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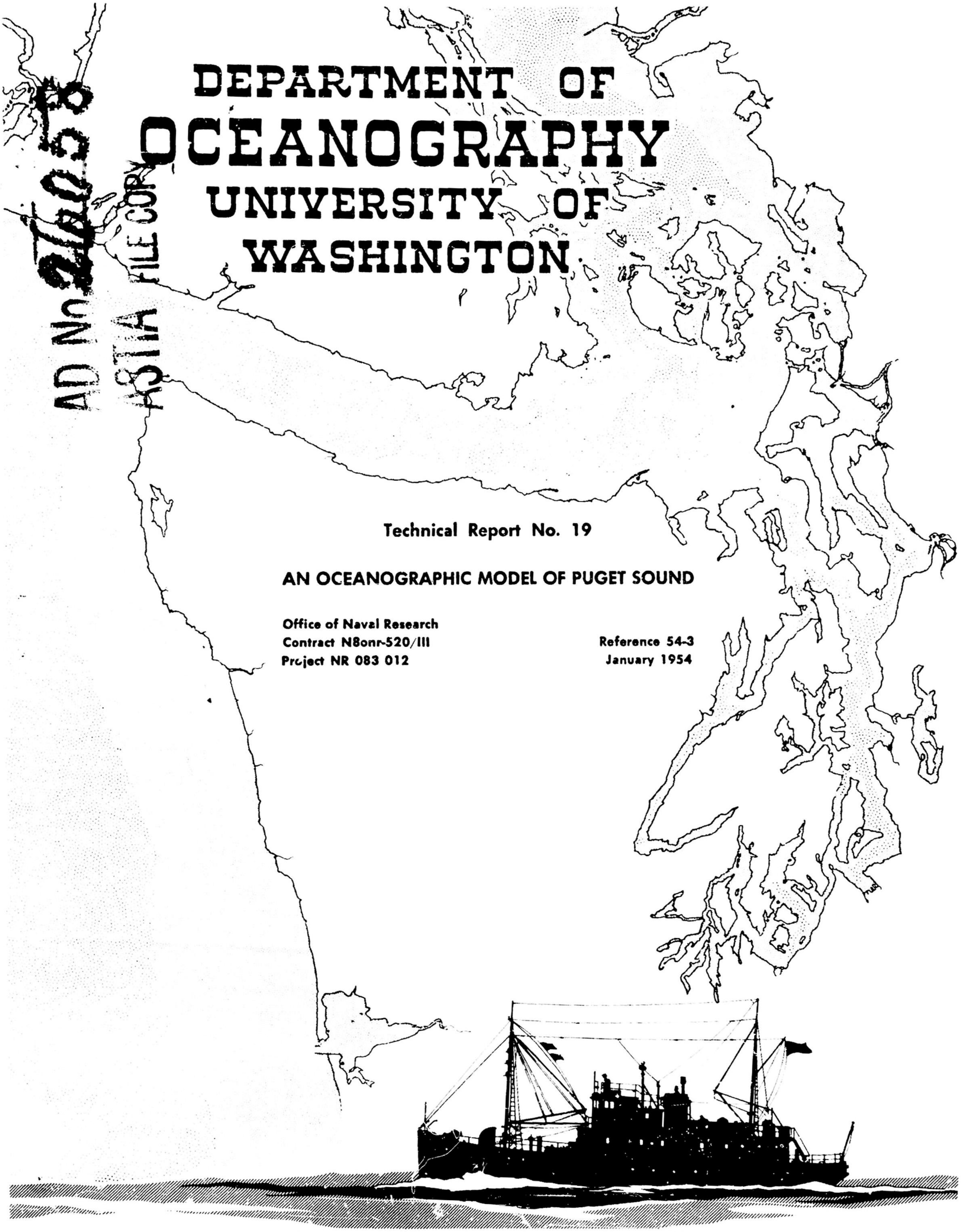

Technical Report No. 19

AN OCEANOGRAPHIC MODEL OF PUGET SOUND

Office of Naval Research
Contract N8onr-520/III
Project NR 083 012

Reference 54-3
January 1954

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UNIVERSITY OF WASHINGTON DEPARTMENT OF OCEANOGRAPHY
(Formerly Oceanographic Laboratories)
Seattle, Washington

AN OCEANOGRAPHIC MODEL OF PUGET SOUND

by

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INTRODUCTION

Oceanographic observations must be made in great numbers and extend over long periods, in many cases years, in order to obtain a relatively complete understanding of the conditions existing in even a small estuary or bay. Resolution of the mass of data to provide the desired information is further complicated by the fact that none can be obtained under controlled conditions. Data obtained at different times are not directly comparable, since the natural conditions never remain constant or precisely repeat. Thus, a synoptic picture of the oceanography of an area may be considered only in general terms at best, and as the size of the area is increased the generalities must of necessity become broader.

In treating an area as large and complex as Puget Sound, the problems of obtaining a complete understanding of the over-all oceanography, under either normal or extreme conditions, from field observations alone are almost insurmountable. In recent years, hydraulic models of tidal estuaries have been used in increasing numbers as a guide in interpreting the conditions within the prototype. It is recognized that it is impossible to construct a rigorous reduced-scale model of the prototype and that distortion and scale effects may easily lead to misinterpretation. Nevertheless, these small-scale models are useful in clarifying the nature of existing conditions and in planning more efficient field programs. Observations may be made under controlled conditions, and, of utmost importance, a particular set of conditions may be set up in the model and repeated at will until all pertinent information is collected.

DESCRIPTION OF THE AREA

Puget Sound (Figure 1) branches to the south from the eastern terminus of the Strait of Juan de Fuca, between the Olympic and Cascade Mountains of Washington. Its various arms, averaging less than 3 miles wide, have a total area of 767 square nautical miles at mean high water. The entire system lies within an area of about 40 by 90 nautical miles. It may be subdivided into four general sections which are partly isolated by vertical or lateral constrictions. The main basin extends south from a 40-fathom threshold sill at the confluence of Admiralty Inlet with the Strait of Juan de Fuca to a 26-fathom sill at the Tacoma Narrows. The section south of the Narrows consists of a 100-fathom primary basin with many branching channels and inlets. Hood Canal, averaging about 2 miles wide and having a depth of 100 fathoms, extends about 50 miles southwest from Admiralty Inlet and is partly separated from it by a 30-fathom sill. The fourth section extends north with diminishing depth from Possession Sound, about 25 miles from the entrance to Admiralty Inlet, through Skagit Bay to Deception Pass. This pass is a very restricted channel about 150 yards wide and 16 fathoms in depth, connecting with the Strait of Juan de Fuca. Puget Sound is relatively deep in comparison with other inshore waters of the United States, with a maximum depth of 155 fathoms and with 50 per cent of its total volume lying below 25 fathoms.

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 for several days each month becomes virtually diurnal. This effect does not extend into the system for any great distance, and the tides are semidiurnal over the rest of the system at all times. The tidal range generally becomes progressively greater with distance landward from the entrance. Port Townsend has a diurnal range of 8 feet while the inlets at the southern extremities have 15 feet. The rate of progression of the tidal wave into the Sound is altered by the topographic characteristics, particularly at the Tacoma Narrows, and changes with the character of the mixed tides.

The tidal currents also are subject to wide local variations and are dependent upon the tide range. The maximum velocities occur in constricted channel entrances and may reach about 7 knots. The tidal prism in Puget Sound amounts to about 5 per cent of the volume below mean lower low water.

Numerous rivers and small streams feed into Puget Sound from a drainage basin of about 11,300 square miles, within which precipitation varies locally from 20 to over 100 inches per year. The eleven largest rivers, having a combined mean yearly runoff of about 40,000 cubic feet per second, account for about 80 per cent of the total fresh-water influx, the Skagit alone contributing about one-third. The peaking characteristics 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. Discharge varies greatly, with flood stages being as much as 150 to 200 times the minimum flow.

The population of the area is over 1.5 million, the principal seaboard cities being Seattle, Tacoma, Bremerton, Port Townsend, Everett, Olympia, and Shelton. Virtually all sewage from the municipal systems is discharged untreated into the Sound. While industrialization of the area is not heavy, some industries, particularly those manufacturing pulp and paper, are potential pollution hazards because of the large volume and high oxygen demand of the wastes.

CONSTRUCTION OF THE MODEL

It is common practice to make tidal models as large as is consistent with space and facilities available and cost. The horizontal scale is ordinarily determined by these empirical factors. The vertical scale is governed by the practical requirements for suitable time scale and water depth in critical areas and by the theories of dynamic and kinematic similitude. Space available limited the present model to a horizontal scale of 1 : 40,000. The vertical scale selected was 1 : 1,152 or 1/16 inch per fathom, giving a distortion of 34.6 : 1.

With these scales, the model is approximately 7 feet by 15 feet and has a maximum water depth of 10 inches with 1 1/2 to 2 inches over the critical sills. As a consequence of the distortion, some channels are deeper than they are wide. The time scale from the Froude modeling law is 1 : 1,178 or 3.05 seconds per hour, permitting a year's tides to be observed in 7.4 hours. With this choice of scales, the Reynold's number in the model will be in the turbulent region over the critical sills for most of the tidal cycle. That the motion is actually turbulent is easily verified by inserting dye into the model and watching its rapid diffusion. The appropriate criterion for turbulence in a fluid with stable stratification is given by the Richardson number $\frac{g\, d\rho/dz}{\rho\,(du/dz)^2}$. With Froude modeling, the salinity scale must be unity to give the same Richardson number in model and prototype. With a reduced salinity scale, the mixing in the model could be expected to be increased.

The customary method of constructing model basins consists of moulding the contours to conform to templates fixed in position within the model area. This technique was found unsatisfactory for reproducing the fine detailing of contours required by the small scale and the complex system of narrow deep channels. A method was developed for casting the model basin in concrete from accurately-contoured hand-carved wood patterns. The contours used, established from the Hydrographic Charts of the area, were the elevations of mean high water, 75 feet, and 150 feet, and successive 10-fathom depth intervals below mean lower low water. The area was divided into 25 sections for convenience in preparing the patterns. The contours of each were transferred to white pine lumber planed to the thickness of the contour interval. The sections were then cut along the contour line and laminated in exact position. Excess wood was removed and the patterns brought to precise shape by careful hand-carving and sanding, with constant reference to the charts for soundings between the contour intervals. Small basins were provided upstream from the river mouths for introduction of the river discharge. The wood was brought to a very smooth surface, sealed and varnished (Figure 2).

The individual patterns were assembled in an inverted position upon a strongly supported platform 8 by 20 feet, constructed as a base for the model (Figure 3). Forms were built around the assembled patterns with sheet metal separators between the pattern sections to form easily handled blocks. Copper tubing was placed from the outside of the forms to the river basins to carry the fresh water. The patterns were oiled to prevent sticking to the concrete. When the steel reinforcing was placed, a coating of smooth cement grouting was applied to the patterns. The forms were then filled to a uniform depth of 15 inches with a standard quick-setting concrete. Twenty-four hours after the concrete was poured, the forms were removed and the blocks separated and inverted. The patterns were sprung out of the concrete by a method analogous to removing a tightly fitting stopper from a bottle.

The blocks were reassembled to form the model basin. A bitumastic compound was used to seal the joints between blocks. Surveying methods, combined with a latitude-longitude grid on the platform, afforded accurate positioning of the patterns and of the completed sections. The method used insured precise fitting together of the blocks. The joints between the blocks and the minor defects which occurred during the casting were smoothed with plaster of Paris. The basin was finished with several coats of a vinyl resin paint (Figure 4).

TIDE-GENERATING MACHINE

The requirements for the tide-generating machine were that it closely reproduce natural tides and that it be adaptable to any model of regional waters that might be constructed here. It was desired further that simple repeating tides could be set up and that a sequence of natural tides could be conveniently interrupted and repeated.

The tidal harmonic constants computed by the U. S. Coast and Geodetic Survey for Seattle and Port Townsend indicated that a minimum of six constituents would be required to reproduce prototype tides within a deviation of ± 1 foot. These, the diurnal K_1, O_1, and P_1, and the semidiurnal M_2, N_2, and S_2, were incorporated in the tide-generating machine using many principles of the Coast Survey's prediction machine. Identical gear ratios were used for corresponding constituents. A one-third horsepower motor was used to drive a line shaft through a 900 : 1 reduction box and spur gears at precisely one revolution in 12 solar hours, model time. Scotch yokes, driven from the line shaft by gear trains at speeds corresponding to the period of each constituent, generate cosine functions. These are fed into a summation wire connected through a suitable pulley and reduction drum arrangement (Figure 5) to a plunger located in the model headbox. The changing water displacement caused by the motion of the plunger, shaped to correct for the tidal prism, produces the rise and fall of the tides. Phase angles and amplitudes for any epoch or location are readily set for the different constituents on the calibrated cranks of the Scotch yokes. A supplementary chain drive is incorporated between the M_2 and K_1 constituents to provide a means of generating repeating tides of either diurnal, semidiurnal or mixed character.

RIVER SYSTEM AND SALT-WATER ADDITION

Provision is made for the introduction of fresh water through eleven major rivers of the area having a yearly mean discharge ranging from approximately 400 to 16,000 cubic feet per second. The water flows by gravity from a constant head tank, through individual flow meters of the expanding bed type, to small basins located a short distance upstream from the river mouths. The rate of flow of the rivers is controlled manually by means of individual needle valves. Loss of salt resulting from river runoff is balanced by a circulation system in the headbox. Water is removed from the headbox through a shaped standpipe and pumped into a reservoir having a capacity of about 125 liters. Salt solution is added to the water in the reservoir to maintain the desired density. A second pump returns the water from the reservoir to the headbox where it is introduced along the bottom at a rate exactly balancing that of removal. In this way the net surface outflow from Puget Sound and the balancing inflow of oceanic water at depth is simulated.

INSTRUMENTATION

The design and development of instruments for measuring and recording tides, tidal currents, and the density structure in the model is complicated by the small scales and distortion. The sensing elements must be such that they do not significantly alter the properties being measured or interfere with the operation of the model. Further, because of the short time scale, it is necessary to obtain measurements rapidly in order to adequately differentiate conditions during the tidal cycle.

A portable recording tide gauge and an instrument for recording the salinity or density structure in the model have been designed and constructed. The recording tide gauge will resolve the model tides to within about 3 inches, or 0.003 inch actual change in water level. The gauge is not affected by surface tension or factors other than change in the water level in the model. In principle it consists of an interconnected probe and recording arm operated by a synchronous motor. The probe alternately rises and lowers as the recording arm sweeps a stylus across electrosensitive paper being moved by a standard recording tape puller. As the probe, tipped by a fine platinum wire, contacts the surface of the water, an electrical circuit is completed which fires a thyrotron tube discharging a condenser. The charge from the condenser passes from the stylus through the paper to a second electrode consisting of a small roller extending across the underside of the paper. The discharge causes a small spark to burn a fine hole in the paper making a permanent black dot. The probe operates at a frequency of once per second.

The instrument for recording the salinity structure is based upon the conductivity of the water. The variations in the conductivity of a vertical section are electronically transposed to a plot of conductivity versus depth on an oscilloscope which may be photographed for a permanent record. The conductivity cell consists of a capillary 0.025 inch in diameter and 3/4 inch long, having electrodes at each end forming an integral part of the capillary. A maximum potential of about 50 volts at 10,000 cycles may be applied across the cell. Alternating current is used to reduce the effects of polarization of the electrodes. Water is drawn through the cell at a rate equivalent to the rate of displacement of water by the cell and tube to which it is attached, as it is lowered through the water. It has been found that measurements must be made while lowering the probe, since some mixing and turbulence occur when the probe is raised, leading to fictitious values. Response is fast because of the rapid flushing of the cell.

Probing rate and depth of sampling may be adjusted as desired, and operation is automatic. Camera operation is manual at present but may easily be adapted to automatic operation if desired.

CURRENT METER

Since the velocities and distances in the model are both very small compared to those in the prototype, it has proven impossible to use small-scale standard current measuring devices. The present method of current measurement consists of introducing small vortex rings of dye into the water at fixed time intervals and then to photograph their relative positions. This method has proven satisfactory and has the additional advantage of measuring both components of horizontal velocity simultaneously. The equipment consists of a glass capillary connected to a dye reservoir through a T-section. A rubber bulb, connected to the other junction, is tapped at 1-second intervals by a hammer driven by a synchronous motor to emit a vortex of dye from the capillary tip.

TIDE AND CURRENT STUDIES

A comparison of the tidal action in the model with that of the prototype was one of the first detailed studies undertaken as a part of the validation. The phase and amplitude changes between Port Townsend and key locations within the Sound were determined for each individual tidal constituent and compared with corresponding values for the prototype. Within the main basin, the time lag error was of the order of 6 minutes, or 0.3 second actual time greater than the Coast Survey values. Amplitude ratios agreed within 10 per cent. Beyond the constrictions of the Tacoma Narrows and those leading to Bremerton, the deviations were approximately double these values. A marigram of the six constituents for the first half of 1951 at Seattle was drawn by means of the tide machine, using the Coast Survey tidal 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 (Figure 6). The average deviation of the recorded tidal heights from the marigram was less than ± 0.5 foot. Measurement of the deviation in time lag was not obtained.

Quantitative measurement of the tidal currents and patterns of circulation have not been completed. Visual observations indicate that the model is giving good representation of prototype circulation, current patterns, and velocities, and the eddy patterns appear to follow quite well.

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 thus necessary to determine the effects and interrelationships of the variable parameters in a model before representation of the prototype may be achieved. A series of studies was initiated to investigate the density structure, as it is one of the major factors influencing the oceanography of Puget Sound. When the model structure under various conditions is known, it can be correlated with nature to establish any major differences and demonstrate possible corrective measures. For the purpose of this work, the salinity structure in each of the four main sections of Puget Sound was typified by measurements at Point Jefferson, Camano Head, Green Point, and Hood Point (Figure 7) under controlled conditions of tide, river runoff, and source salinity. (Repeating tides with an average range and diurnal inequality were used throughout this series of studies.)

In the first experiment, the equilibrium situation was obtained for mean river flow with a source salinity of 16 °/oo which, for the purpose of simplifying comparisons, has been related to a prototype salinity of 32 °/oo. The results (Figure 8) in general show a fresher surface layer with sharp gradients to a depth of 10 to 30 meters, 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 Head, the bottom salinity is about 1 °/oo less than the source, while for Green Point the difference is about 1.5 °/oo which compares favorably with the differences obtained in nature. It must be that the mixing in these lower layers is sufficient to destroy any initial gradient.

The influence of the fresh-water runoff on the salinity structure is best seen from the results of raising the flow of the Skagit River to the normal flood discharge rate of 50,000 cubic feet per second (Figure 8). After 1,000 consecutive days of flood, the effect of fresh water was noticed only to a depth of 80 meters at Point Jefferson, although the surface layer had definitely freshened and deepened. At Camano Head, on the other hand, the deep water had freshened somewhat with no perceptible change in the surface layers. Since the mechanism of these changes is not immediately clear, it will be a subject for further investigation. Off Green Point, the whole water column was freshened as would be expected since strong mixing occurs in that region and its water source is mainly the surface layers of the main basin. Thus, even under these extremely extended conditions of flood, a noticeable gradient can not be maintained beneath the surface layers, and another mechanism must be found to simulate the gradients which occur in nature.

Since in nature the source water of the Strait of Juan de Fuca does not hold a constant salinity throughout the year, the effects of a change in source salinity was investigated in the model. In order to make results clear-cut, a sudden decrease of salinity of 10 °/oo was maintained for 166 days and then increased back to its original value.

The decrease in source salinity (Figure 9) was first noticed at Point Jefferson. A uniform gradient to a depth of 100 meters 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 the proximity and 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 layer. At Hood Point, the fresher water was only noticed to a depth of 50 meters after 45 days, and only to about 70 meters 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 density gradients markedly different than above in both shape and rate of change (Figure 10). 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 30 and 150 meters. After 38 days, the surface gradient was increased to a depth of 50 meters 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 20 and 70 meters. 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 100 meters before there was any effect above that level. After 38 days, however, there was more saline water at all layers with a relatively uniform gradient existing between 10 and 80 meters. At this time, the salinity below 100 meters had practically attained its maximum value. Equilibrium conditions were closely approached by the end of 89 days.

It is seen from these results that, with the exception of Green Point, significant salinity gradients will appear at all depths for appreciable lengths of times following a change in source salinity;

whereas a change in river runoff will only have 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 of its greatest annual density and not during periods of maximum local runoff.

MODEL APPLICATIONS

The model has been operated with good success for groups of engineers interested in sewage disposal and pollution studies. The insertion of dye at present or proposed sewage outfalls gives a clear and rapid picture of the pollution likely to occur at various localities. The value of a tidal model for this type of study may readily be appreciated when the ease with which a particular mass or type of water may be "tagged" by a suitable dye is seen. The transport and rate of dispersion of the water mass may be observed directly and continuously followed over large areas for the equivalent of long periods in the prototype.

The model has proven useful in support of a fisheries-biology study concerned with the drift of fish eggs. The drift of dye in the model correlated with field observations clarified the movement of the eggs, location of the hatching areas, and distribution of the larvae. Continuous observations were made for a period representing many days in the prototype. Thus a detailed picture could be obtained from field observations which were somewhat scattered with respect to both location and time.

In planning field work, the model can be set to operate for the anticipated period of the cruise. The probable water structure and movement can be observed and locations selected for most efficiently collecting the desired information. In an area of mixed tides, a tidal model which can be set to duplicate tides for a specific calendar period is a distinct advantage.

The model has proven to be a valuable teaching aid. The processes occurring in nature over a large area are readily observable, and a clear synoptic picture of their interrelations is thus obtained. Examples of various features of inshore circulation can be pointed out and explained simply and easily. The student can use the model to obtain data corresponding to field measurements, and then work it up in the usual manner.

SUMMARY AND CONCLUSIONS

An hydraulic model of Puget Sound has been built and tested under various conditions. Equipment for controlling and measuring the oceanographic variables has been designed and put into satisfactory operation. Prototype tide and current are well represented by those in the model. It has been demonstrated that density structure similar to that in nature can be obtained by proper control of operating conditions, but no detailed comparison has been made between prototype and model structure under corresponding conditions.

ACKNOWLEDGMENT

The authors are indebted to Dr. Robert G. Paquette for his advice and assistance in the construction of the electronic and mechanical devices used with the model. Messrs. Donald J. Farmer, C. C. Andrew, James S. Tallman, L. J. Istas and J. C. McKernan have contributed materially in the various stages of the construction and instrumentation.

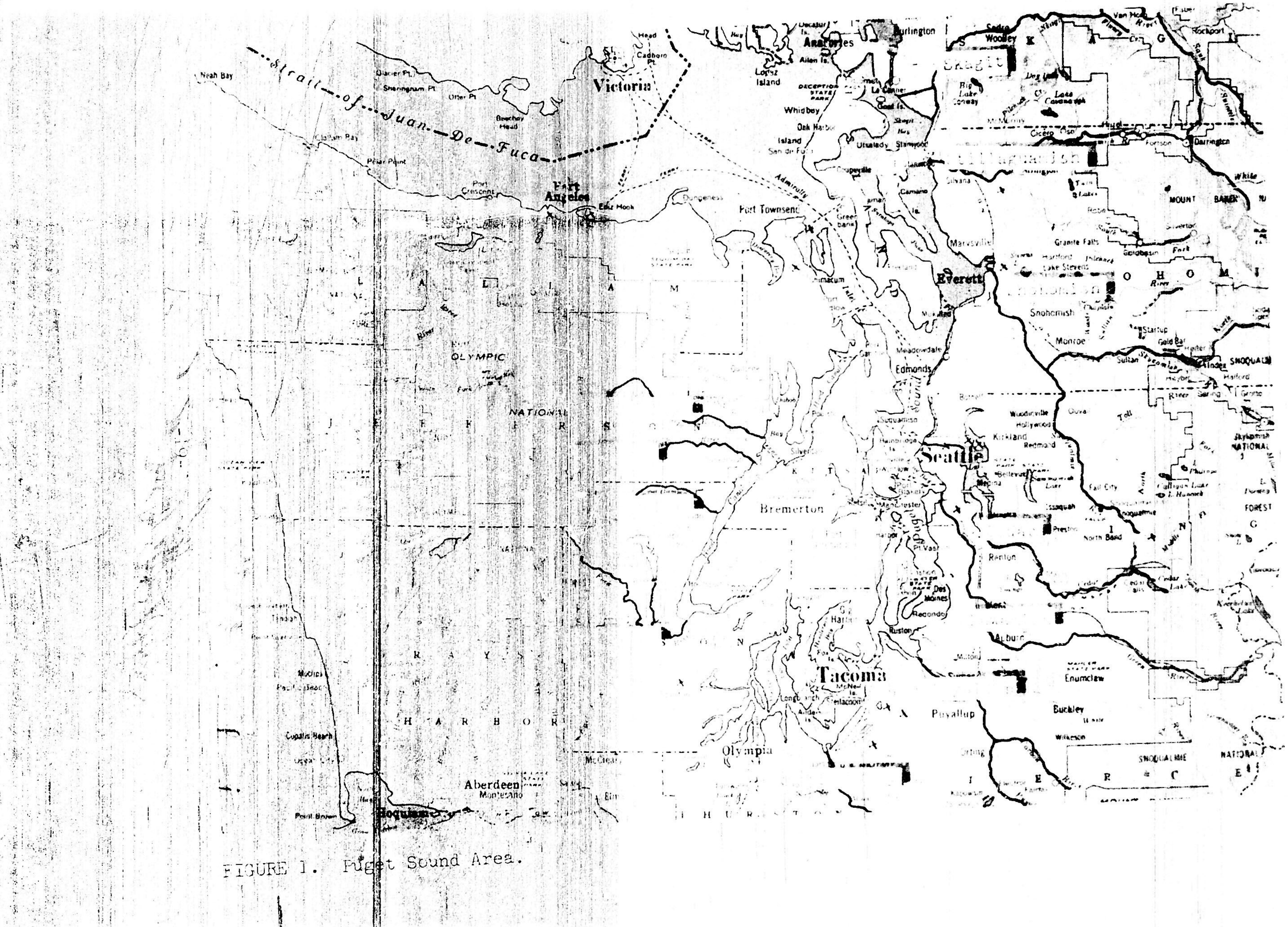
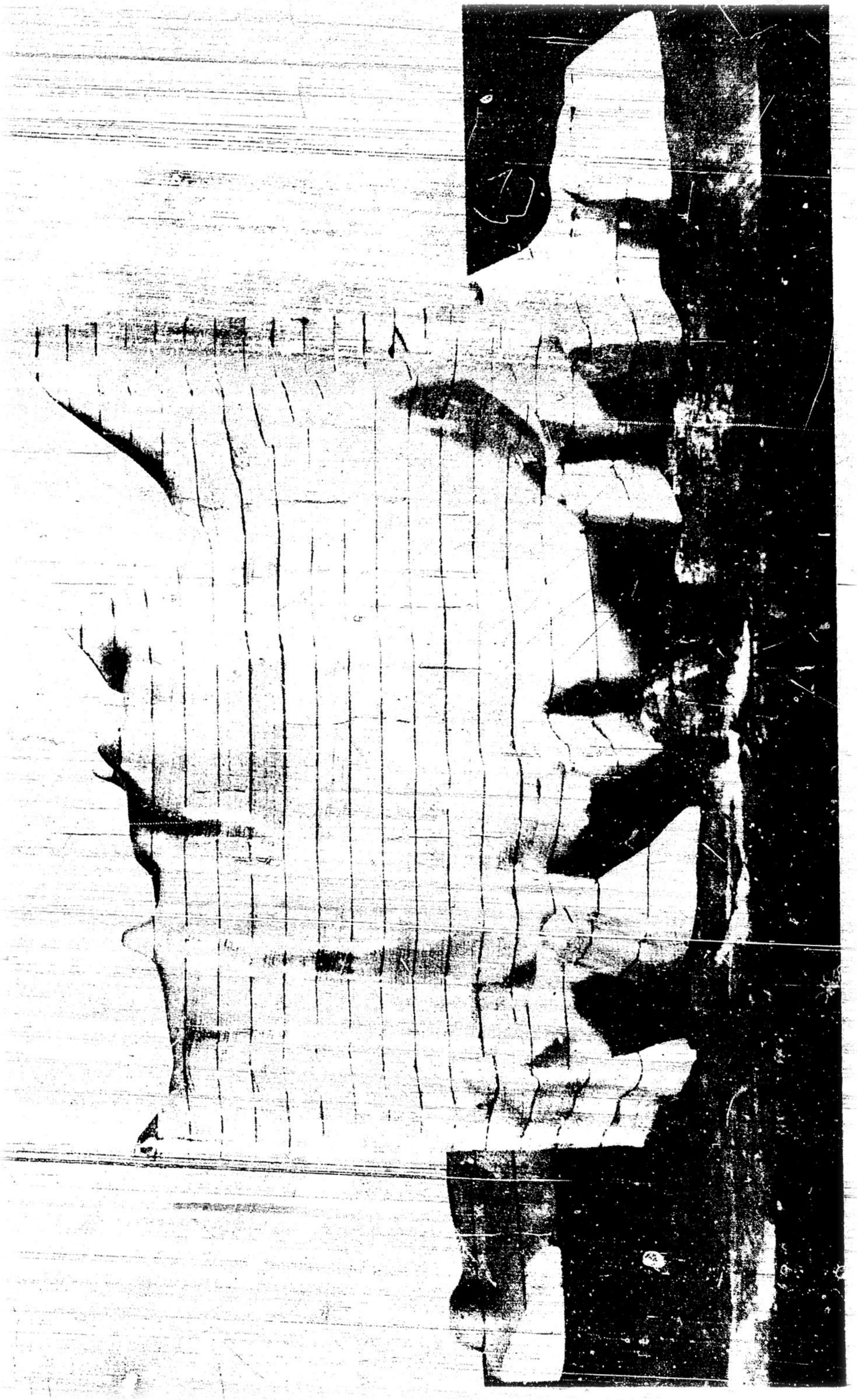


FIGURE 1. Puget Sound Area.



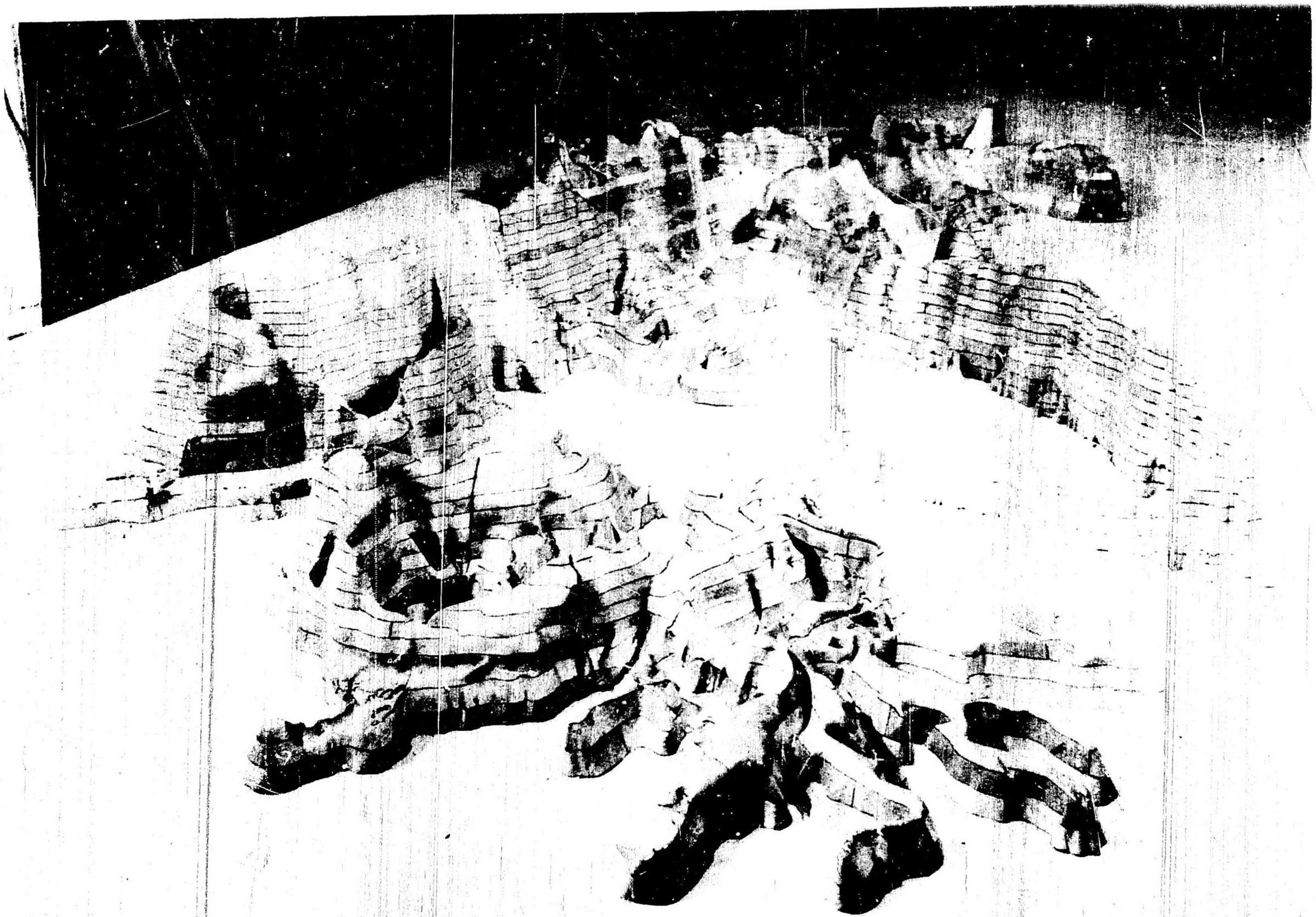
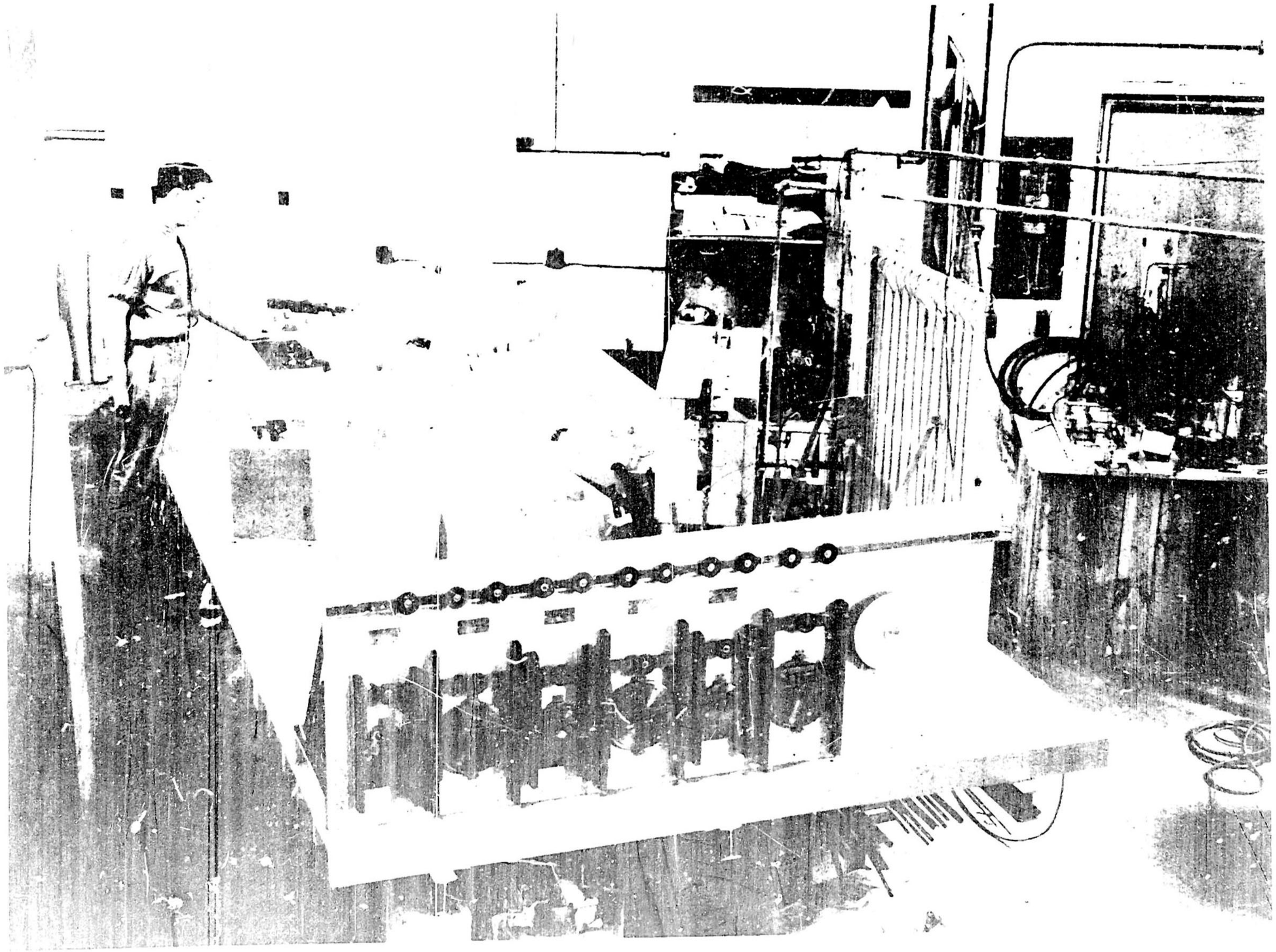


FIGURE 5. Assembled patterns.



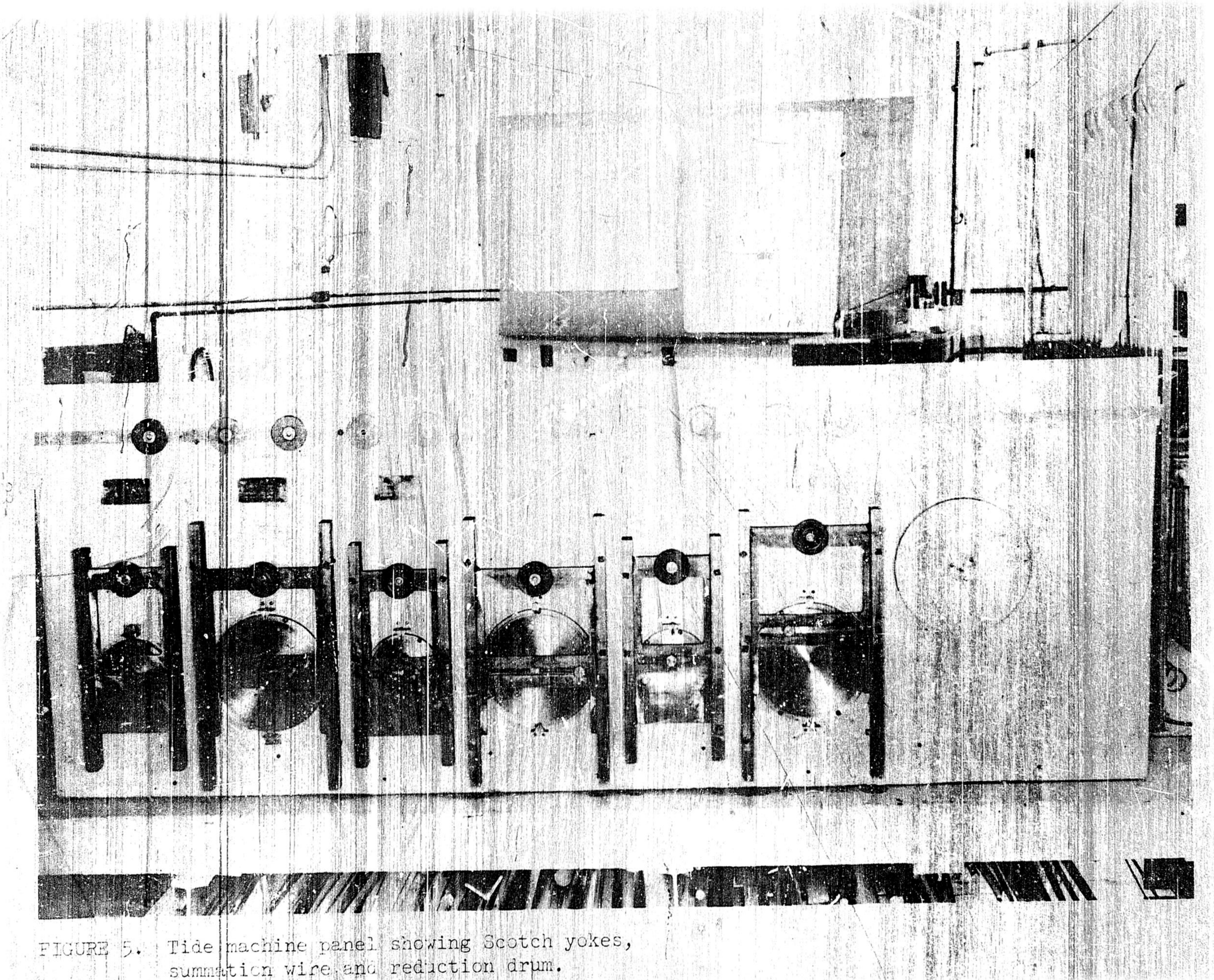


FIGURE 5. Tide machine panel showing Scotch yokes, summation wire and reduction drum.

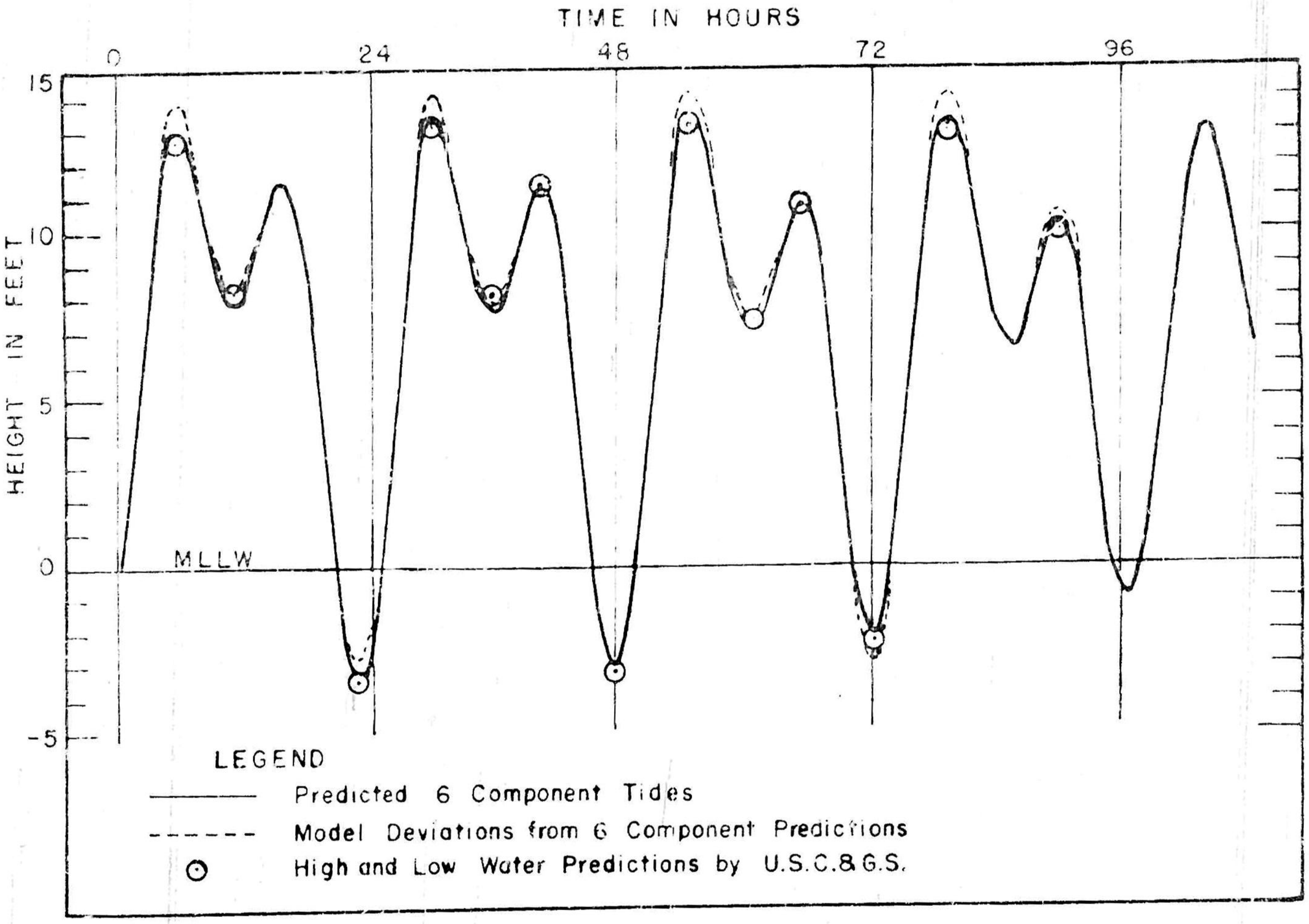


FIGURE 6. Comparison of prototype and model tides of Puget Sound, based on six components and corresponding heights of high and low water taken from the U. S. C. & G. S. Tide Tables.

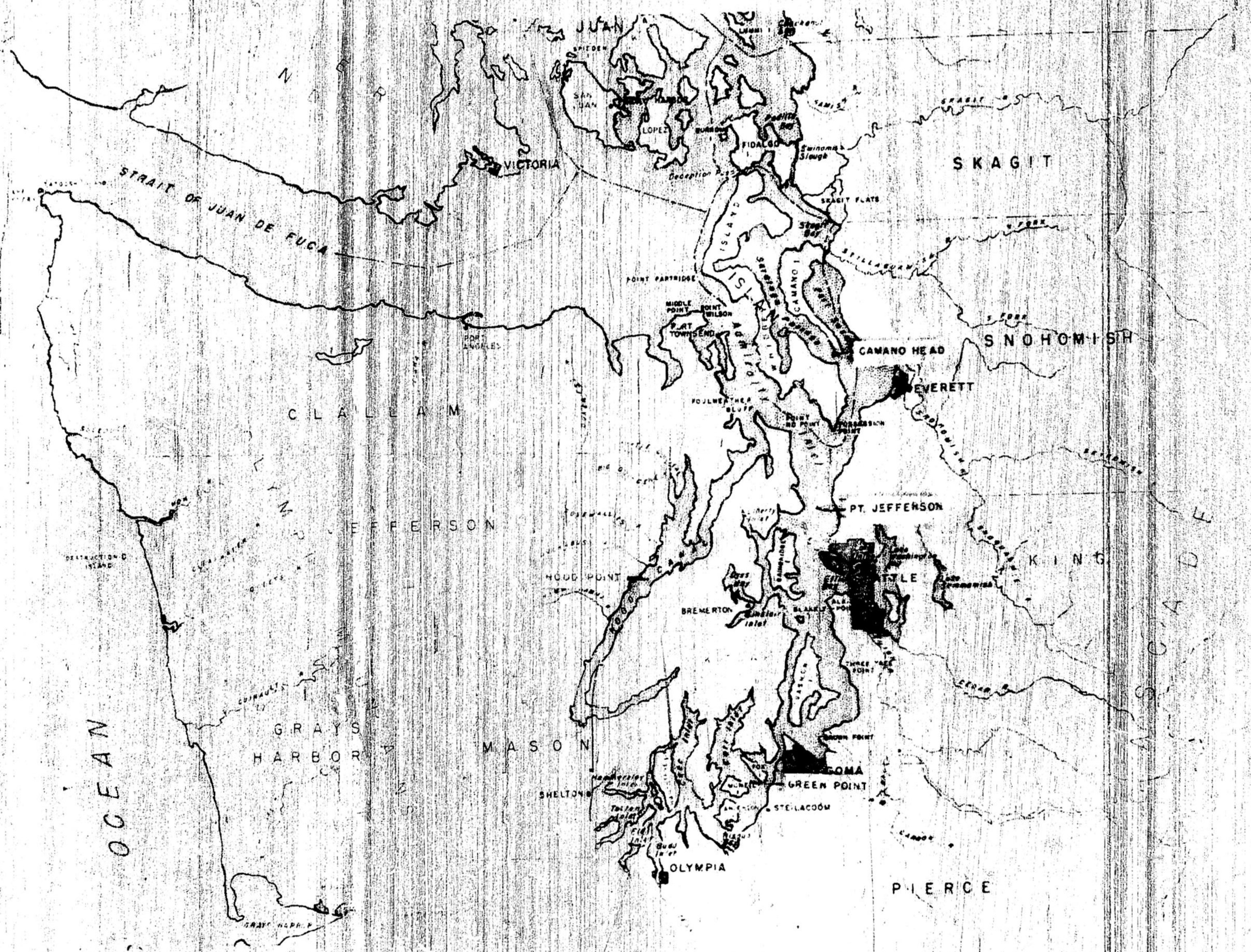


FIGURE 7. Location of sampling stations for salinity study.

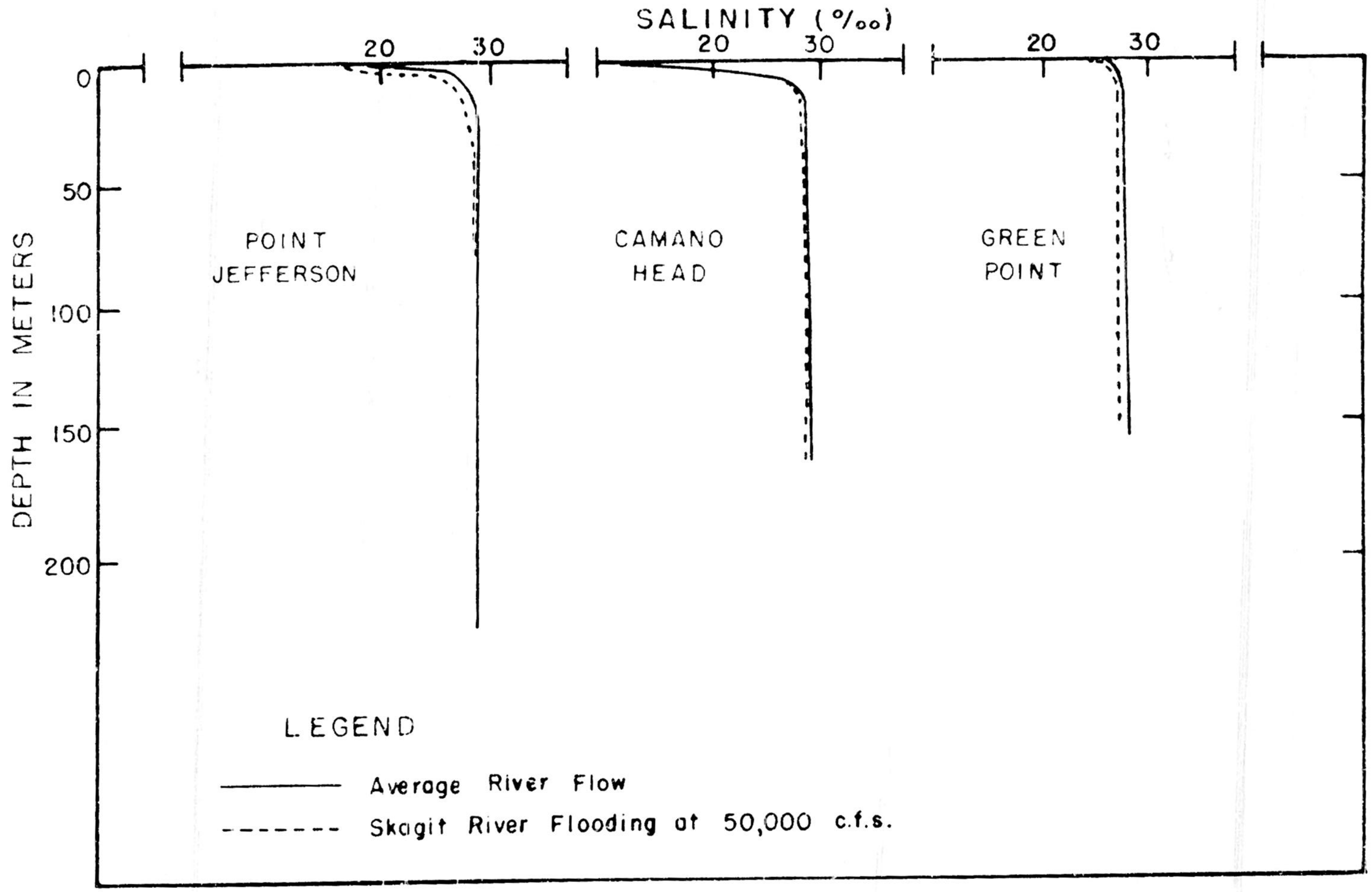


FIGURE 8. Comparison of equilibrium salinity structures.

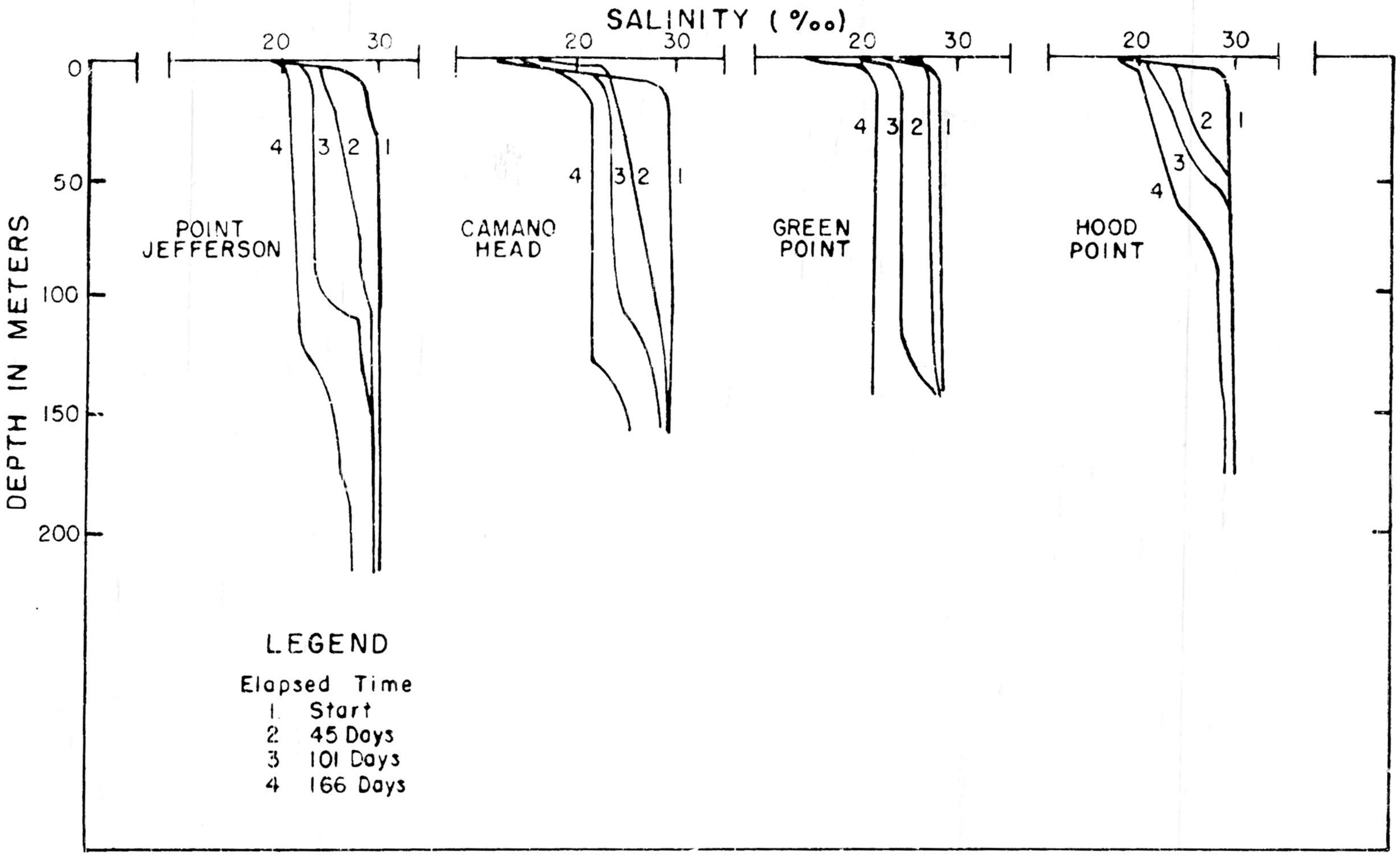


FIGURE 9. Change in salinity structure resulting from decrease in source salinity.

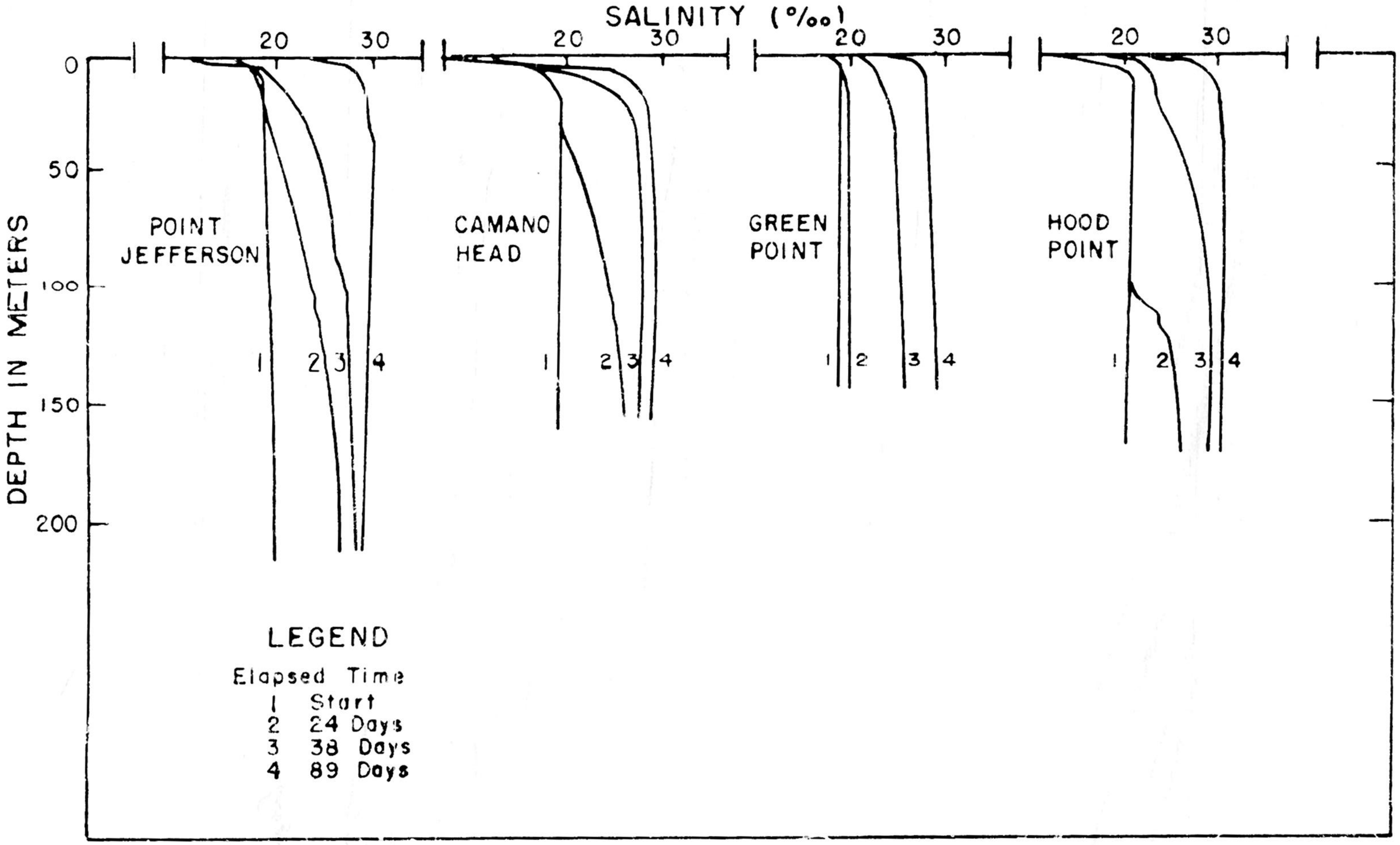


FIGURE 10. Change in salinity structure resulting from increase in source salinity.

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