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SPECIFIC SCATTERING BY UNIFORM MINEROGENIC SUSPENSIONS

by
Wayne V. Burt

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OPERATING CHARACTERISTICS OF AN OCEANOGRAPHIC MODEL OF PUGET SOUND

by
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OPERATING CHARACTERISTICS OF AN OCEANOGRAPHIC MODEL OF PUGET SOUND

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Abstract--The model, constructed to a horizontal scale of 1/40,000 and vertical of 1/1152, is equipped with a tide-producing mechanism and means for adding regulated amounts of fresh and salt water. Tests made include the following: the response of the water level to individual tidal constituents and to typical tides; current patterns throughout tidal periods; and density structure under equilibrium conditions and subsequent to controlled changes in source water. The behavior of the model agrees well with the prototype.

Introduction--A model with a horizontal scale of 1/40,000 and a vertical of 1/1152 has been built as an aid in the oceanographic investigation of Puget Sound. Its small scale and large distortion make it unique among models used to investigate the mechanisms of sea water under inshore and estuarine conditions.

The area under consideration (Fig. 1) extends southward from the eastern terminus of the Strait of Juan de Fuca in a series of arms averaging 34 fm in depth and less than three miles in width. It is divided into four deeper sections by vertical and lateral constrictions. The main basin extends south from a 40-fm threshold sill at the confluence of Admiralty Inlet with the Strait to a 26-fm sill at the Tacoma Narrows. The section south of the Narrows consists of a 100-fm primary basin with many branching channels and inlets. Hood Canal, averaging about two miles wide and having a depth of 100 fm, extends about 50 mi southwest from Admiralty Inlet and is separated from it by a 30-fm sill. The fourth section extends north with diminishing depth from Possession Sound, about 25 mi from the entrance to Admiralty Inlet, through Skagit Bay to Deception Pass. This pass, about 450 ft wide and 16 fm deep, connects with the Strait of Juan de Fuca.

The tides of Puget Sound are of the mixed type characterized by marked differences in the successive heights of low waters. Considerable changes in the tide with respect to character, range, and time occur within the area. Periodically, the tide at Port Townsend loses its mixed characteristics and several days each month becomes virtually diurnal. This effect does not extend into the system for any great distance, and the tides are semi-diurnal over the rest of the system at all times. The tidal range generally becomes progressively greater with distance from the entrance. Port Townsend has a diurnal range of eight feet while the inlets at the southern extremities have 15 ft.

The tidal currents in Puget Sound bear no constant relationship to the tide, either in velocity or time, though in general they increase with increasing tidal ranges. Normally a net outflow exists at the surface, and net inflow at depth. The greatest velocities occur in constricted channels, such as Admiralty Inlet, Tacoma Narrows, and Deception Pass, which have tropic velocities of 4.2, 5.1, and 7.2 knots respectively. The corresponding velocities in the deeper and wider channels are generally less than one knot.

Numerous rivers and small streams feed into Puget Sound from a drainage basin of about 11,300 mi^2, within which precipitation varies locally from 20 to over 100 inches per year. The 11 largest rivers, having a combined yearly runoff of about 40,000 ft^3/sec, account for about 80 pct of the total fresh water influx, the Skagit alone contributing about one-third. The times and magnitudes of peak flows of the rivers are governed by the major water sources. Lowland rivers peak during the winter from rainfall. Those rivers having mountainous areas as their principal watershed peak during the late spring from snow-melt. Others may have both peaks. Hydroelectric developments on some rivers tend to flatten the peaks and maintain a more uniform runoff. Discharges vary greatly, with flow at flood stages being as much as 150 to 200 times the minimum.

Description of model and equipment--The oceanographic characteristics of the area depend in part on the deepness of the waters, particularly in the basins, the strong turbulence over and the depth of the connecting sills, and the small effect of fresh-water runoff. In order to obtain the

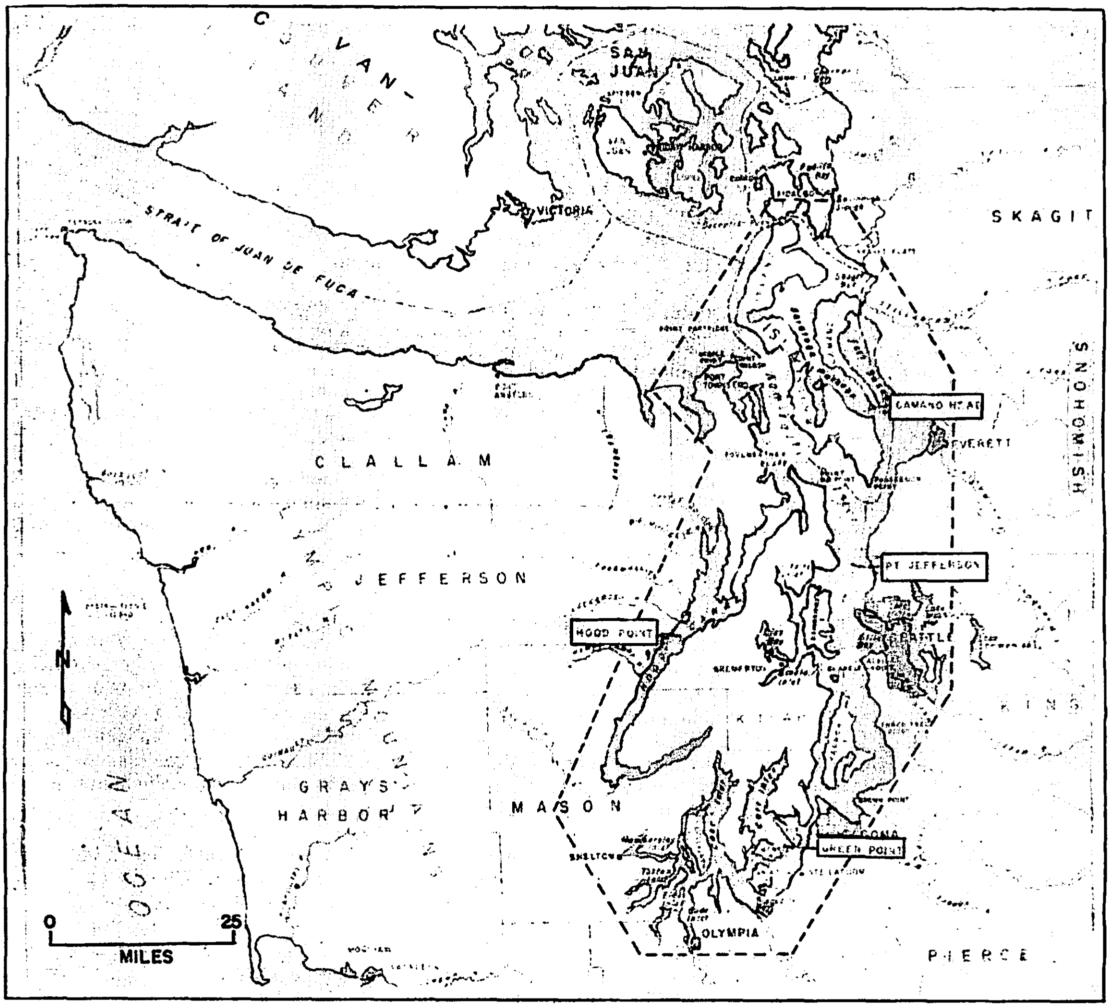


Fig. 1--Area included in Puget Sound model and locations of sampling stations

natural macroscale of turbulence the very rough bathymetry of the region was accurately reproduced by casting the model basin in concrete from accurately contoured hand-carved wood patterns. The model scales chosen are given in Table 1. Further details on model construction and equipment are given in previous reports [BARNES, LINCOLN, and RATTRAY, 1954; LINCOLN, PAQUETTE, and RATTRAY, 1954; PAQUETTE and LINCOLN, 1954].

Table 1--Model scales

Scale	Ratio	Prototype	Model
Horizontal	1/40,000	1 nautical mile 1 mile (statute)	1.82 inches 1.58 inches
Vertical	1/1152	1 foot	0.0104 inch
Velocity	1/34	1 knot	0.60 inch/sec
Time	1/1178	1 hour	3.055 sec
Flow	$1/1.56 \times 10^9$	1000 ft^3/sec	0.067 $inch^3$/min
Salinity	1/2	32 °/oo	16 °/oo

The tide-generating machine is of the Kelvin type employing Scotch yokes and a summation wire which controls the motion of a displacement box. The six constituents included in the machine give a tide within ±1 ft of the predicted prototype tide. They are the diurnal K_1, O_1, and P_1 and the semi-diurnal M_2, S_2, and N_2. In addition, repeating tides can be set up so that any desired daily cycle continuously recurs.

Fresh water is introduced through the 11 major rivers of the system from a constant-head tank. The rates of flow, measured by individual expanding bed type flow meters, are controlled manually. Salt water is continuously circulated between the head box and a salt water reservoir maintained at constant temperature and salinity. A change in ocean or source salinity is accomplished by adjusting the salinity of the reservoir.

The tide heights are recorded with a precision of ±0.002 inch over a range of 0.2 inch by means of a portable gage. Currents are measured photographically from the spacing and position of small vortex rings of dye injected in the desired location at one-second intervals. The salinity is determined to within one per cent by a probing conductivity cell. A permanent conductivity versus depth record is obtained photographically from an oscilloscope trace.

Tide and current--The tidal behavior of the model has been investigated and found to be satisfactory without the use of any artificial roughening. The phase and amplitude changes between Port Townsend and key locations within the Sound were determined for four individual tidal constituents and compared with corresponding values for the prototype (Table 2). Within the main basin, the time lag error was about six minutes (0.3 sec model time) greater than the values of the U. S. Coast and Geodetic Survey. Amplitude ratios agreed with ten per cent. Beyond the constrictions of the Tacoma Narrows and those leading to Bremerton, the deviations were approximately double these values.

Table 2--Comparison of model and prototype tidal behavior

Location	M_2 constituent				S_2 constituent			
	Model		Prototype		Model		Prototype	
	Amplitude ratio	Phase difference degrees	Amplitude ratio	Phase difference degrees	Amplitude ratio	Phase difference degrees	Amplitude ratio	Phase difference degrees
Port Townsend	1.0	0	1.00	0	1.0	0	1.00	0
Seattle	1.4	21	1.57	21	1.7	26	1.57	23
Tacoma	1.5	21	1.68	21	1.8	26	1.66	24
Olympia	2.0	49	2.14	39	2.4	51	2.09	48
Bremerton	1.4	36	1.61	27	1.7	39	1.53	27

Location	K_1 constituent				O_1 constituent			
	Model		Prototype		Model		Prototype	
	Amplitude ratio	Phase difference degrees	Amplitude ratio	Phase difference degrees	Amplitude ratio	Phase difference degrees	Amplitude ratio	Phase difference degrees
Port Townsend	1.0	0	1.00	0	1.0	0	1.00	0
Seattle	1.1	8	1.08	7	1.1	7	1.03	6
Tacoma	1.1	8	1.09	6	1.1	6	1.04	5
Olympia	1.3	16	1.15	16	1.2	14	1.08	14
Bremerton	1.1	14	1.07	11	1.1	10	1.02	9

A marigram of the six constituents for the first half of 1951 at Seattle was drawn by means of the tide machine, using the U. S. Coast and Geodetic Survey constants. The model tides at Seattle for the same period, generated by the tide machine adjusted to produce the correct tides at Port Townsend, were recorded. Portions of the recorded tides were compared with corresponding portions of the prepared marigram and with the tide table predictions (Fig. 2). The average deviation of the recorded tidal heights from the marigram was less than ±0.5 ft. Measurement of the deviation in time lag was not obtained.

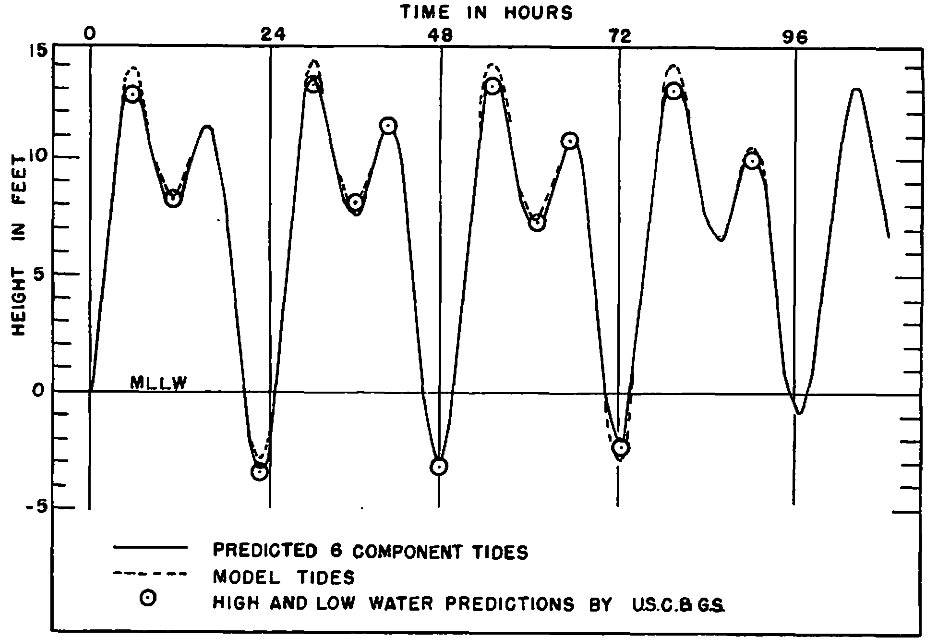


Fig. 2--Comparison of prototype and model tides of Puget Sound, based on six components and corresponding heights of high and low water taken from the U. S. Coast and Geodetic Survey Tide Tables

Horizontal current patterns, investigated by dye movements, are found to be similar to those occurring in nature. Dye has also been used to demonstrate a net inflow from the Strait of Juan de Fuca at depth with a return outflow in the surface layers. Quantitative comparisons of net flow between model and prototype have not been possible because of the difficulty in obtaining adequate field measurements and of correcting for effects of wind and variations in runoff. However, current harmonic constants for the surface layers off Bush Point were compared to those given by the U. S. Coast and Geodetic Survey. The measurements were made during a repeating tide continuously recorded at model Seattle. The ratios of the semi-diurnal current to tide amplitude in model and prototype are respectively 0.58 knot/ft and 0.51 knot/ft. The corresponding phase differences are 63° and 73°. For the diurnal tide the results are 0.25 knot/ft and 0.28 knot/ft respectively for model and prototype with phase differences of 85° in both cases. These results are in excellent agreement considering the different measurement techniques used and the relatively large contribution of the higher harmonics to the current.

Density structure--In the past, most tidal model studies have been concerned with silting in an estuary or harbor rather than the processes involved in and resulting from a variable density structure. Little work on the dynamics of a heterogeneous system resulting from the interchange of oceanic water and river discharge in tidal models has been reported in the literature, and the theoretical requirements for similitude in this respect are not well resolved. It is therefore important to establish the relationship between density structure in the model and the factors by which it is controlled. The density structure in each of the four main sections of Puget Sound was typified by salinity measurements at models Point Jefferson, Camano Head, Green Point, and Hood Point (Fig. 1), under controlled conditions of tide, river runoff, temperature, and source salinity. Repeating tides with average range and diurnal inequality were used throughout these studies. The results of measurements are expressed as prototype values.

The equilibrium salinity structure under conditions of mean river flow is shown in Figure 3 by the curves labeled 'start.' In general, there is a fresher surface layer with sharp gradients to a depth of 30 to 60 ft, below which there is a practically homogeneous, more saline layer extending to the bottom. At first, it might appear that the homogeneous bottom layers were due to a lack of mixing of fresh water down from the surface, but that this is not the case is shown when the salinity of this bottom water is compared with that of the source water. At Point Jefferson and Camano

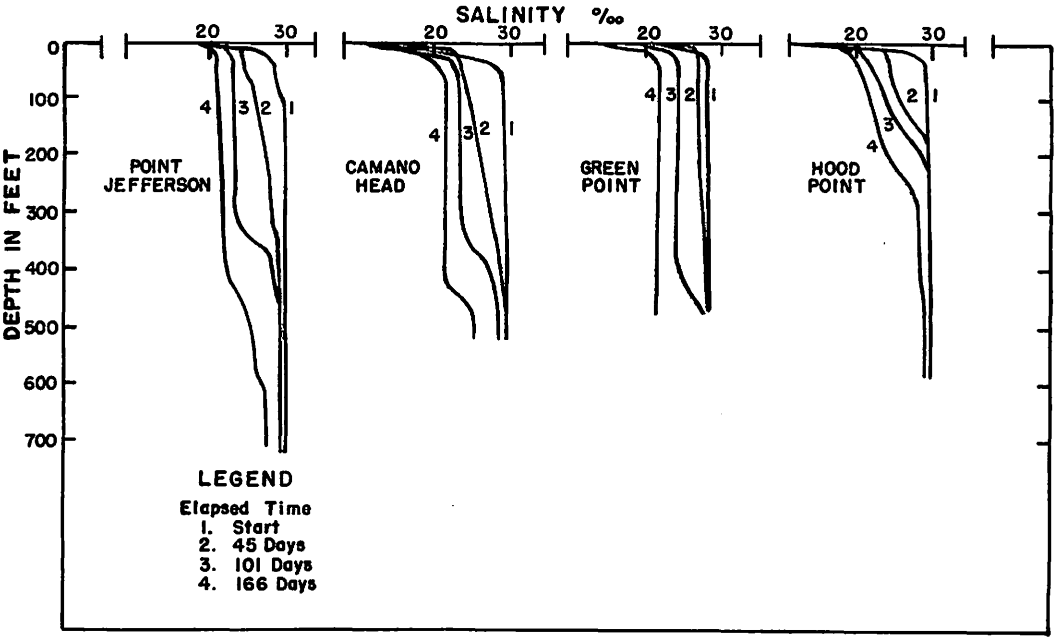


Fig. 3--Change in salinity structure resulting from decrease in source salinity

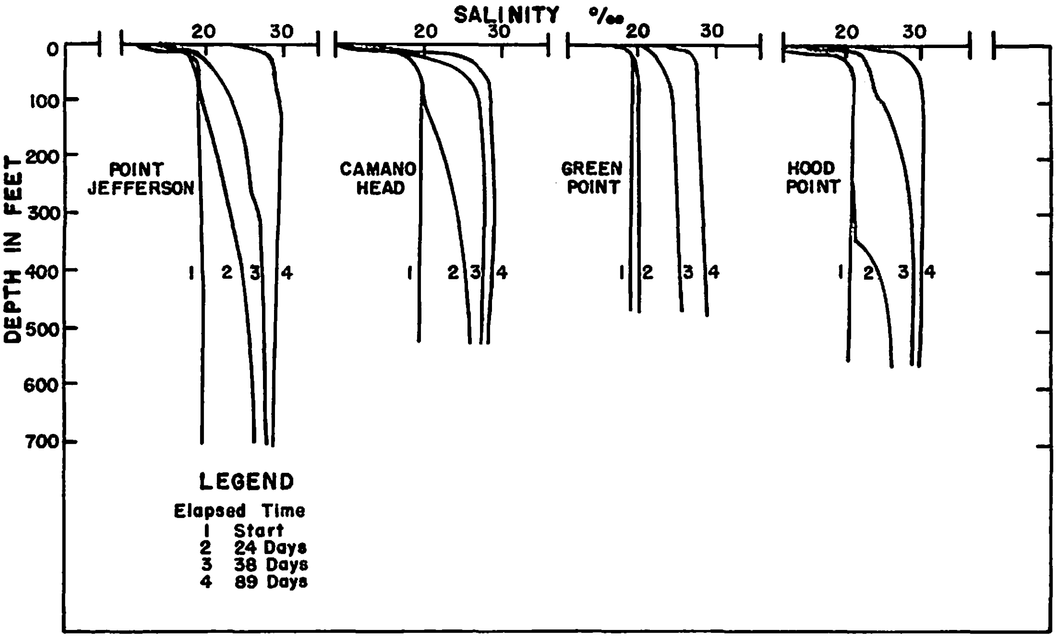
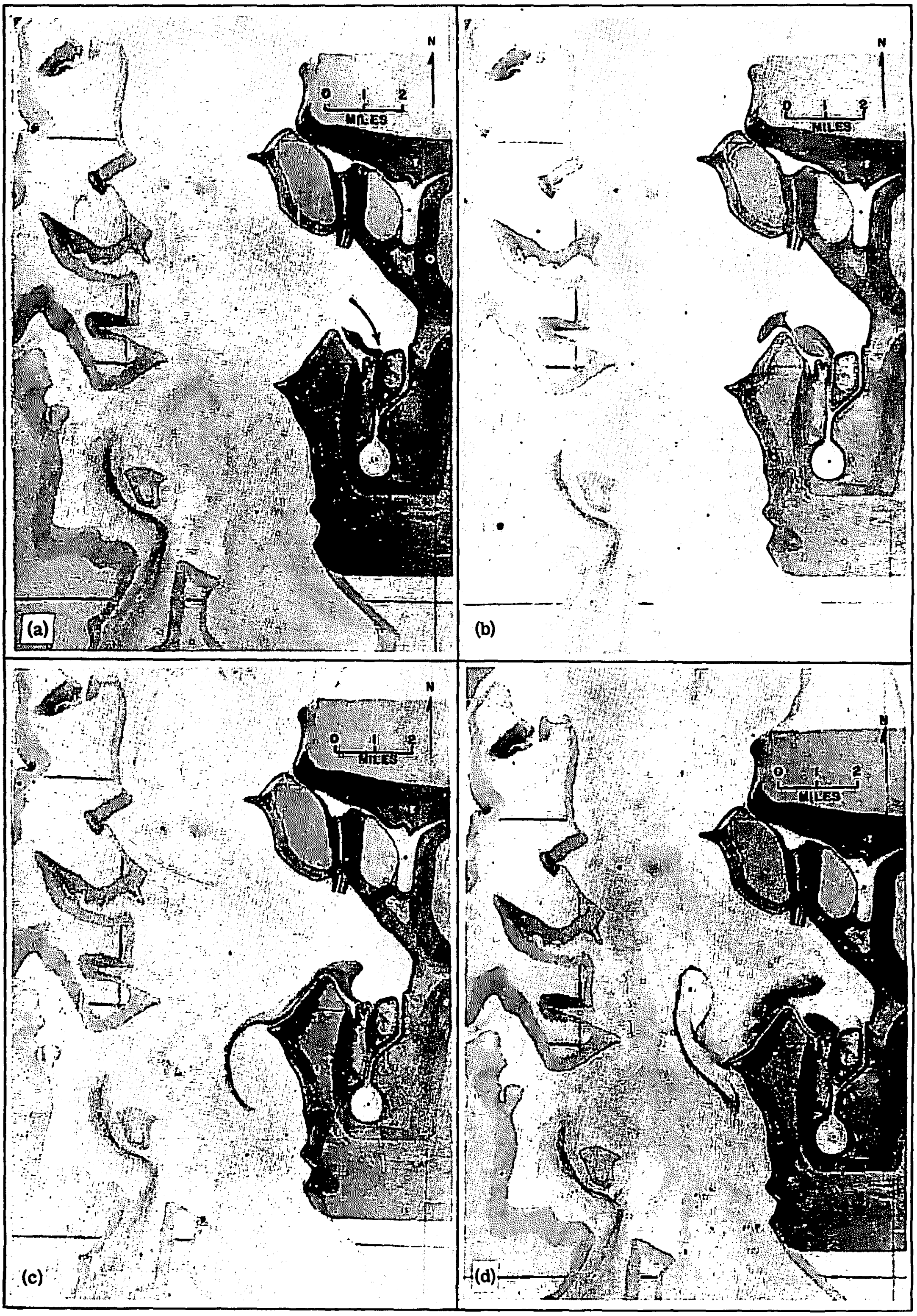


Fig. 4--Change in salinity structure resulting from increase in source salinity

Head the bottom salinities are about 1 ^{o}/oo less than the source, while for Green Point the difference is about 1.5 ^{o}/oo. These differences compare favorably with those found in nature. The mixing in the lower layers must, therefore, be sufficient to destroy any initial gradients in this case. The upper layers have the following features which correspond to those in nature: the layer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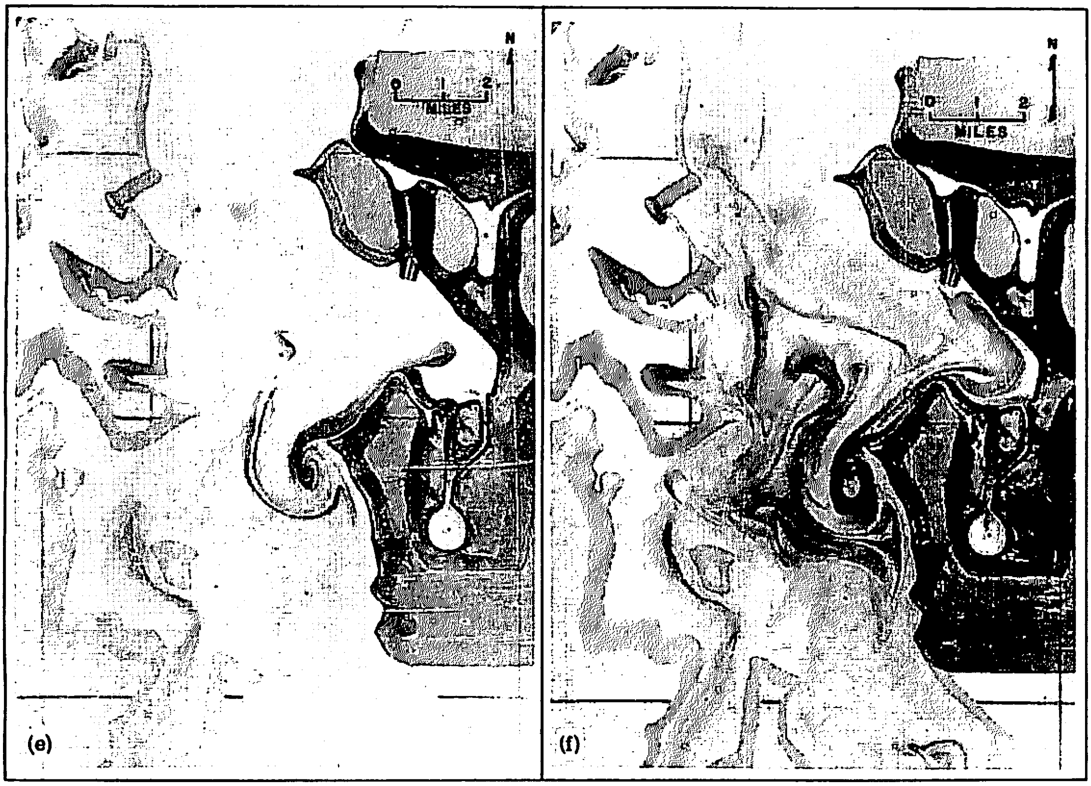

Fig. 5--Dye studies; Duwamish River (see arrow, Fig. 1a) and main basin;
(a) lower high water 10.0 ft, 18.6 hr; (b) lower low water 0.0 ft, 24.8 hr;
(c) lower high water 11.5 ft, 31.0 hr; (d) higher low water 6.0 ft, 37.2 hr;
(e) lower high water 10.0 ft, 43.4 hr; (f) lower high water 10.0 ft, 93.0 hr

depths are within the proper range, and the minimum surface salinity occurs at Camano Head while the surface salinity south of the Narrows is relatively very little less than that in the lower layers. However, under the above conditions, the surface salinities throughout are appreciably less than those found in nature.

A change in river flow causes a noticeable change in the salinity of the model bottom layer within six months south of the Narrows only. Here a salinity change is evident within two weeks for a decrease or two months for an increase in runoff. This is attributed to a combination of several factors: the large tidal exchange, the strong mixing which occurs in that region, and the fact that the source waters are mostly the upper waters of the main basin. At Point Jefferson the salinity of the upper 150 ft reflects the change in salinity of the bottom water south of the Narrows, indicating the Narrows as the source. In all cases, with increase of river flow the upper layer salinity decreases although the relative dilution is less thanthe relative increase in flow. The depth of the upper layer, however, changes very little with change in flow.

The effect of a change in source salinity was demonstrated by a sudden salinity decrease of 10 $^{o}/oo$ maintained for 166 days and then a return to the original value.

The effect of decreasing the source salinity (Fig. 3) was first noticed at Point Jefferson. A uniform gradient to a model depth of 300 ft developed within 45 days. Subsequent mixing of these waters for a 101-day period produced a homogeneous salinity to this depth, with a sharp interface separating it from the more saline and little affected bottom water. Mixing for a longer period gradually lowered the interface. As would be expected from their proximity and the lack of sill between Camano Head and Point Jefferson, the sequence of events was very similar for the two stations. At Green Point the salinity decrease was later at the surface, but when it did occur it was felt almost to the very bottom. After 166 days the salinity was homogeneous in the bottom

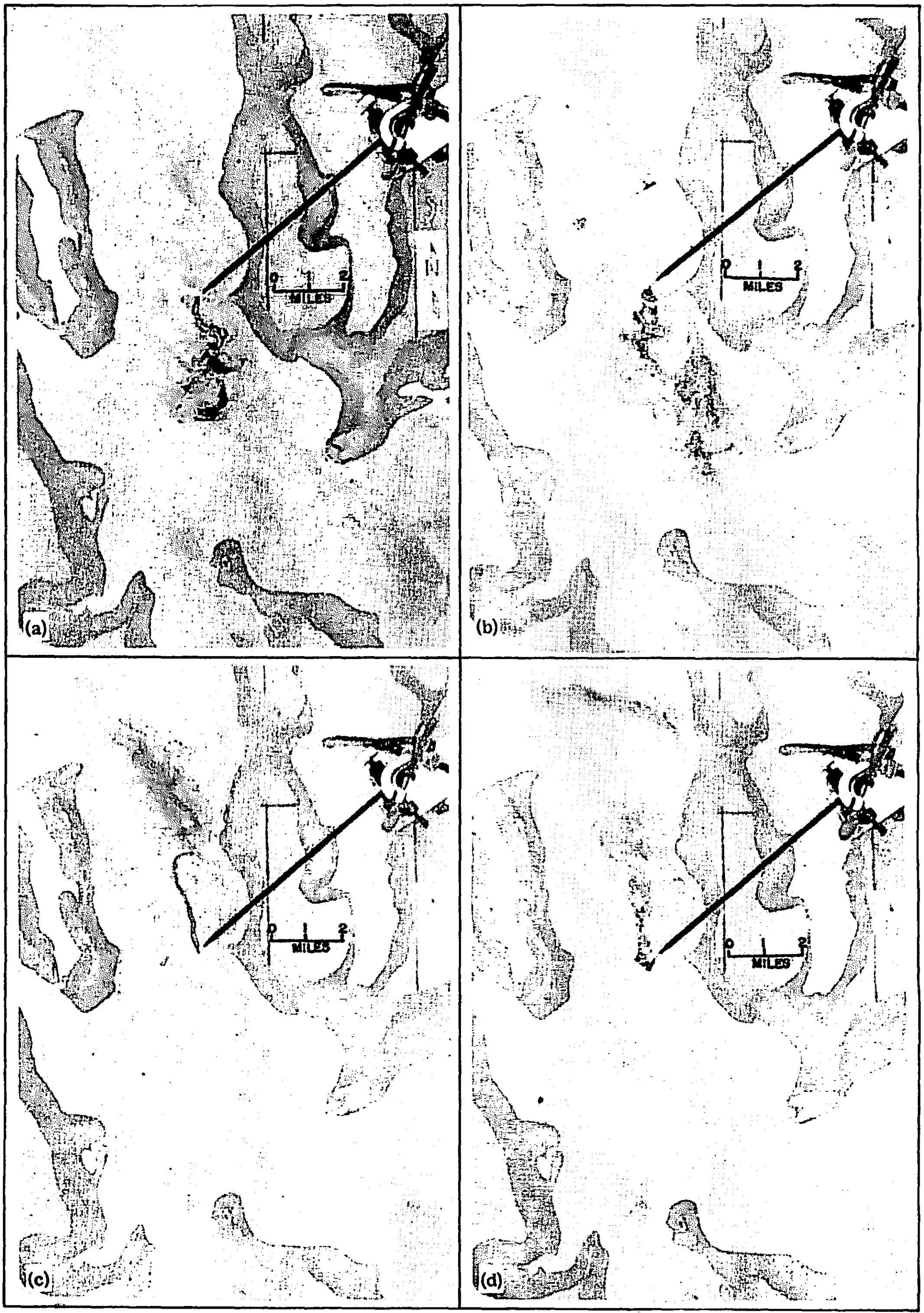

Fig. 6--Dye studies; threshold sill at Admiralty Inlet; (a) 0.7-knot flood; (b) lower high water 10.0 ft; (c) 2.8-knot ebb; (d) lower low water 0.0 ft

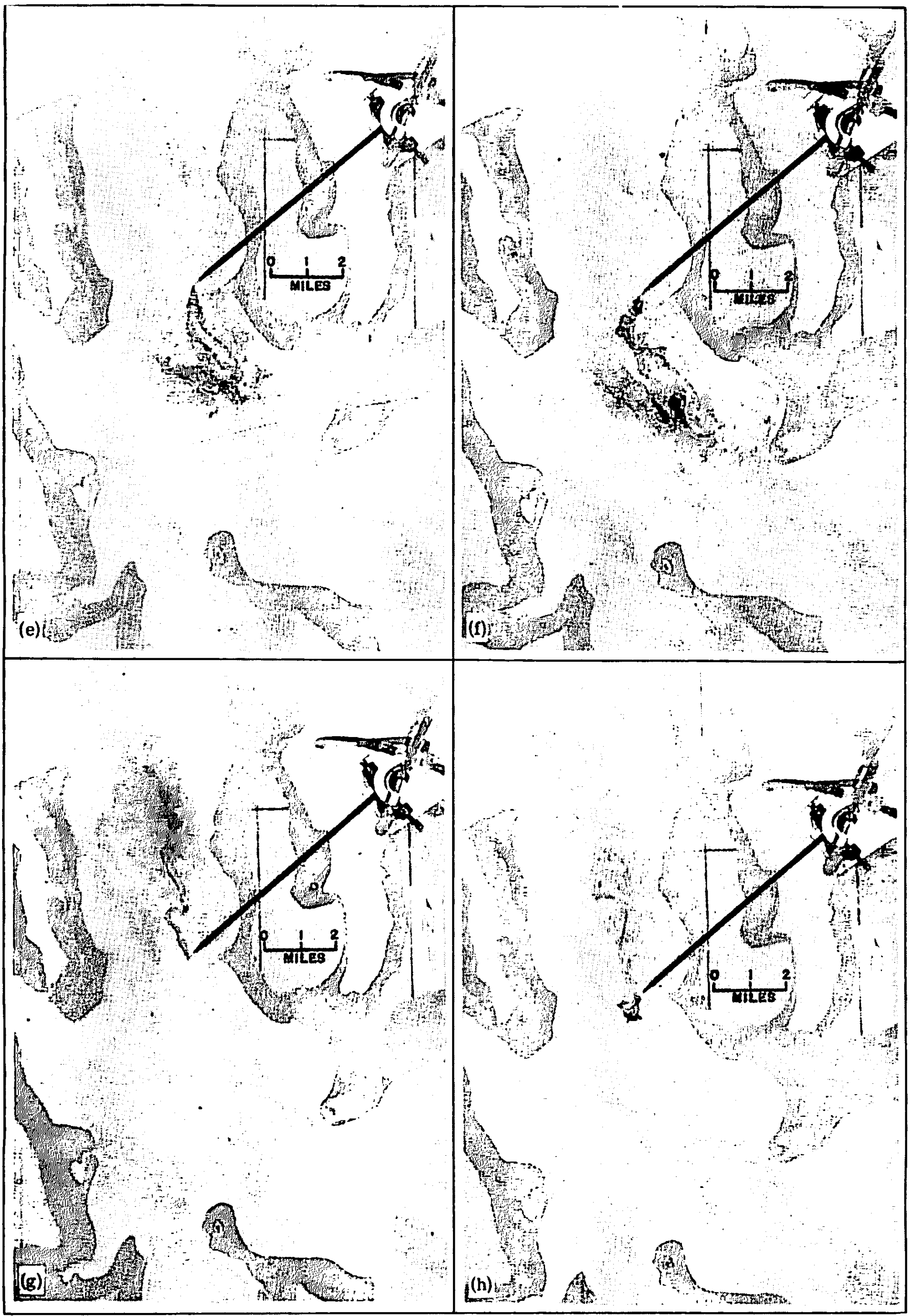

Fig. 6--Dye studies; threshold sill at Admiralty Inlet; (e) 0.7-knot flood; (f) lower high water 10.0 ft; (g) 2.8-knot ebb; (h) lower low water 0.0 ft

layer. At Hood Point, the fresher water was noticed only to a depth of 150 ft after 45 days, and to about 210 ft after 166 days, with very little change in the salinity of the bottom waters. Correspondingly, in nature the bottom water in Hood Canal has a tendency to stagnate.

An increase in source salinity produces a series of gradients markedly different from those described above in both shape and rate of change (Fig. 4). Within 24 days there was a considerable increase in salinity of the bottom water at Point Jefferson with the appearance of an almost constant gradient between the depths of 90 and 450 ft. After 38 days the surface gradient was increased to a depth of 150 ft and decreased below that depth. This pattern continued until equilibrium conditions were reached after 89 days. At Camano Head, the salinity structure went through the same sequence, although the mixing appeared to be faster between 35 and 115 ft. At Green Point the increase in salinity was small for the first 24 days; thereafter, a marked increase of salinity occurred at all levels without appreciable gradients below the surface layer. At Hood Point the heavier water appeared to flow into a bottom layer below 300 ft before there was any effect above that level. After 38 days, however, there was more saline water at all depths with a relatively uniform gradient existing between 30 and 240 ft. At this time the salinity below 300 ft had practically attained its maximum value. Equilibrium conditions were closely approached by the end of 89 days.

It is evident from these results that, with the exception of Green Point, significant salinity gradients appear in the model at depths other than the surface for appreciable lengths of times following a change in source salinity, whereas a change in river runoff has only a minor and local effect. Qualitatively these results are borne out in the prototype. Characteristically, the Puget Sound basins flush most rapidly in the fall when the Strait of Juan de Fuca water, the salinity source, is at its greatest annual density and not during periods of maximum local runoff. There is little or no correlation between the mean salinity in the lower layers of the Sound and the amount of fresh water discharge.

Mixing and turbulence--Mixing and turbulence in the model have been investigated qualitatively by means of dye studies with repeating average tides. Two typical examples are presented illustrative of conditions within a basin and those over a sill. Wind and other non-scaled factors require interpretation for comparison with the prototype.

Commencing at lower low water, Congo-red dye solution was continuously injected one-half mile upstream from the model mouth of the West Waterway of the Duwamish River and its movement followed photographically (Fig. 5). After 18.6 hr, at lower high water, the dye has progressed about a mile past the mouth in a northwesterly direction. The dye comes out of the river mouth in the form of a jet on the ebb tide, and then on the flood it is pushed toward the west. At the following lower low water, a second cloud of dye can be seen off the river mouth, while the first has now mainly rounded the point to move in a southwesterly direction. Some of the latter, however, has gone in the opposite or northeasterly direction. During the succeeding flood, the rate of southwesterly flow increases past Alki Point, the western land extremity, where it takes part in a gyre or back eddy set up behind the point. Some additional movement is also noticed in the northeast direction. Since leaving the river, the dye has maintained its identity with little mixing. However, by the next higher low water, the horizontal mixing caused by Alki Point is evident. After the flood, the pattern of mixing in the back eddy is shown more clearly. The line of dye is wound around itself in eddies formed by the current flow past the point. After a total of 93.0 hr this mechanism has spread the major portion of the dye throughout a region about five miles square. A few wisps of dye are evident both to the north and south. The action shown around Alki Point illustrates the primary mechanism of mixing of the surface water in the basins of the Puget Sound model. It is mostly horizontal with only small vertical components.

At Admiralty Inlet the turbulence is so strong that injected dye is rapidly spread throughout the whole area preventing later dye movements from being readily observed. It was therefore necessary to use a starch-iodine solution adjusted to fade at an appropriate rate. The colored solution was introduced continuously at a position 3/4 mi west of Bush Point. Photographs of the dye patterns (Fig. 6) are presented for approximately the strengths of current and slack waters during two similar half tidal days. The similarity between (a) and (e), (b) and (f), (c) and (g), and (d) and (h) is striking, especially since their timing was not exact. Not only is the current pattern reproduced on successive tidal cycles, but also the turbulent pattern apparently repeats. The very rapid mixing which occurs in this region is then due to current fluctuations which are at least in large part predictable. Direct measurements in both model and prototype verify that these fluctuations are similar on consecutive days. On the other hand, the patterns are considerably different at different stages of the current cycle, indicating that the fluctuations are strongly dependent upon the mean tidal current. In contrast to the mixing in the surface layers of the basins, that over the sills is both horizontal and vertical and results in a dilution of the salt water that flows inward to the Sound. This process is one of the most important in controlling the circulation in the system.

Summary and conclusions--An oceanographic model of Puget Sound has been built and subjected to a number of tests to determine its operating characteristics. Results in the model are found to agree well with those in the prototype with the exception that the salinity of the surface layer is too low. This agreement can be attributed to the fact that the major turbulent mixing and friction effects in nature, which occur over the sills, are well reproduced in the model. Not only is the model flow turbulent here, but this turbulence is apparently initiated and controlled by the large scale roughness elements which are accurately modeled. The disagreement in the surface salinities indicates that they do not depend mainly on these factors. Most probably a proper wind effect will in part correct this discrepancy. It is planned to explore this possibility further. Other non-scalable factors such as surface tension and Coriolis force may act to limit the representation of the prototype by this model, but their effects have not been evaluated.

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