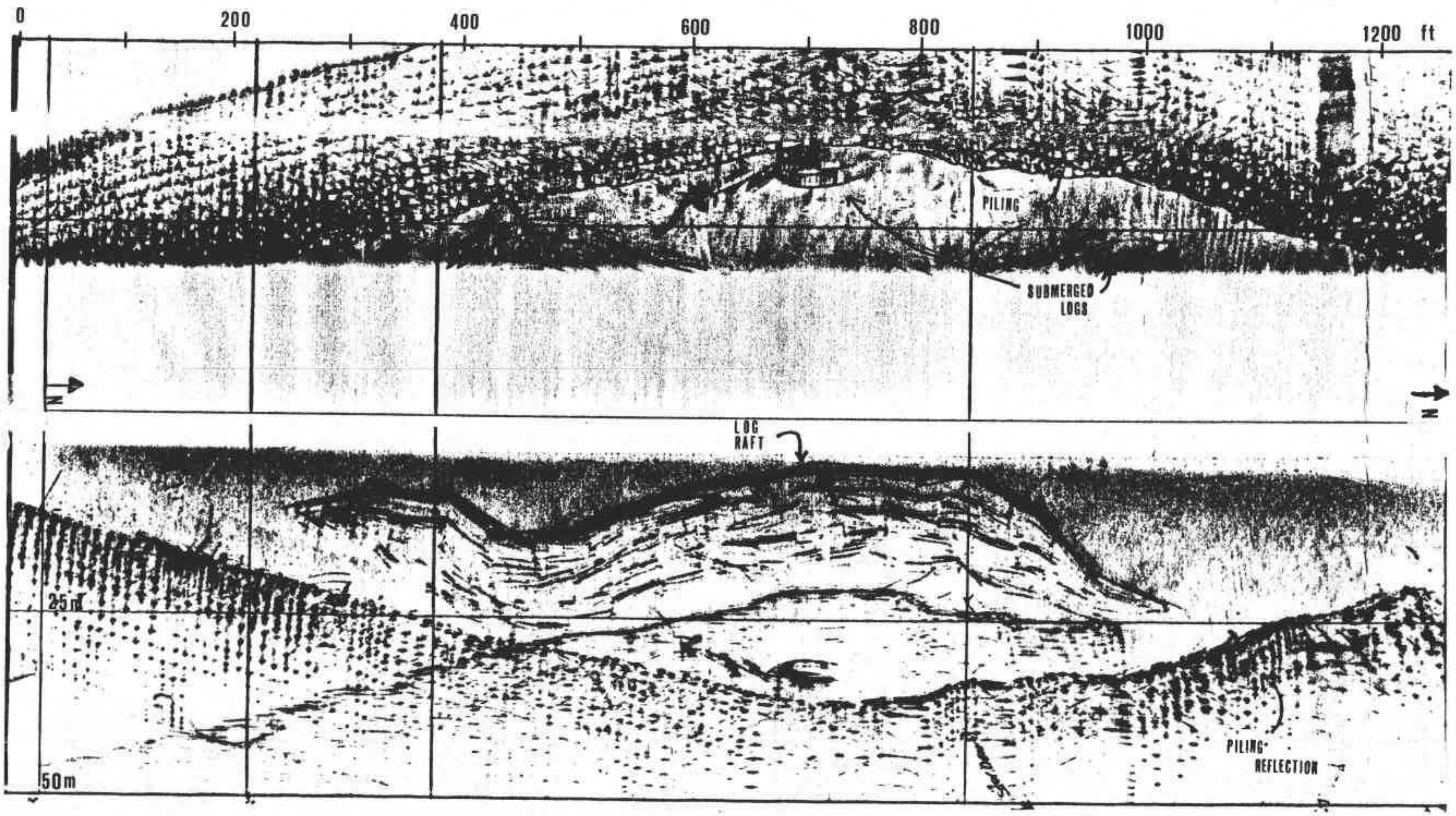


FIGURE 18. SIDE-SCAN SONAR RECORD, PORT OF ASTORIA, SLIP 2.

Dye Study

Dye releases, using Rhodamine WT, were made on August 18, 1982 in and near the Port slips. Aerial photography of the resulting dye patches and quantitative measurements of dye motion and dilution were attempted. The objective was to collect data to verify/calibrate the theoretical models described earlier.

Unfortunately, Port shipping was particularly active during this period and severely hampered data collection. Some equipment problems were also experienced. Consequently, observation results were sketchy and no discernible pattern of relative dye flourescence could be found from water sampling.

A series of color aerial photographs taken at 15-minute intervals for two hours after a dye release showed the patterns of dye motion quite satisfactorily. These results tended to confirm the physical model, as discussed earlier. Further details are given in Mustain (1982).

Brief Summary of Field Research Findings

The grain size analysis information does not differ with that obtained by previous authors. Krone (1971) and Crane et al. (1981), dealing with pre- and post- eruption data, respectively, show almost no differences in grain size, uniformity coefficients, or mean diameters. This was expected since the currents, the flow regimes, and, in general, the estuary processes have not changed as a result of the eruption. Therefore, the particles of any determined size which settle in an area do so based on hydrodynamic conditions which vary similiarly over the seasons -- independent of volcanic releases.

The velocities within the slip were found to be extremely low -- usually under the threshold velocity of available current measuring instruments. However, it was observed that boat activities and ship propeller wakes induce relatively high velocities; high enough to resuspend the sediments on the bottom. The suspended sediment profiles were surprisingly variable; more sampling would be required in order to describe the behavior for different tidal conditions.

The sediment deposits within the slips seems to be most affected by dredging or lack of dredging and by ship propeller wash.

4. INVESTIGATION OF SEDIMENT ORIGIN

One of the questions to be answered regarding the Port of Astoria shoaling problem was whether or not the harbor had been affected from the runoff associated with the eruptions of Mt. St. Helens. In studying this problem, core sampling was done August 18-19, 1982 within the Port's slips. From these cores, samples were taken for clay mineralogy analysis, microprobe tests, and heavy mineral analysis.

Clay Mineralogy Tests

The samples used for clay mineralogy tests were taken from cores 2, 4, and 5. Their locations are shown in Figure 19. Samples were chosen by visually noting each core's appearance and selecting sections likely to contain clays. From core 2 (slip 1), a sample was chosen from a section four inches long with upper limit located five inches below the surface. In slip 2, from core 4, a section was selected from the middle 16-20 inches. Core 5 was sampled from the layer 24-28 inches below the surface. A final sample, number 105, was taken from a core sample obtained from Youngs Bay in 1975 (Slotta et al., 1975). Its location is shown in Figure 20. This latter sample was chosen to compare the type of sediment that was present earlier in the Youngs River area with that of the Columbia River and the slips at the Port of Astoria.

The clay mineralogy tests (Berggren and Hickey, 1982) included dispersing all core section samples in a 2 percent solution of sodium carbonate to separate the sand from silt and clays. The sand fraction was then separated by wet sieving. Silt and clay were then separated by centrifugating. The x-ray diffraction procedures used involved preparation of oriented specimens of K^+ and Mg^{++} saturated clays on glass slides by the paste method of Theisen and Harward (1962). These were analyzed using a Norelco x-ray Diffractometer with a focusing monochromer. The dominant clay mineral phases were estimated based upon a comparison of relative peak intensities. For identification purposes, nontronite, beidellite, montmorillinite or any other smectite mineral were all considered as smectite; poorly crystalline micas were referred to as "illite"; and kaolinite and chlorite were separately differentiated.

The results of the analyses indicate that all samples possess similar clay mineral suites (Berggren and Hickey, 1982). Smectite appears to dominate the crystalline clay mineral fraction of all samples. The sample from Youngs Bay, however, appears to be dominated to a greater extent by smectite than any of the other samples. Also, minor amounts of illite and chlorite were found in each sample of sediment examined. All of the samples, with the exception of the Youngs Bay sample, contained minor amounts of kaolinite.

The sample from Youngs Bay was taken far upstream, which reduces the possibility of diagenesis, a process which can occur in marine environments

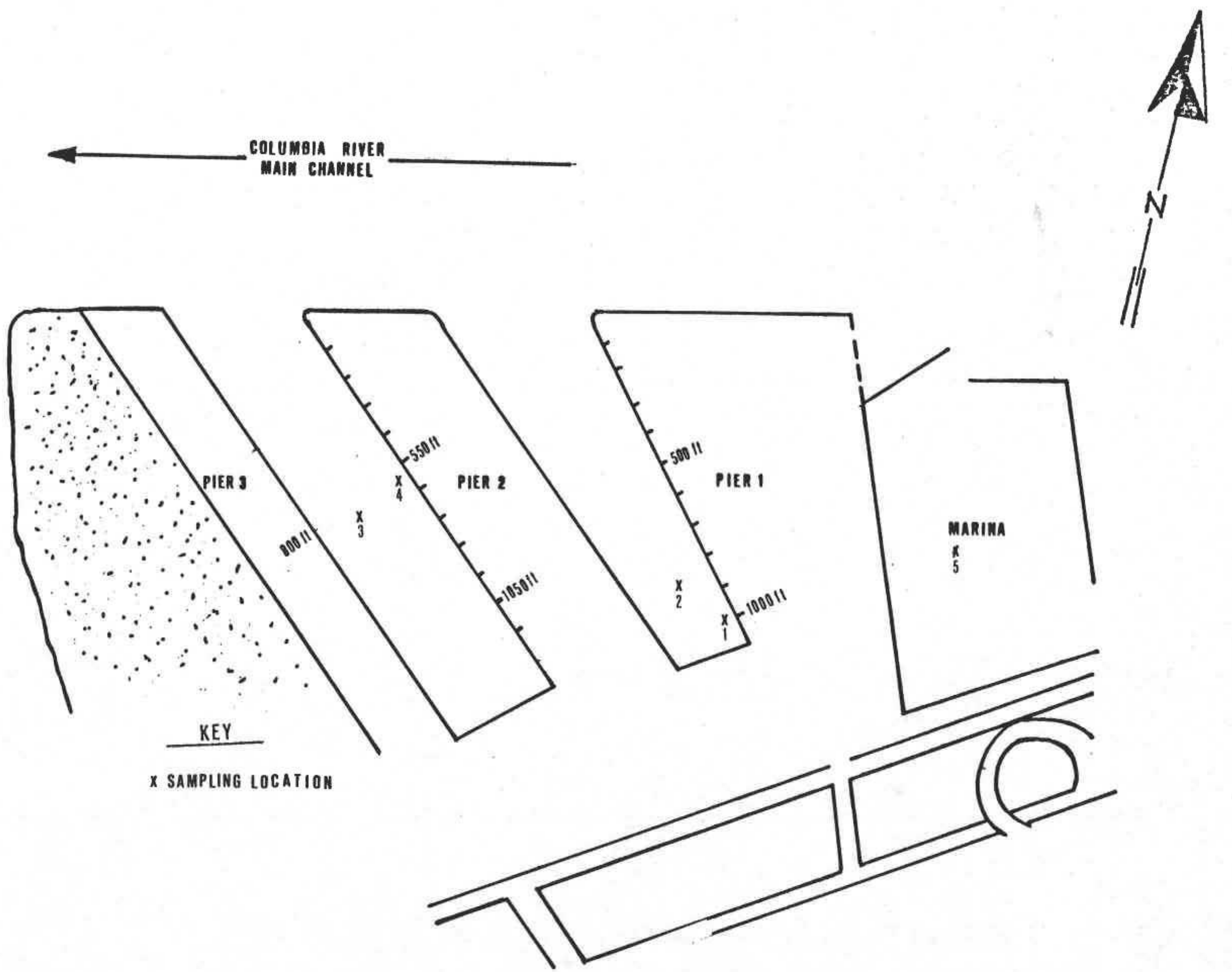


FIGURE 19. CORE SAMPLING FOR CLAY MINERALOGY ANALYSIS.

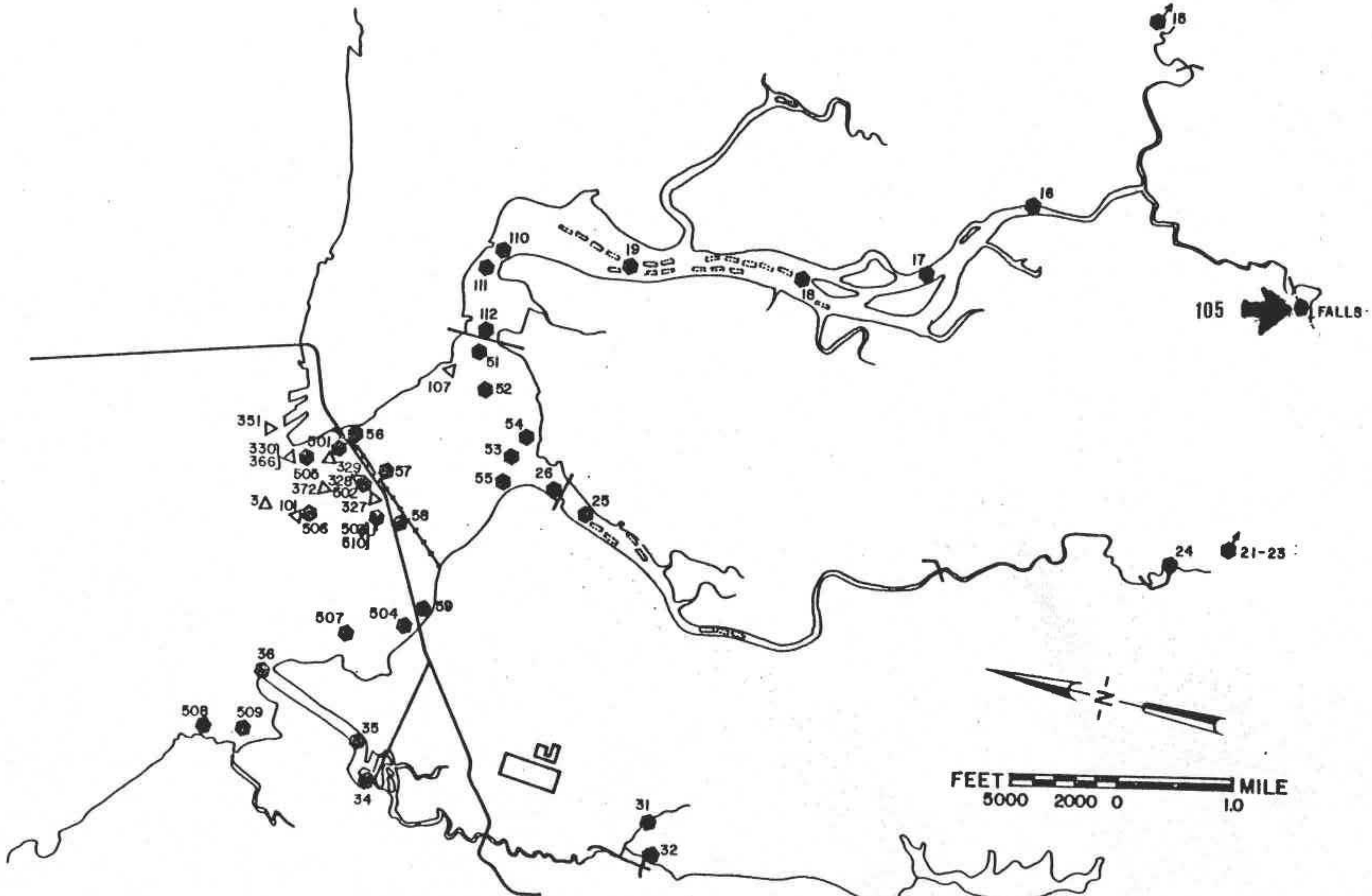


FIGURE 20. SEDIMENT SAMPLING LOCATIONS (Source: Slotta et al., 1975).

with high salt concentrations. The lack of kaolinite on the Youngs Bay sediment suggests that kaolinite had to be transported by the Columbia River, with the sediment's source probably being the Willamette River because kaolinite is a common clay in Oregon's mid-valley soils (Russell, 1967). If this is true, it indicates that the Columbia River is one of the sources of sediment into the Port of Astoria, although it does not disregard Youngs Bay as another source.

Since the sample from Youngs Bay contained no kaolinite and the Port of Astoria slips contained kaolinite, there remains only a remote and unlikely possibility that a tributary near Youngs Bay, such as the Skipanon, Lewis and Clark or Youngs River, might contain kaolinite that could have been transported through Youngs Bay and upstream via the Columbia River to the Port of Astoria. More clay samples would be necessary to confirm that alternate hypothesis.

Microprobe Tests

Glass was found in some of the core samples taken in the Astoria slips. The glass was believd to be juvenile and it was thought that a microprobe test on the sample would confirm the origin of the sediment. Five samples (one from each core shown in Figure 19) were selected for this test. Samples were taken from the first core from the layer at 8-12 inches, from the second core in the top inch, and from the third core from the layer between 10-15 inches. The fourth and fifth samples were taken from 22-25 inches and 28-29.5 inches in depth in the respective cores.

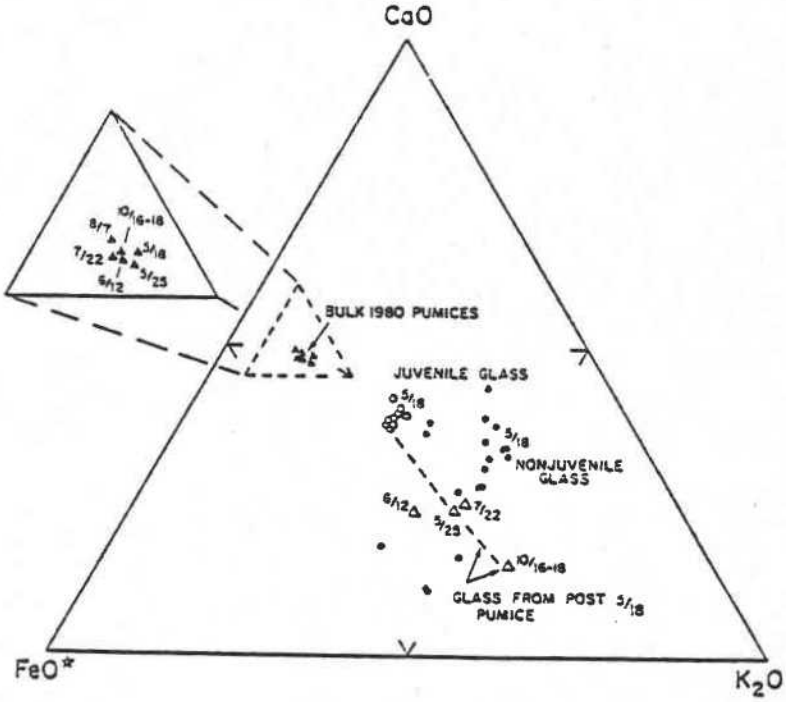
The microprobe test results were somewhat different than expected. The glasses found were of extremely heterogenous composition; not one of the analyses plotted in the graphical field where most of the May 18, 1980 juvenile glass components plotted. However, the heterogenity observed is consistent with the nonjuvenile glass components from the May 18th eruption. Dr. Scheidegger, Oregon State University School of Oceanography, analyzed the samples and concluded that the ash in the samples came from the most voluminous phases of the May 18, 1980 Mt. St. Helens eruption (see also Scheidegger and Frederman, 1982).

The results of the microprobe test are shown in Table 8. Figure 21 shows a ternary plot with locations for the juvenile glass and non-juvenile glass from the 1980 eruptions of Mt. St. Helens. Figure 22 shows data for the Astoria samples plotted on a similar diagram. It can be seen that the samples are in the same general area of non-juvenile glass. If more samples were analyzed it might have been possible to find some juvenile glass. Unfortunately, project fund limitations prevented this.

The microprobe results, together with the interpretation from the clay minerology tests, confirm that much of the sediment had the Columbia River as its source.

TABLE 8. MICROPROBE RESULTS.

Sample #	Na_2O	SiO_2	Al_2O_3	K_2O	MgO	CaO	TiO_2	MnO	FeO*	Total
1	2.17	73.85	11.69	4.52	---	.22	.11	.39	.57	93.53
	2.64	70.49	13.37	2.57	.38	1.31	.38	.12	1.94	93.20
	2.85	71.54	14.42	2.50	.35	1.67	.44	.37	2.07	96.21
	2.02	74.54	11.51	3.28	.09	.93	.30	.37	.94	93.98
	2.52	75.13	11.92	4.03	---	.11	.15	.39	.52	94.75
2	2.73	73.90	12.72	3.13	.23	1.24	.20	.28	1.09	95.52
	2.11	73.90	12.68	2.00	.24	1.27	.18	.04	.86	93.27
	2.82	73.02	14.30	2.43	.45	1.40	.43	.20	2.03	97.06
	1.43	73.32	11.00	4.81	.01	.49	.21	.13	1.34	92.73
	3.23	73.54	12.16	2.07	.14	1.31	.21	.13	1.14	93.93
3	2.31	74.40	12.30	4.25	---	.38	.14	.19	1.00	94.97
	1.81	73.96	11.26	4.75	---	.40	.16	.11	1.54	94.00
	2.58	72.32	13.13	2.24	.18	1.37	.29	.28	1.23	93.63
	2.18	75.14	11.82	4.53	---	.54	.25	.28	.98	95.71
	1.96	72.11	11.99	3.02	.04	.61	.11	.20	1.63	91.66
4	1.55	71.70	11.52	4.46	.07	.80	.30	.13	2.11	92.63
	3.01	70.88	13.78	2.57	.43	1.41	.46	.30	1.61	94.46
	1.19	72.67	11.47	5.38	.05	.49	.25	.28	1.46	93.22
	1.54	72.65	11.87	3.79	---	.40	---	.27	.95	91.48
	1.59	71.65	10.89	5.13	---	.58	.21	.22	1.86	92.14
5	2.25	75.46	11.53	4.16	---	.17	.16	.01	.93	94.68
	2.53	70.63	13.78	4.00	.13	.81	.25	.16	1.96	94.24
	2.23	74.41	11.64	3.42	.11	.78	.18	---	.69	93.46
	2.47	70.41	14.18	2.26	.46	1.54	.41	.29	1.89	93.91
	3.10	71.33	14.12	2.60	.45	1.73	.44	.34	1.66	95.77



A ternary plot of FeO*-CaO-K_2O for bulk pumices from the 1980 eruptions of Mount St. Helens (data from Lipman et al. [1981]), nonjuvenile glass from samples Wye 1330, 1430, and 1530 (see Table 1), juvenile glass from Wye time series samples, and glass found in selected post-May 18 pumices. Data on bulk pumices indicate that post-May 18 pumices have lower K_2O and relatively higher CaO+FeO* values, suggesting a trend toward more andesitic compositions (see Table 3). In contrast, note opposite trend associated with glasses found in post-May 18 pumices.

FIGURE 21. TERNARY PLOT SHOWING JUVENILE AND NON-JUVENILE GLASS FROM THE 1980 MT. ST. HELENS ERUPTIONS (Source: Scheidegger and Frederman, 1982).

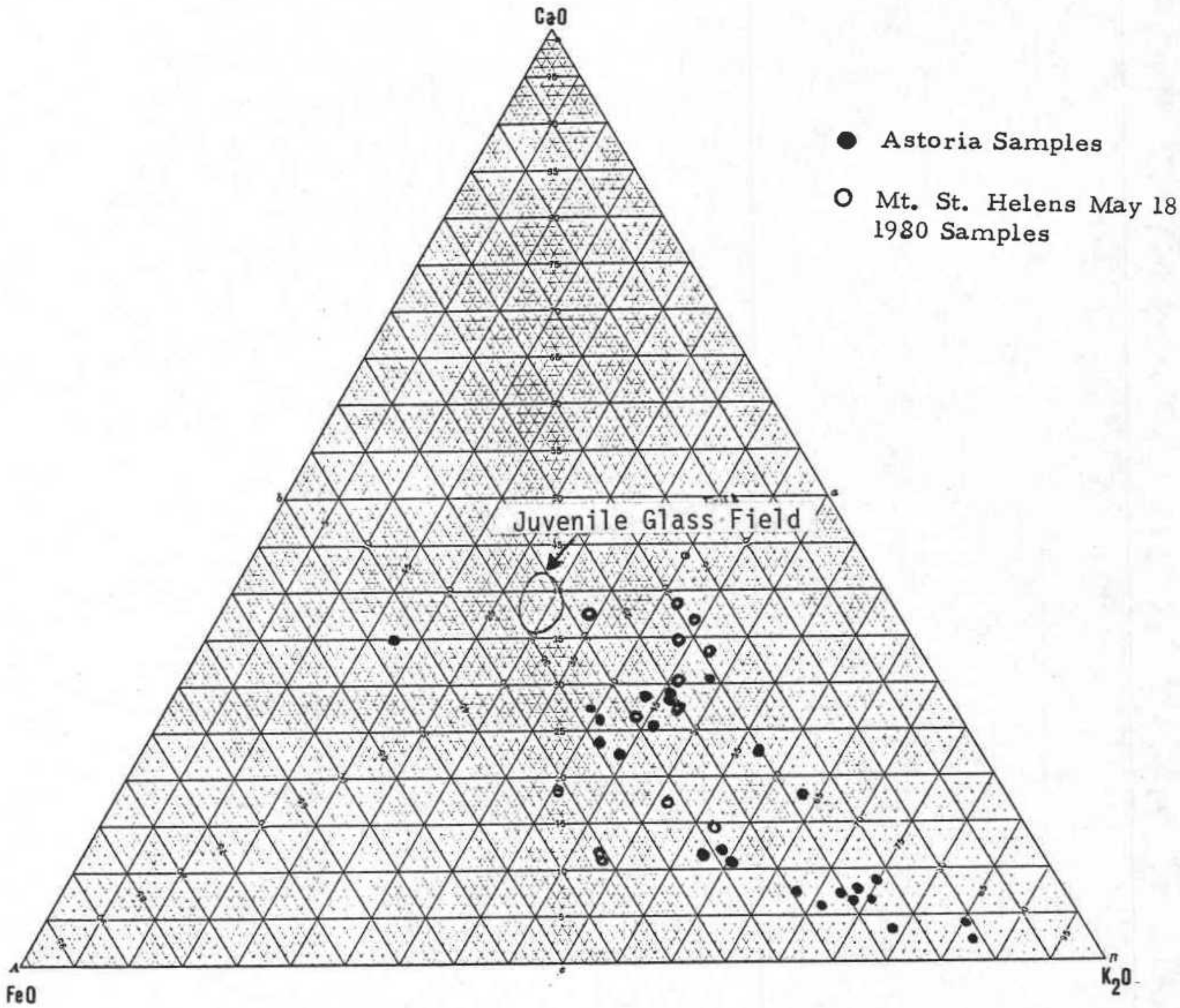


FIGURE 22. COMPOSITIONAL HETEROGENEITY OF THE ASTORIA SAMPLES AND RELATIVE RELATION TO MT. ST. HELENS MATERIAL.

Heavy Mineral Analysis

A heavy mineral analysis was made to aid in the determination of whether or not the material found in the Astoria Harbor slips was from Youngs Bay or the Columbia River. If the analysis indicated sediment from the tributaries of Youngs Bay, then the assumption would be that the Mt. St. Helens eruptions had little or no effect upon sedimentation in the slips; if the analysis indicated sediment of Columbia River origin, then the assumption would be that there is a cause-and-effect relationship between the Mt. St. Helens eruptions and sedimentation in the slips (however, the heavy mineral analysis would not identify the specific minerals as being from Mt. St. Helens). Tracing the path of heavy mineral sediments from their source to their final deposition site is not a new procedure and has been successfully accomplished for the heavy minerals found on the continental shelf off the mouth of the Columbia River (Schiedegger et al., 1971).

Cores were taken at several sites in the Port of Astoria slips number 1 and 2 (See Figure 19). The field procedures were described in a prior section of this report.

In the laboratory, cores were extruded intact and observed. Several of the cores were prepared for x-radiographs. This consisted of cutting out a 1-inch thick longitudinal section extending the entire length of each core. X-radiographs were than made of these samples.

The x-radiographs aided in the identification of distinct layers within each core. Both cores 4 and 5 from the August 18, 1982 Port of Astoria field trip had a number of distinctive layers. Cores were highly deformed due to coring and extruding procedures, but core 5 yielded four distinctive layers ranging in thickness from 1 cm to 3 cm. One of the 1 cm thick layers appeared at the 70 cm depth in the core. This layer was light gray in color (5Y-6/1) and was mottled in appearance. Depositional features consist of moderate bioturbation and laminations throughout the cores. Laminations are indicative of suspension deposition.

Curt Peterson (doctoral candidate in Oceanography at Oregon State University) performed the mineral analysis of Port of Astoria silt sediments on our behalf, determined the percentages of heavy minerals, and discussed the implications of the results. His results on two samples collected in 1982 from the slips are given in Table 9. Tables 10-14 provide results of heavy mineral analyses from previous studies in Youngs Bay and vicinity. In comparing results, it must be noted that certain opague minerals may or may not appear in the analyses. These opague minerals may consist of magnetite, ilmenite, and, often, hematite. To facilitate comparisons, the percentages enclosed by parenthesis in the tables are based upon fractions of the total with the opaque minerals omitted. The origin of these minerals may be implied by a comparison of the heavy mineral identifications made in the Columbia River and in Youngs Bay. Slotta et al. (1975) included magnetite (an opaque mineral) as one of the identified minerals.

From a comparison of the various studies given in Tables 9 through 14, two general dispersal patterns are distinguishable. First, the pyroxene

TABLE 9. HEAVY MINERAL ANALYSIS OF PORT OF ASTORIA SEDIMENT SAMPLED ON AUGUST 18-19, 1982.

Mineral	Sample #1 (% of fraction)		Sample #3 (% of fraction)	
Opaques and rock fragments	42		29	
Pyroxene Group:	39	(70)	52	(75)
Orthopyroxene (hypersthene)	25	(45)	26	(38)
Clinopyroxene augite	14	(25)	26	(38)
Amphibole Group	12	(21)	14	(20)
Hornblende				
Basaltic hornblende (lamprobolite)				
Garnet	3	(1)	1	(1)
Epidote	1	(1)	0	
Clinozoisite	1	(1)	2	(1)
Tourmaline	1	(1)	1	(1)
Staurolite	1	(1)	1	(1)
Apatite	1	(1)	0	
Zircon	1	(1)	1	(1)
	100%		100%	

Sample #1 was located beneath the 1000 foot mark on the west side of Pier 1. Sample #3 was taken opposite the 800 foot mark on the east side of Pier 3, midway across the slip. The first number listed represents total heavy minerals including opaques (probably magnetite). The number in parenthesis represents percent of fraction with opaques omitted.

TABLE 10. HEAVY MINERAL ANALYSIS OF YOUNGS RIVER SEDIMENTS, 1975.

Mineral	Sample 13	14	15	16	17
Magnetite	45	80	80	50	50
Pyroxene Group	40(74)	10(48)			18(38)
Orthopyroxene	5(9)	0(48)			10(21)
Clinophyroxene augite	35(65)				8(17)
Amphibole Group	12(22)	10(48)	20(95)	48(100)	30(63)
Balsaltic Hornblende		10(48)	20(95)	18(37)	30(63)
Green Hornblende	12(22)			2(95)	30(63)
Apatite	2(4)				
Zircon					
Spessartite	1(1)	1(4)	1(5)	1(2)	1(1)

Samples 13-17 were taken from the upper reaches of the Youngs River (Source: Slotta et al., 1975).

TABLE 11. HEAVY MINERAL ANALYSIS OF LEWIS AND CLARK RIVER SEDIMENT NEAR YOUNGS BAY, 1975

Mineral	Sample 21	22	23	24	32
Magnetite	85	70	65	80	60
Pyroxene Group	2(26)	6(21)	15(60)		15(38)
Orthopyroxene	1(13)		10(33)		5(13)
Clinophyroxene augite	1(13)	6(21)	5(17)	20(100)	20(50)
Amphibole Group	1(13)	7(25)	5(17)	20(100)	20(50)
Balsaltic Hornblende					
Green Hornblende	1(3)	7(25)	5(17)	20(100)	20(50)
Apatite					
Zircon					
Spessartite	6(61)	15(54)	10(33)		5(13)

Samples 21 through 24 are from the upper waters of the Lewis and Clark River. Sample 32 is from an upper area of the Skipanon River (Source: Slotta et al., 1975).

TABLE 12. HEAVY MINERAL ANALYSES OF YOUNGS BAY SEDIMENT NEAR COLUMBIA RIVER, 1975.

Mineral	501	502	503	504	505	507	508	509	510
Magnetite	15	53	30	30	40	30	50	40	25
Pyroxene Group	36(54)	10(50)	10(18)	15(100)	---	5(9)	10(26)	24(49)	25(48)
Orthopyroxene	35(53)	10(50)	10(18)	15(100)		5(9)	10(26)		25(48)
Clinopyroxene									
augite	1(1)							24(49)	
Amphibole Group	30(46)	10(50)	45(80)		30(100)	40(91)	29(74)	23(51)	27(52)
Basaltic Hornblende	30(46)	10(50)	45(80)	---	30(100)	40(91)	29(74)	25(51)	27(52)
Green Hornblende									
Apatite	<1	---	1(2)	<1(<1)	<1(<1)	---	<1(<1)	<1	<1
Zircon							1(<1)	<1	
Spessartite									

Samples 501 through 510 are from near the confluence of Youngs Bay and the Columbia River, north of the railroad bridge (Source: Slotta et al., 1975).

TABLE 13. HEAVY MINERAL ANALYSIS OF YOUNGS BAY SEDIMENTS, 1974.

Mineral	Sample				
	15	28	37	46	56
Magnetite	15	18	12	20	24
Pyroxene Group	22(39)	28(44)	30(48)	28(47)	24(43)
Orthopyroxene	18(32)	20(32)	22(35)	18(31)	18(32)
Clinophyroxene augite	4(7)	8(13)	8(13)	10(17)	6(11)
Amphibole Group	21(38)	22(35)	18(39)	20(34)	16(29)
Balsaltic Hornblende					
Green Hornblende					
Apatite					
Zircon	8(14)	4(6)	4(6)	2(3)	4(7)
Spessartite					

Samples are from various locations in Youngs Bay (Source: Johnson and Cutshall, 1975).

TABLE 14. HEAVY MINERAL ANALYSIS OF COLUMBIA RIVER SEDIMENTS, 1968.

Mineral	Columbia River[1]	Columbia River[2]
Pyroxene Group	69	64
Orthopyroxene	37	36
Clinophyroxene augite	32	28
Amphibole Group	22	28
Balsaltic Hornblende		
Green Hornblende		
Apatite		
Zircon		
Spessartite		
Other Minerals	9	8

[1]Source: Schiedegger et al., 1971.

[2]Source: Kulm et al., 1968.

group is the major constituent of the Columbia River non-opaque, heavy mineral assemblage in the 250-62 micron (fine sand) size range. Pyroxene represents over 60 percent of the heavy minerals identified in the Columbia River samples. Schiedegger et al. (1971) and Kulm et al. (1968) have both come to this finding in their respective reports. The amphibole group represents approximately 25 percent of the non-opaque heavy mineral species in the Columbia River. The second pattern becomes obvious as one travels away from the Columbia River southward into the tributaries of Youngs Bay. The percentages of the amphibole group increase as one travels up the tributaries. The range of the amphibole percentages is wide (13-100 percent), but an overall higher percentage of amphibole as compared to the Columbia River samples is clear.

In the Port of Astoria slips pyroxene represents nearly 75 percent of the minerals identified. Amphibole constitutes approximately 20 percent of the sample. These percentages agree favorably with the two Columbia River studies and the study by Johnson and Cutshall (1975) for the northern sections of Youngs Bay. The 1975 Alumax study by Slotta et al. (Table 12) shows too much scatter in the heavy mineral constituent percentages at the mouth of Youngs Bay to reliably relate the Youngs River as mineral source to the Port of Astoria slips. However, based upon a comparison of the percentages of the different mineral species identified, the slips appear to have the Columbia River as the main contibutor of the heavy minerals that were identified. If a greater percentage of amphibole were found in the slips, then the Youngs Bay tributaries might be considered to give more of a contribution to infilling of the slips.

This hypothesis agrees with the earlier Youngs Bay study (Slotta et al., 1975) which included observing sediment stakes that were positioned about Youngs Bay. The observations of these stakes indicated that the area at the northeast end of the causeway was subject to accretion or erosion depending upon the flow level of the Columbia River. Examining a map and interpreting flow condition would indicate that if this area is controlled by the Columbia River then certainly the slip sediments should be also dominated by Columbia River source materials. The 1975 study also concluded that sediment in the area between Pier 2 and the causeway were all of Columbia River origin.

Based upon a comparison of the 1982 findings with past studies, the heavy minerals found in the slips can be implied to be from a Columbia River origin. Whether or not the material is from Mt. St. Helens could not be determined solely by heavy mineral analysis.

The material found in the slips has a range of sizes from clay to the fine sand range (Cobos, 1983). Usually less than 20 percent of a sample could be classified as being in the fine sand size range. The majority of the material was in the silt range. Therefore, the origin of less than 20 percent of the material in the slips has been determined by this analysis.

Earlier studies suggest that resuspended deposits may responsible for siltation in the slips. Hubbell et al. (1971) state that the "near-shore shoaling of port slips" may be due to the resuspension of silts and clays on a flood tide during periods of low flow. Then on slack tide this fine material settles out. On the ebb tide only 20 percent of the material is resuspended, producing a net gain in the slips. The high percentages of silts and clays found in the slips can be hypothesized as being a result of suspension deposition. In fact, x-radiographs of several of the cores indicates this type of sedimentation.

Brief Summary of Sediment Origin Investigation

The three tests (clay mineralogy, heavy minerals, and microprobe) indicated that the Columbia River is the primary source that produces shoaling in the Astoria Harbor. In this study, the microprobe analysis provided the most definitive answer regarding the questions about the effects produced on the Port of Astoria by the Mt. St. Helens eruption, indicating that part of the sediment sampled from the port slips contained non-juvenile glass from Mt. St. Helens. However, although the Columbia River is the main source of suspended sediment deposits in the port slips, it is possible under certain conditions for Youngs Bay sediments also to enter the Astoria Harbor.

5. DESCRIPTION OF THE SEDIMENTATION PROCESS

The sedimentation process in estuaries is complex due to the many variables involved. These include river flow, wind, temperature, tides, physical characteristics of the sediment, and the shape and form of the estuary. Some of these variables have seasonal patterns; others vary with each tidal cycle. In this study, a descriptive model of sedimentation was developed by use of relatively few variables. An attempt to calibrate the model was then made with available field information.

General Features

Sediment Source and Characteristics

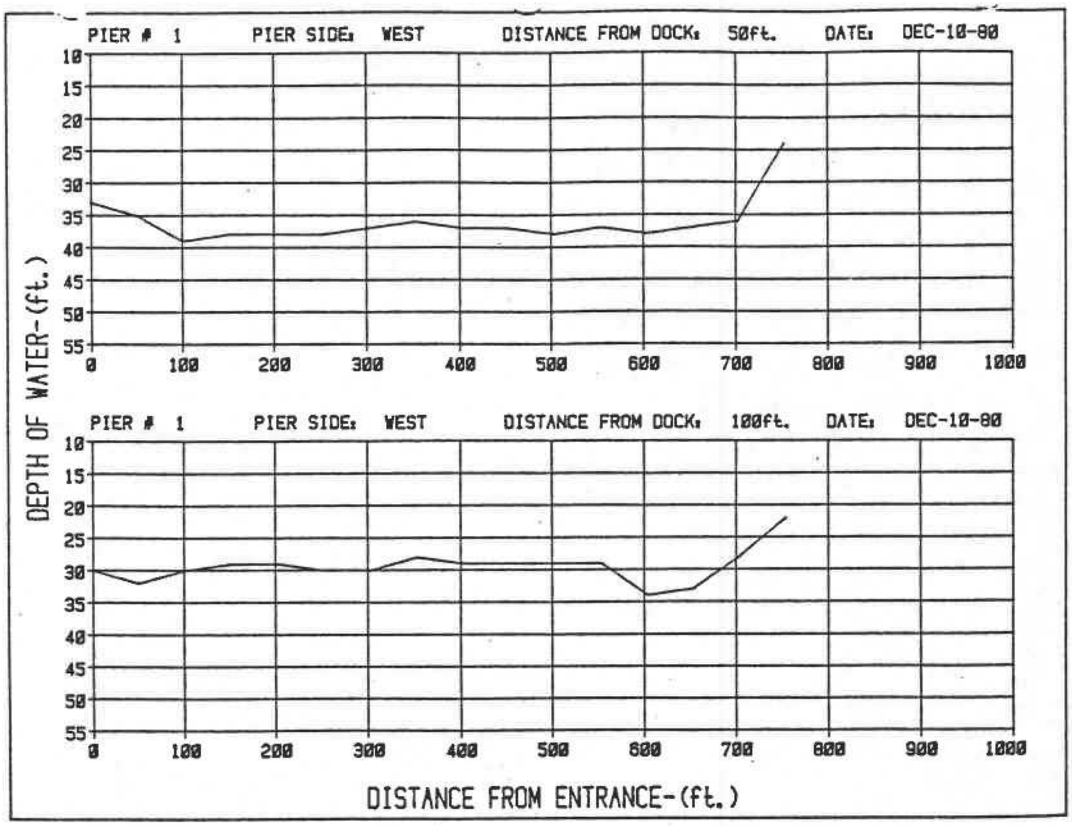
As already discussed, the main source of sediment reaching the Port of Astoria is the Columbia River, with Youngs Bay as a secondary source of sediment. Physical characteristics of the sediment such as size and specific gravity agree with such information reported by other authors (Crane et al., 1981; Krone, 1971; unpublished reports of the U.S. Army Corps of Engineers; Moore, 1982). The sediment in the Astoria slips is primarily formed of silts and clays with an average specific gravity of 2.6.

Bottom Depths and Shoaling Rates

Depth sounding records made by the Port of Astoria were analyzed to determine bottom features. Figures 23 and 24 illustrate some of the post-eruption depth profiles at piers 1 and 2, respectively. Based upon such records, an arbitrary reference depth was chosen for making a sediment mass balance. The 35-foot depth was chosen as the reference depth and sediment volumes above this depth were considered positive, volumes below this depth were assumed negative. The volumes thus determined from records between 1979 and 1981 were plotted with respect to time. The resultant graph is shown in Figure 25. The rates of sedimentation were also computed; these results are shown in Table 15. Time restrictions for this study did not allow searching out sounding records made prior to 1979.

Unfortunately, the Port of Astoria sounding records presented some difficulties in making a complete sediment mass balance. The records with a few exceptions, were only kept for two sectors of each slip, as shown in Figure 26. Also, the records were taken irregularly and the dates and places of dredging were not consistently recorded, nor was the location where the spoil material was dumped. Furthermore, more sounding information was collected in slip 1 than in slip 2. Accordingly, slip 1 data was chosen for the analysis shown in Figure 25.

A relatively small difference was detected between deposition at one side versus the other side of the slips: one side of each slip may have been partially dredged during the time interval between sounding records or currents inside the slips may have produced more sedimentation on one side than on the other. Neither of these two speculations can be supported from available data. Analysis was limited because of a lack of recorded dredging



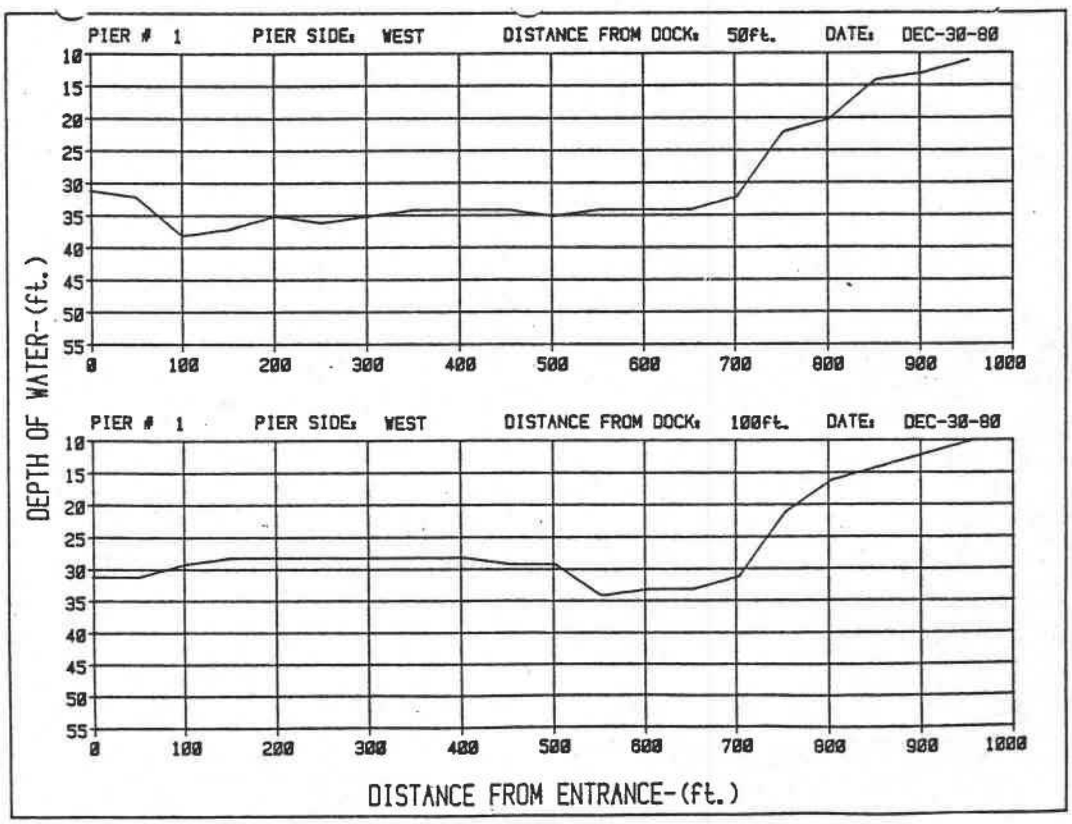
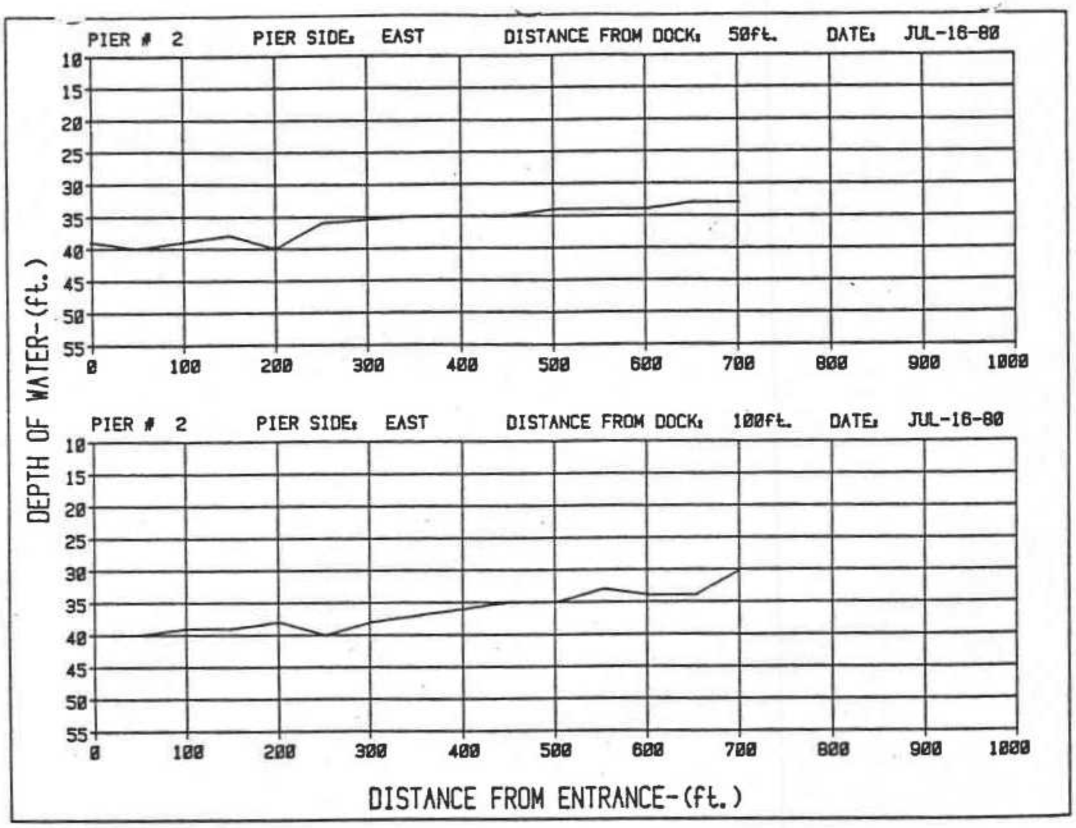


FIGURE 23. DEPTH PROFILES PIER 1.



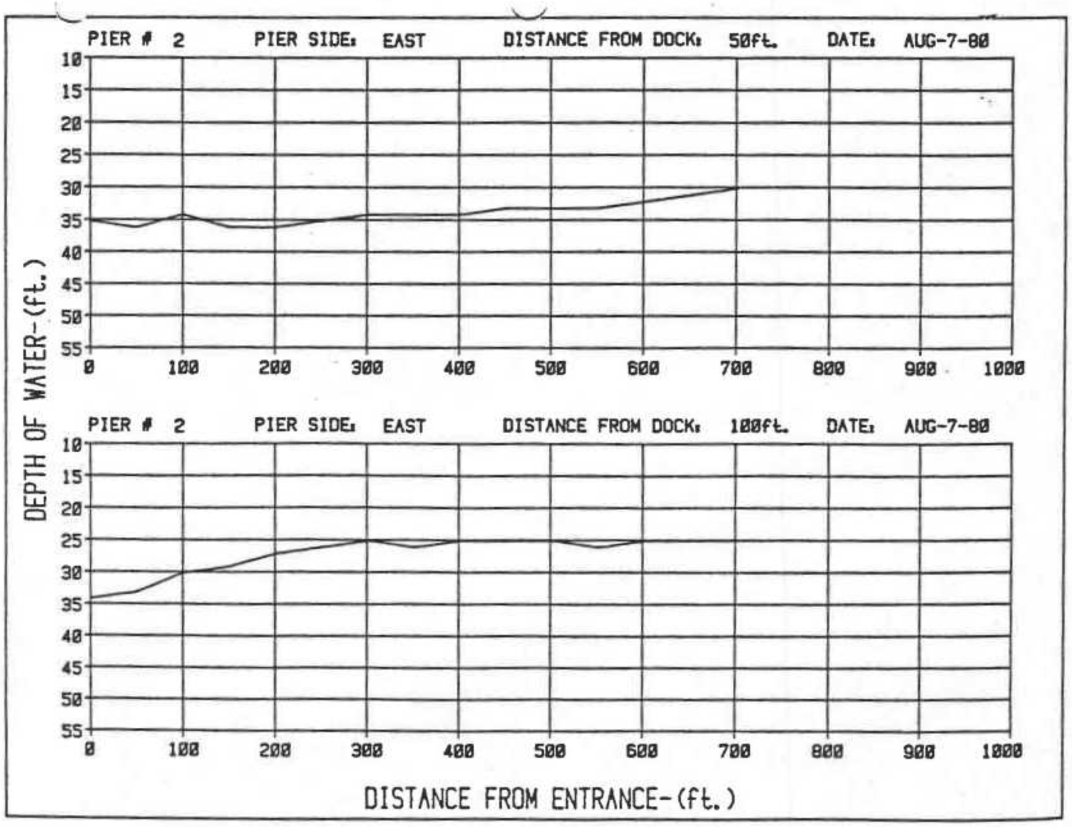


FIGURE 24. DEPTH PROFILES PIER 2.

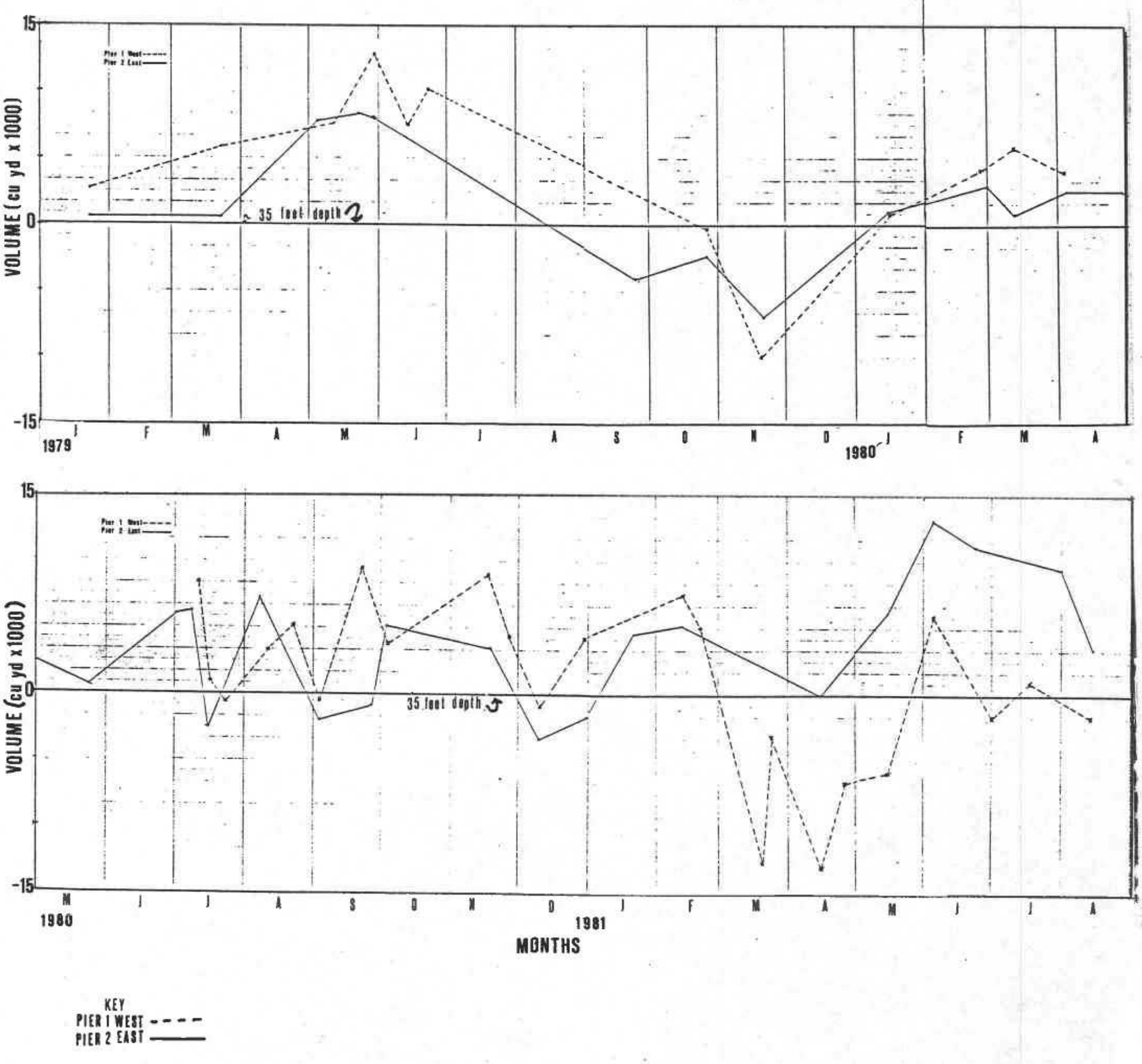


FIGURE 25. CHANGES IN VOLUME OF SEDIMENT IN SLIP 1 OF THE PORT OF ASTORIA, JANUARY 1979 TO AUGUST 1981.

TABLE 15. SEDIMENT VOLUME, SEDIMENT RATE, AND DREDGING RATE AT SLIP 1, JANUARY 1979 TO DECEMBER 1981.

SLIP 1 PIER 1 WEST

DATE	Volume Present cu.yards	Sediment Rate (mm/day)	Dredging Rate cu.yards
Jan/22/79	2644.04		
Mar/22/79	5745.89	6.80	
May/11/79	7644.04	4.46	
May/29/79	12839.52	33.93	350.48
Jun/13/79	7582.30		
Jun/22/79	10226.33	34.54	
Oct/26/79	-380.67		86.49
Nov/20/79	-1018.52		25.51
Jan/15/80	874.48	3.97	
Feb/25/80	4331.28	9.91	
Mar/12/80	6049.38	12.62	
Apr/03/80	4104.94		88.38
Jul/11/80	8374.43	5.07	
Jul/16/80	915.64		1491.76
Jul/23/80	-730.45		235.16
Aug/11/80	3384.77	25.46	
Aug/22/80	4269.55	9.46	
Sep/03/80	-502.06		397.63
Sep/22/80	9465.02	61.67	
Oct/03/80	3981.43		498.50
Nov/17/80	9006.17	16.88	
Nov/26/80	4341.56		518.29
Dec/10/80	-936.21		376.98
Dec/30/80	4197.53	30.18	
Feb/12/81	7469.14	8.95	
Feb/20/81	5154.33		289.35
Mar/19/81	-7613.19		472.87
Mar/23/81	-3117.28	132.14	
Apr/15/81	-13240.74		440.15
Apr/27/81	-6635.81	64.72	
May/14/81	-6013.37	4.30	
Jun/04/81	5792.16	66.09	
Jun/30/81	-1676.96		287.28
Jul/17/81	905.35	17.86	
Aug/13/81	-1625.51		93.74
Sep/02/81	-246.91	8.10	
Nov/23/81	4773.66	7.20	
Dec/14/81	-6862.15		554.09

TABLE 15 CONT.

SLIP 1 PIER 2 EAST

Date	Volume Present cu.yards	Sediment Rate (mm/day)	Dredging Rate cu.yards
Jan/22/79	442.37		
Mar/22/79	514.41	0.14	
May/04/79	7736.63	19.75	
May/21/79	8307.63	3.95	
May/29/79	8055.56		31.51
Sep/24/79	4115.22		103.14
Oct/26/79	-2376.56		51.00
Nov/20/79	-9465.04		262.00
Jan/14/80	1013.37	22.40	
Feb/29/80	3235.60	5.68	
Mar/12/80	997.94		186.47
Apr/03/80	2726.34	9.24	
Apr/28/80	1635.80		44.02
May/23/80	545.27		43.62
Jul/01/80	6069.96	16.65	
Jul/08/80	6208.85	2.33	
Jul/16/80	-2561.73		1096.32
Aug/07/80	6640.33	48.11	
Sep/03/80	-1962.96		311.23
Sep/26/80	-853.91	5.67	
Oct/03/80	5144.03		34.89
Nov/18/80	3539.03		1985.60
Nov/23/80	-6388.89	67.66	
Dec/10/80	-3395.06	9.68	
Dec/31/80	-1666.67	34.15	
Jan/21/81	4434.16	3.68	
Feb/12/81	5123.46		98.69
Ap/15/81	-8.23	26.13	
May/13/81	6213.99	36.97	
Jun/04/81	13131.61		107.43
Jun/23/81	11090.53		39.39
Jul/31/81	9593.63		431.00
Aug/14/81	3559.67	62.64	
Sep/2/81	13683.13		
Oct/22.81	17407.41	8.70	
Nov/01/81	21368.31	46.57	
Dec/23/81	22839.51	3.33	

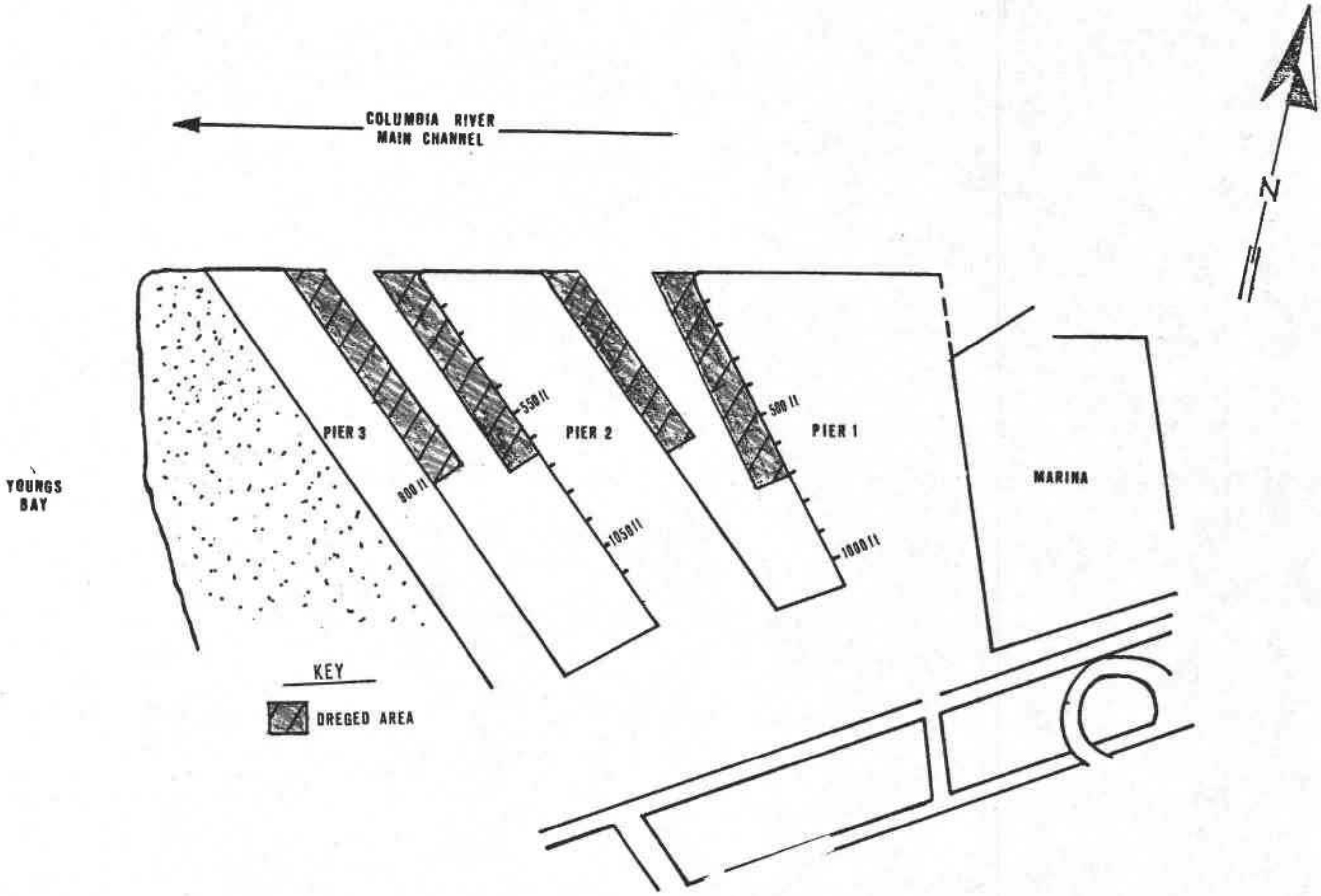


FIGURE 26. AREAS REGULARLY DREDGED

dates and unreliable current meter records during the 1981 field work associated with this project.

Some of the bathymetry changes may have been produced by propeller wash and associated ship activity. During the 1982 field studies, an increase of suspended material was noticed due to tug activity. Also, an increase of velocities was observed during continuous recording of flows with the Savonius current meter (see Field Research discussion).

In spite of data limitations of the sounding records, a relationship was determined between periods of low flow and periods of high rate of sedimentation. For example, between March 19 and 23, 1981 a sedimentation rate of 132 mm per day was computed; the Columbia River discharge during this period was relatively low, as shown in Figure 27, for Vancouver, upstream of the Cowlitz River mouth). Also, it can be seen from Figure 25 and Table 15 that there was a deposition rate increase after the Mt. St. Helens eruption.

Tidal Influence--The Turbidity Maximum

Hubbell et al. (1971) described the behavior of a "turbidity maximum" phenomenon in the Columbia River estuary. This develops as a result of the flow circulation pattern, whereby high concentrations of sediment are associated with a saline wedge--upriver flow of denser salt water near the bottom and downriver flow of the overlying less-dense fresh water. The location varies with river discharge and tidal condition. Hubbell et al. found that although the general shape of the turbidity maximum remained the same, the entire wedge feature shifted longitudinally from one season to the next. In May, 1970 the turbidity maximum (750 mg/l) during high discharge was centered around RM 9 (km 15) near Hammond, downstream of Astoria, while in September during low discharge the turbidity maximum (60 mg/l) was centered upstream of Astoria near RM 16 (km 26). Astoria is thus within the seasonal excursion zone of the turbidity maximum.

Gelfenbaum (1981) studied the turbidity maximum in the lower Columbia River during the period of low river flow (early autumn) and placed the turbidity maximum around Astoria at such conditions. He also indicated that the turbidity maximum shifts with flood and ebb tides. Suspended sediment concentrations near the turbidity maximum may be as high as 10 times the average suspended sediment concentration for the estuary as a whole.

If the increase of sedimentation shown in Figure 25 is assumed correct, this increase should be somewhat related to the position of the turbidity maximum. Sediment concentrations will be large in the vicinity of the turbidity maximum. Currents near the turbidity maximum but within the Port slips have low velocity. This should give the incoming sediment associated with flood tide ample opportunity to settle out during each tidal exchange. During ebb tide, the settled sediment will not be resuspended again unless bottom velocities exceed the threshold velocity needed to reinitiate transport.

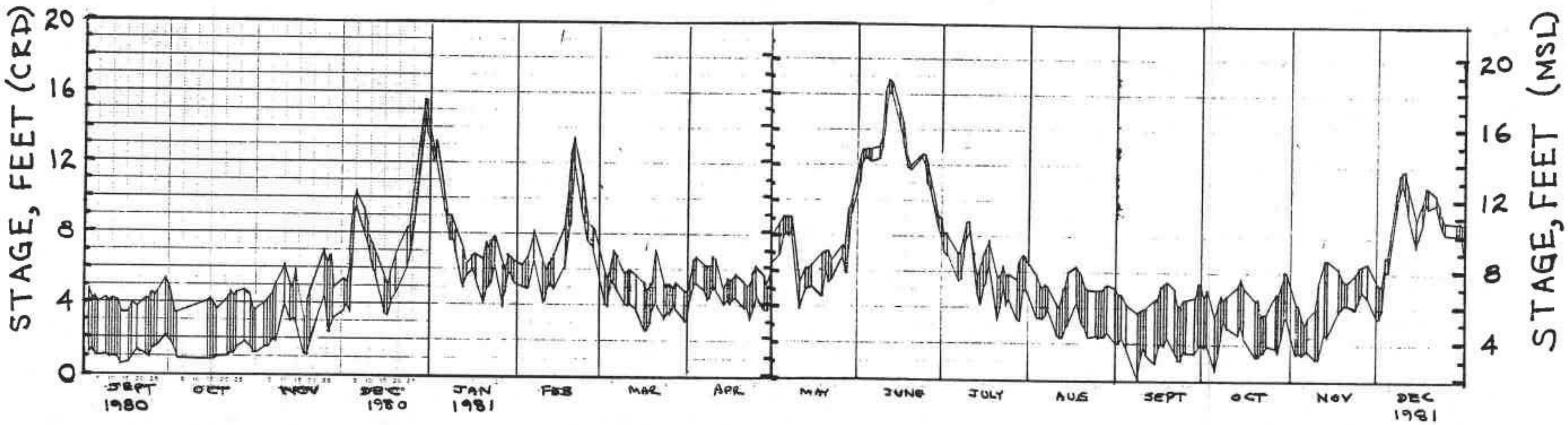


FIGURE 27. COLUMBIA RIVER STAGE AT VANCOUVER, WASHINGTON. SEPTEMBER 1980 - DECEMBER 1981.

Velocity data obtained inside the slips indicate that the velocities there are small enough to let the sediment settle out and remain at the bottom during ebb tide. The computed settling velocities based on individual particles underestimate the higher setting rate produced when the particles collide and flocculate. With kaolinite and illite, at adequate concentration, flocculation is complete when the salinity is above 4 percent (Dyer, 1979). The average salinity during the August 1980, low-flow period in the Columbia River was 15 percent (Gelfenbaum, 1981). This implies that there is a good chance for complete flocculation and settling. The salinities measured by us in 1982 in the slips had a large range of values but seemed to increase consistently at the end of flood tide.

Flow eddies are a second mechanism whereby deposited sediment might be resuspended. However, no evidence of eddies within the slips could be deduced from our velocity records, although intuitively they should exist. The velocity records obtained showed sudden changes from still water conditions to relatively high velocities. These changes were often associated with ship and tug activity, as was previously mentioned. Such velocities were large enough to produce resuspension of the sediment. It is reported by the Port of Astoria staff that 100,000 cubic yards were moved in a one 12-hour period in the slips by means of intentional propeller-wash activities. If sediments are resuspended during the ebb tide, they will be subsequently flushed out. Such methods have been used in lieu of maintenance dredging for small harbors in Florida (Mehta et al., 1981).

Wind also affects an estuary's sedimentation processes, especially at times of changing surface current direction and combined with tidal effects. It is believed that sediment from the Youngs Bay area has been put into suspension by wind-wave agitation and transported to the slips by wind and tidal currents.

Research Needs

As mentioned earlier, the information gathered to date was insufficient to either calibrate or reinforce the hypothesis for a sedimentation model of the port slips at Astoria (Mustain, 1982). The studies and data necessary for future successful sedimentation studies are discussed by Cobos (1983).

6. SEDIMENT BUDGET FOR PORT OF ASTORIA

Method Used

To compute the sediment budget at Astoria, information from the U.S. Geological Survey (USGS) was used to estimate the sediment load in the Columbia River in the pre- and post-eruption periods. Also, profiles from the depth soundings of the Port of Astoria, mentioned earlier, were used.

A sediment budget consists of making a mass balance of the sediment entering, leaving, and stored a defined area. For this case, Figure 28 shows the selected area. The amount of sediment trapped can be described as the rate of change in the volume with respect to time. The "mass in" is all the mass that comes from the source, in this case the Columbia River. The "mass out" is the dredged material and the resuspended sediment that is flushed out. It has been assumed here that the amount of material resuspended and flushed out is so small that it can be ignored.

Columbia River Suspended Sediment Discharge

To estimate the suspended sediment load, USGS records were reviewed. The selected upstream station on the Columbia River is Warrendale (USGS Station 14128910), at RM 141 (km 227), 5 miles downstream from Bonneville Dam. This station has records of suspended sediment for 1979 and 1980, which coincide with the study and are useful to make comparisons with soundings. Since there is no other downstream station on the Columbia River with suspended sediment data during the period of interest, the sediment transport from the Willamette and Cowlitz rivers must be added. To do this, station 14211720 on the Willamette River at Portland and station 14244200 on the Cowlitz River at Kelso, Washington were used. Both stations have records for 1979 and 1980. The calculated suspended sediment load of the Columbia River below Longview is shown in Table 16.

The average suspended sediment load computed for 1979 agrees fairly well with data of other authors. For example, Hubbell et al. (1971) estimated the suspended sediment discharge at the mouth to be about 10 metric tons. To compare, some estimate is needed of the increases of suspended sediment due to minor rivers and local runoff that were not taken into account in Table 16.

Sedimentation Rates and Sediment Budget for Port of Astoria

Using values of sediment volume given in Table 15, the annual volumes of sediment accumulated and the material dredged were computed. The values are shown in Table 17. Also shown is the net sediment accumulated per year.

Although results are rough estimates of sedimentation, comparison of the relative numbers shown in Table 16 and 17 is of interest. The suspended sediment concentration in the Columbia River increased dramatically after May 1980. Unfortunately, the 1981 data were not available before this report was completed and thus do not allow comparison here of the behavior of the

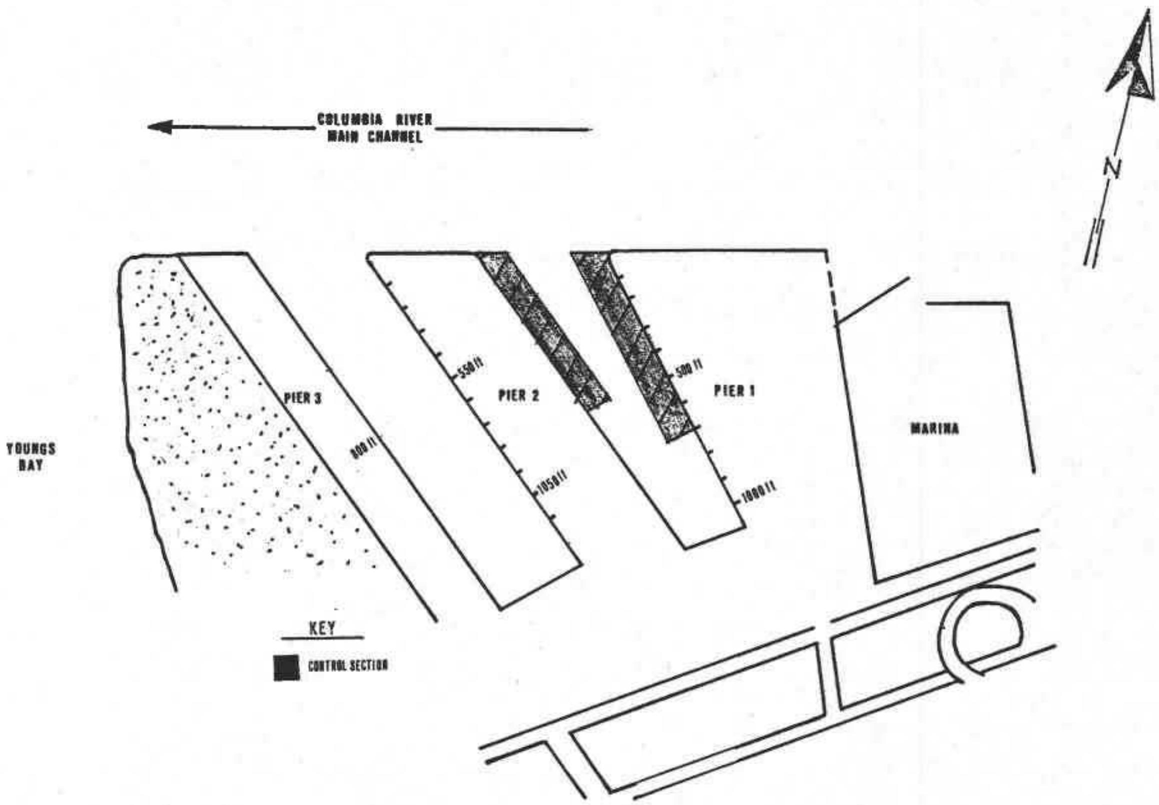


FIGURE 28. CONTROL SECTION FOR SEDIMENT BUDGET

TABLE 16. APPROXIMATE CONCENTRATION AND SUSPENDED LOAD IN THE COLUMBIA RIVER AFTER LONGVIEW, WASHINGTON.

Year	Month	Discharge, 1000 cfs	Sed. Conc. Mg/L	Sed. Load Ton/Day
1979	Feb.	333	102	92294
	Mar.	303	55	44680
	Apr.	238	16	9941
	May	338	27	24450
	June	230	19	12092
	July	176	13	6146
	Aug.	145	8	3269
	Sept.	126	7	2473
	Oct.	384	12	12718
	Nov.	159	8	3497
	Dec.	273	43	31415
1980	Jan.	351	72	68171
	Feb.	205	67	37030
	Mar.	---	---*	-----
	Apr.	281	24	18206
	May	239	124	80067
	June	311	127	106320
	July	158	26	16965

Average Ton/Day for 1979 = 22088 Ton/Day

Average Ton/Day for *1980 = 54460 Ton/Day

*no data available

TABLE 17. SEDIMENT BUDGET FOR SLIP 1.

YEAR	TOTAL IN TONS (cu.yards)	TOTAL OUT TONS (cu.yards)	NET SEDIMENT TONS (cu.yards)
1979	40 (20695)	66 (34274)	-26 (-13579)
1980	146 (76581)	124 (64716)	+22 (11865)
1981	132 (68888)	117 (61185)	+15 (7703)

Net sediment at the end of the period - Σ 11 tons (5989 cu. yards).
Negative quantities represent overdredging at the end of the period.

sediment in the river and the sediment of Astoria after July 1980. However, it can be observed that the sediment load during June 1980 is almost 10 times higher than for June 1979. It is assumed that much of this sediment could settle temporarily in the upper part of the estuary and later be resuspended and carried downstream to within the reach of the turbidity maximum. Gelfenbaum (1981) mentioned that between Hammond and Astoria there is an area of relatively quiet water where sediment might be temporarily stored, which fits this hypothesis on sedimentation of the port slips.

Table 17 shows an obvious change in the magnitude of sediment being settled and being dredged over the years. The numbers imply that in 1979 dredging involved only approximately half as much volume as that during 1980. The bed level was below the minimum safe depth in 1979; in 1980 the relation is the opposite. Figure 29 shows the annual sediment budget for the 1979-1981 period.

During 1981 a decrease in the amount of sediment seems to have occurred. If this is true, it implies a slow decrease on the sedimentation rate. Figure 30 shows a projection of the sediment budget. The discharges after 1981 were estimated using a table of random digits. The rate of sediment is assumed to decrease at a constant rate of 21 percent each year. Because of lack of analysis of pre-1979 dredging records, the values are only estimates. Table 18 shows the assumed values.

The estimates are gross and should be considered indicative only. Their importance is only relative to each other and to show how, qualitatively, they fit in the process of sedimentation and the effects produced by Mt. St. Helens.

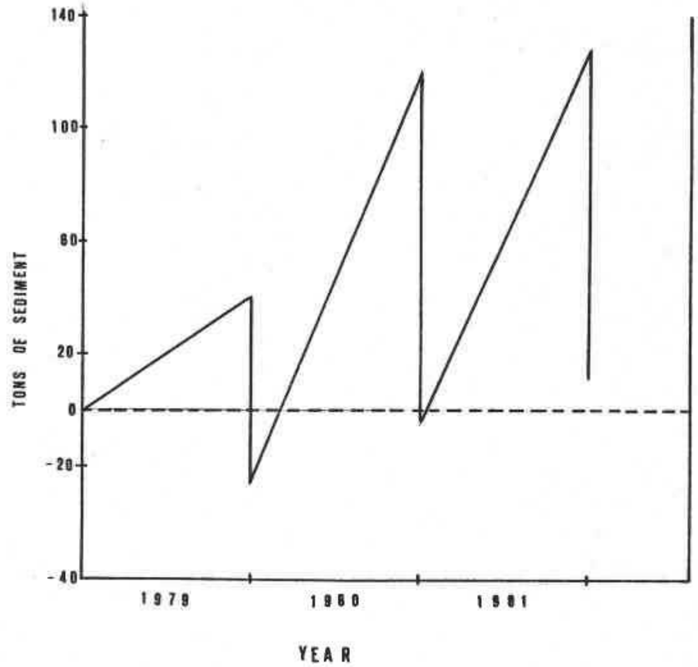


FIGURE 29. SEDIMENT BUDGET.

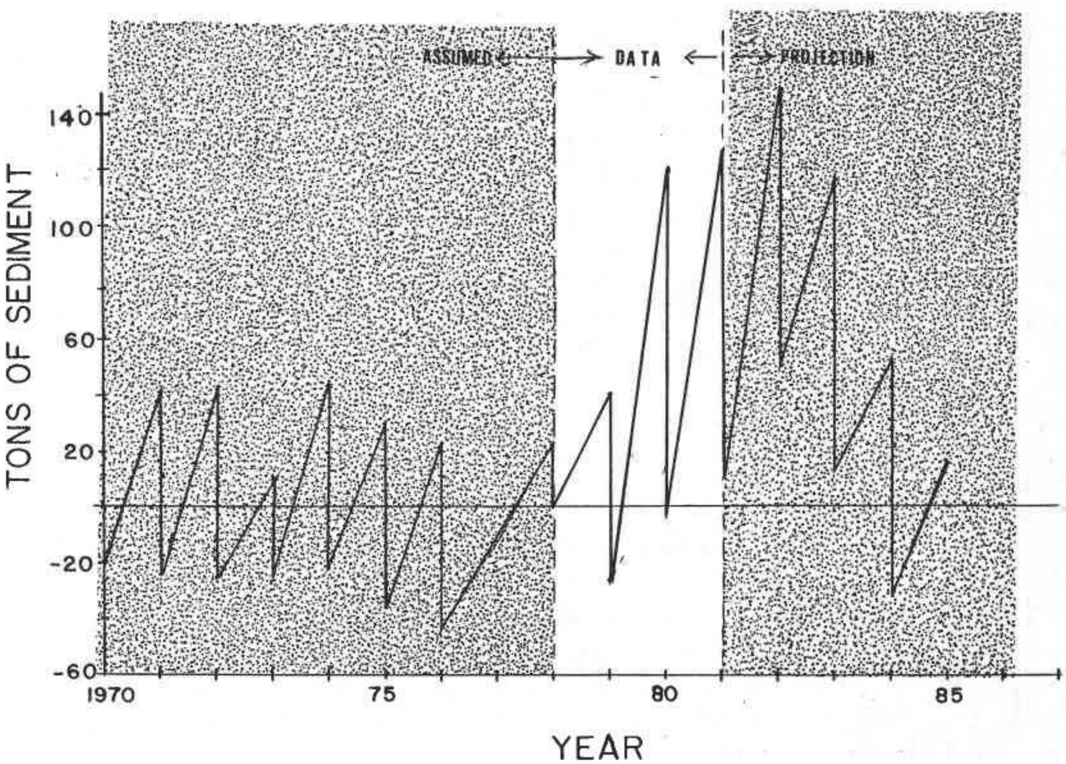


FIGURE 30. PROJECTION OF SEDIMENT BUDGET

TABLE 18. PROJECTION OF SEDIMENT BUDGET.

Year	Discharge (cfs) x1000	Sediment in the Slip Ton/Year	Dredge (Assumed) Ton/Year
1970	238.8	46	66
1971	318.3	62	66
1972	348.3	67	36
1973	187.5	36	66
1974	346.7	68	66
1975	261.9	51	66
1976	303.8	59	66
1977	153.4	30	None
1978	184.9	36	33
1979	205.4	40	66**
1980	220.3	146	124**
1981	249.8	132	117**
1982	331.6*	138	111
1983	200.3*	67	105
1984	156.1*	41	80
1985	227.8*	47	66

*Generated by a Random Digit Table
**Based on profiles of Table 14.

7. GENERAL CONCLUSIONS

Field data collection, laboratory sample analyses, and various modeling techniques allowed much to be learned about shoaling at the Port of Astoria. By inference, this provided insight to related shoaling problems at other lower Columbia River ports. This information allows an assessment of the magnitude of the problem caused by the Mt. St. Helens eruption, the quickness of the impact at locations far downriver, and the likely duration of the impact. Associated problems of harbor sediment management can also be evaluated. Because of its economic importance as a major lower Columbia River port, the Port of Astoria was the focal point for this investgation.

The water circulation and sediment shoaling features of the Port of Astoria could be modeled in a qualitative sense. Physical modeling provided useful information on overall circulation patterns and the nature of water exchange between the harbor slips and the Columbia River during incoming and outgoing tides. The physical model demonstrated the futility of disposing of harbor dredge spoils into the Columbia River unless tidal patterns are carefully considered, lest the material return to the harbor slips. Numerical circulation modeling provided additional information on hydraulic exchange between the harbor slips and the river, the mean residence time of water and associated suspended matter in the slips, and the tidal flushing rate for the slips. This model predicted about 90 percent flushing over eight tidal cycles (about four days) at the landward end of the slips -- adequate to prevent stagnant water conditions from occurring. Numerical sedimentation modeling provided very approximate estimates of the sedimentation rate in the harbor slips. Because the output predictions were quite sensitive to input assumptions made about sediment characteristics, considerable refinement of this model and better field data are needed before confidence can be place in the predictions.

The rate of sedimentation in the Port of Astoria was significantly affected by the eruption of Mt. St. Helens on May 18, 1980. The results from analysis of heavy minerals and clay minerology and, especially, from microprobe tests indicated that the sediment deposited at Astoria originated from the Mt. St. Helens eruption. Hence, the nearly-immediate impacts of the May 18th eruption extended throughout the runoff system and, presumably, reached the Pacific Ocean some 13 miles beyond Astoria.

A sudden increase in the Port of Astoria's sedimentation rate was noticed in 1980. The volume of sediment accumulated was 300 percent higher than that recorded for the previous year; in fact, the volume of accumulated suspended sediment transported by the Columbia River during the first seven months of 1980 was one and a half times the total amount of the accumulated suspended sediment load for the entire previous year.

More recently, a small decrease in the rate of sedimentation at Astoria has been noted from interpreting dredge records and data obtained after 1981. It is anticipated this trend of higher-than-normal but slowly decreasing sedimentation will last for several years. Large quantities of sediment were added to storage in tributaries of the Columbia River by the Mt. St. Helens eruptions. This material will progressively move downstream in the river channels whenever it is disturbed, until it ultimately is either transported out of the Columbia River estuary into the ocean or settles in areas where it becomes protected against further resuspension and transport. Since the material found in the slips is silt and clay, which are quite easily transported by water, it is moved downstream faster than coarser material. This probably means that the worst part of the sedimentation problem at the harbors in the lower Columbia River is presently occurring or has already occurred.

8. BIBLIOGRAPHY

Berggren, Brad and Michael Hickey, Clay Mineralogy of Sediments From Near Astoria Harbor, Special report, Department of Soil Science, Oregon State University, Corvallis, 1982.

Bogardi, Janos, Sediment Transport in Alluvial Streams, Akademiai Kiado, Budapest, 1974.

Cobos, Carlos R., Shoaling of Port of Astoria by Sediment From Mt. St. Helens Eruption, Engineering Report, Department of Civil Engineering, Oregon State University, Corvallis, 1983.

Crane, Stephen, Larry S. Slotta and Chong Chu Teng, Flow Lane Disposal Monitoring, Department of Civil Engineering, Oregon State University, Corvallis, August 1981.

Dyer, K.R., Estuarine Hydrology and Sedimentation, Cambridge University Press, 1979.

E.G.G., Side-Scan Sonar Bulletin, 1974.

Everts, Craig H., A Method to Forecast Sedimentation Rates Resulting from the Settlement of Suspended Solids Within Semi-enclosed Harbors, Coastal Emergency Tech. Aid No. 81-6, U.S. Army Corps of Engineers, Coastal Engineering Research Center, 1981.

Gelfenbaum, Guy, Suspended Sediment Response to Semi-diurnal and Fortnightly Tidal Variations in a Mesotidal Estuary: Columbia River, USA, School of Oceanography, University of Washington, Seattle, 1981.

Hamilton, Stanley F., Oregon Estuaries, Oregon State Land Board, Salem, 1973.

Higley, D.L., R.L. Holton and P.F. Komar, Analyses of Benthic Infauna Communities and Sedimentation Patterns of a Proposed Fill Site and Nearby Regions in the Columbia River Estuary: Part II, pp. 26-30, 1976.

Holeman, John N., The Sediment Yield of Major Rivers of the World, Water Resources Research, Vol. 4, pp. 737-747, 1968.

Hubbell, D.W.; J.L. Glenn and H.H. Stevens Jr., Studies of Sediment Transport in the Columbia River Estuary, Proceeding of the 1971 Technical Conference on Estuaries of the Pacific Northwest, Circular 42, Engineering Experiment Station, Oregon State University, Corvallis, Oregon, pp. 190-226, 1971.

Johnson, V.G. and N.H. Cutshall, Geochemical Baseline Data, Youngs Bay, Oregon, 1974. Final report to Alumax Pacific Aluminium Corporation, pp. 55-56, 1975.

Krone, Ray B., Investigation of Causes of Shoaling in Slips One and Two, Port of Astoria, unpublished report to the Port of Astoria. Davis, California, 1971.

Kulm, L.D. et al., A Preliminary Investigation of the Heavy Mineral Suites of the Coastal Rivers and Beaches of Oregon and Northern California, The Oregon Bin. Vol. 30, No. 9, pp. 165-180, 1968.

McDougal, William G., 1-Dimensional Marina Flushing Model, School of Engineering, Oregon State University, Corvallis, 1980.

Mehta, A.J., J. Weckmann and B.A. Christensen, Sediment Management in Coastal Marinas: A Case Study, 1981. Proc. International Symposium on Urban Hydrology, Hydraulics and Sediment Control, University of Kentucky, Lexington, July 27-30, 1981.

Moore, Pamel A., personal communication, U.S. Army Corps of Engineers, Portland, Oregon, November 1982.

Mustain, Roger S., Circulation and Shoaling Study of the Port of Astoria, Engineering Report, Department of Civil Engineering, Oregon State University, Corvallis, 1982.

Roy, E.H. et al., An Investigation to Determine Sedimentary Environments Near the Entrance to the Columbia River Estuary, School of Oceanography, University of Washington, Seattle, September 1982.

Russell, K.L., Clay Minerology Origin and Distribution on the Astoria Fan. M.S. Thesis, Oregon State University, Corvallis, 1967.

Schiedegger, K.F., L.D. Kulm, and E.S. Runge, Sediment Sources and Dispersal Patterns of Oregon Continental Shelf Sands, Journal of Sedimentary Petrology, Vol. 42, pp. 1112-1120, 1971.

Scheidegger, K.F. and A. N. Frederman, Compositional Heterogeneity of Tephras from the 1980 Eruption of Mt. St. Helens. School of Oceanography, Oregon State University, Corvallis, 1982.

Seaman, M. et al., Columbia River Estuary Inventory of Physical, Biological and Cultural Characteristics, Report for the Columbia River Estuary Study Task Force, 1972.

Slotta, L.S. et al., Physical Characteristics of the Youngs Bay Estuarine Environs, Final Report to Alumax Pacific Aluminum Corporation, pp. 55-310, 1975.

Theisen, A.A., and M.E. Harward, A Paste Method for Preparation of Slides for Clay Mineral Identification by X-ray Diffraction, Soil Science Society Am. Proc., Vol. 26, pp. 90-91, 1962.

U.S. Geological Survey, Water Resources Data for Oregon, U.S. Geological Survey, Water Resources Div., Portland, 1979.

U.S. Geological Survey, Water Resources Data for Oregon, U.S. Geological Survey, Water Resources Div., Portland, 1980.

U.S. Geological Survey, Water Resources Data for Washington. U.S. Geological Survey, Water Resources Div., Tacoma, 1979.

U.S. Geological Survey, Water Resources Data for Washington. U.S. Geological Survey, Water Resources Div., Tacoma, 1980.