

CHEMISTRY OF PUGET SOUND WATERS  
AND  
INFLUENCING FACTORS

by  
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may be contributing 1,000 tons of phosphorus annually. High phosphate values in the southern reaches of the Sound suggest local concentrations of phosphate due to biological activity in the more stagnant regions.

The productivity of the main basin of Puget Sound is evaluated on the basis of annual phosphate depletion. A range of 30 to 111 grams of carbon per square meter of surface area per year is estimated. Compared to other areas reported in the literature this productivity is low.

Seasonal and long term variations are shown for phosphate and other nutrient salts. Factors affecting the distribution and variation of other chemical constituents in Puget Sound and in adjacent waters are discussed.

Some suggestions are enumerated for future work in the geochemical-oceanographic line.

## ABSTRACT

This report presents the results of a geochemical investigation, based on existing data, of the waters of Puget Sound. Rivers draining into Puget Sound and upwelled water moving in at depth from Juan de Fuca Strait are the chief sources of the chemical constituents in Puget Sound. Distinctive features of the rivers and drainage area tributary to Puget Sound are discussed. On a comparative basis the rivers tributary to Puget Sound discharge more water and more dissolved material per square mile of drainage area than other comparable rivers in North America for which data are available.

In the marine area two distinct water masses can be identified on the basis of T-S diagrams plotted for stations from Pillar Point, central Juan de Fuca Strait, to Devils Head, southern Puget Sound. These two water masses can also be differentiated on the basis of oxygen and phosphate data. For July almost linear curves are obtained by plotting phosphate vs  $\sigma_t$  and phosphate vs dissolved oxygen. February plots show a closer grouping and more random distribution of points for both graphs. From these relationships it is concluded that the summer distribution of phosphate represents mainly the effects of currents and biological activity. The <sup>winter</sup> ~~water~~ situation is dominated by turbulent mixing as a result of winds and tides. Summer stratification of properties due to insolation is augmented by the intrusion of cold, high-salinity, high-phosphate waters from the Pacific Ocean.

An annual phosphate budget for Puget Sound is developed taking into consideration all the possible contributing and depleting factors. No surplus appears at the end of a year from natural interchange of waters but pollution

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## CHEMISTRY OF PUGET SOUND WATERS AND INFLUENCING FACTORS

### Introduction

Puget Sound has been regarded unusual if not unique oceanographically in many ways. It is a deep, heavily dissected marine basin, predominantly glacial in origin, and separated from the open Pacific by another seaway, Juan de Fuca Strait (Figure 1). Along its extensive perimeter of 1,157 nautical miles (McLellan, 1954, p.1) are scattered eleven prominent river estuaries with numerous other small streams of minor consequence. The composition of the marine waters is influenced by these rivers as well as the ocean water which enters through Juan de Fuca Strait. Various factors such as seasonal changes in runoff, winds, upwelling and biological activity tend to complicate the oceanography of the system.

Perhaps the most significant biogeochemical factor in the makeup of the water of Puget Sound is its high nutrient concentration. Average dissolved inorganic phosphate content in the upper 25 meters seldom drops below  $2\mu\text{g-at/l}$ . Compared to some of the other known regions of the world, which rarely exceed  $1.5\mu\text{g-at/l}$ , Puget Sound is a well fertilized area. The concentration of silicates may be less striking but is still significantly higher than in the surface waters of other regions. Table I gives the average concentrations of some of the dissolved constituents in Puget Sound on a comparative basis with some other marine waters of the world. With few exceptions the values listed are averages for the surface or upper 25 meters of water.

Phosphate concentrations in Puget Sound seldom vary by more than  $0.5 \mu\text{g-at/l}$  from the surface to a maximum at a depth of 250 meters.

This high nutrient concentration in Puget Sound is of importance biologically in that it provides an index for production of phytoplankton, zooplankton and ultimately the higher forms of marine life. Phosphates rarely become depleted to a concentration below  $0.55 \mu\text{g-at/l}$  set up by Riley (1946, p.64) as the limiting value for plankton synthesis. This would suggest that the factors limiting organic production may be light and minor constituents such as iron and manganese which have been regarded as growth factors (Harvey, 1950).

It will be mainly the topic of this paper to discuss the annual budget of the nutrients in Puget Sound and present some of the data on source waters which may help to explain the high concentrations and seasonal variations.

#### Possible Sources of Chemical Constituents

The ultimate source of most of the inorganic constituents in sea water are the mechanical and chemical weathering products of terrestrial materials carried to the sea by runoff. Therefore, a natural starting point in the study of the origin of the chemical constituents is the rivers. After making an analysis of the available data on the contribution of rivers, it was found that measurable additions to the concentrations of the dissolved substances could be made by the inflowing silicates, nitrates, sulfates and trace metals such as copper and iron. But phosphates could not be accounted for by the river waters as only traces of this ion were found in the fresh water entering Puget

Sound. The logical second step is analysis of the marine waters entering Puget Sound inasmuch as they constitute the bulk of the total water. The seasonal variation of the phosphate concentration in the deep water of Juan de Fuca Strait indicates generally a higher concentration in summer than in winter. This observation might lead one to suspect that some process of replenishment of nutrients at intermediate levels is occurring seasonally. A mechanism which would bring nutrients from depth toward the surface would also necessarily move the water upward. Evidence of this can be seen in the temperature, salinity and dissolved oxygen content of the water. A study of the seasonal variation of salinity and temperature below 100 m. depth at the eastern end of Juan de Fuca Strait shows clearly the presence of highest-salinity and lowest-temperature water in the summer months (Figure 2). This is contrary to the seasonal climatic trend, and it is obvious that an outside water mass has been moved in during the summer months. This inference would indicate that upwelling is occurring off Juan de Fuca Strait during the summer months. Thompson, McCorkell and Bonnar (1930) were the first to suggest that the process of upwelling off the coast contributes to the high phosphate concentration in the water of the San Juan Archipelago as opposed to the river-source hypothesis offered by Hutchinson and Lucas (1929, 1931). Tully later (1942, p. 407) proposed a jet-stream and wind-effect mechanism for this upwelling. The jet-stream is a result of the surface outflow of brackish water from rivers and the summer prevailing northwest wind causes a wind current southward off the coast. These two forces combined essentially form a divergence of surface water and a rise of deep water to take its place. Tully also showed that the phenomenon

is quite local and occurs in cells of a cyclonic-eddy nature at the entrance to Juan de Fuca Strait. Oceanographers are not all agreed on the process by which the deep water comes to the surface, but there remains little doubt that a seasonal invasion by deep Pacific water occurs in Juan de Fuca Strait.

Other processes which may be active in contributing to the nutrients or at least altering the nutrient picture in Puget Sound are biological activity, chemical precipitation, shoreline solution and man-made pollution. Biological activity can be discussed in at least two categories. In the ~~one~~ case, the photosynthetic activity in the euphotic zone utilizes the dissolved inorganic constituents. Coupled with the grazing by zooplankton the nutrients may be redistributed vertically as well as slightly horizontally. Various authors (Harvey, 1950; Cooper, 1952) have shown that zooplankton will graze on the phytoplankton during the night and return to depth during the day where they excrete their waste products high in nutrient concentration. Thus surface layers become depleted and the deeper waters experience enrichment in nutrients. As a result of the motility of many forms, currents may not be as effective in moving them out of an area, and the nutrients may tend to be concentrated in a locality in this way. Due to sinking of dead organisms there is further enrichment of the bottom waters and sediments. A second process of biological activity is that which occurs on the sea bottom. Here regeneration of nutrients is occurring by the action of bacteria. Also a major consideration in the transformation is the benthic fauna. Concentrations of the various species of ~~pl~~ecyopods, echinoderms, annelids,

and crustaceans may have a very pronounced effect on the chemistry of the sediments and water overlying them.

Chemical precipitation may occur in conjunction with biological activity. Photosynthesis and respiration may enter into the carbon dioxide-bicarbonate-carbonate cycle causing deposition or solution of calcium carbonate. In certain cases photosynthesis reduces the  $\text{CO}_2$  content of the water and promotes precipitation of  $\text{CaCO}_3$ . This seems to have occurred to a large extent in the waters of Hood Canal where sediments are very high in  $\text{CaCO}_3$  (Fang, personal communication) and the bottom water is relatively low in  $\text{CO}_2$  content. In Admiralty Inlet, on the other hand, sediments are low in chemically-combined  $\text{CaCO}_3$  and the  $\text{CO}_2$  content of the bottom waters is quite high. Calcium carbonate does occur, however, in liberal quantities in the form of shell fragments. Another form of chemical precipitation and solution which may be of some consequence is that which occurs in euxinic environments. Hydrogen sulfide will precipitate heavy metal ions. Over prolonged periods a considerable quantity of certain metals may be precipitated in the form of sulfides. On occasion when a low tide occurs these sulfides may be exposed to the atmosphere or to the high oxygen concentration of surface waters. The sulfides are oxidized releasing sulfate and the ions of the heavy metals. This process (Thompson, personal communication) has been suggested for the high concentrations of copper at the head of East Sound, Orcas Island, where sulfide waters are found. A further biochemical activity which seems to be in operation is the effect of oxidation on organic detritus high in nutrient concentration on tidal mud flats.

Leaching of the regenerated phosphates and other nutrients leads to high concentrations. It was this type of process which Thompson and Phifer (1936, p. 129) suggested was contributing to the high phosphate concentrations outside the Skagit River estuary. Skagit River water itself has been shown to carry only trace concentrations of phosphate. A combination of this process with the intensive activity of bottom forms in concentrating the phosphates may be the reason for the very high phosphate concentrations in the southern reaches of Puget Sound.

Shoreline erosion has been found to be a principal contributor to the sediments of Puget Sound (Wang, personal communication). With its long coastline Puget Sound receives about three times as much sediment from its shore formations as from the rivers. The powerful tidal currents and waves may also be agents for the solution of chemicals from the shoreline sediments and rocks. Although the extent of dissolved constituents from shoreline solution is somewhat indeterminate, it seems reasonable to suppose that it is negligible compared to river contribution. The small area of the beach undergoing chemical weathering compared to the large area of the drainage basin would suggest that the ratio of weathered products would also be small.

Since the advent of man's industries into Puget Sound, a purely artificial source of chemicals has been established due to pollution. The discharge of sewage is generally inimical to the animal life locally but may add measurably to the dissolved constituents in the whole region. Domestic sewage is known to contribute substantially to the amount of phosphate near the point of discharge. Canneries return much of the

nutrients in the form of waste products from fish. Smelters of the Tacoma region dump much of their mill tailings into Puget Sound and copper concentrations in that area have been found to be particularly high (Chow, personal communication). Paper mills at Everett discharge effluent which is high in concentration of sulfite, calcium, lignin, and many other organic substances.

Withdrawal of some phosphate also occurs due to man's activities such as fishing and kelp harvesting. This will be shown in a later section to be small. In areas of much fish-eating bird life nutrients taken out by the fish may be significant, as off Peru, for example. But in Puget Sound only scattered numbers of gulls, cormorants and loons (Miller, Lumby and Hall, 1935) make a practice of living on fish. No estimate has been made of the fish consumed by water fowl locally, but it is presumably small.

#### River Runoff and Drainage Basin

Two of the major distinguishing features of the rivers discharging into Puget Sound are the large volume of water and large amount of dissolved material per unit area of drainage basin. The Skagit River alone, because of its position in the Puget Sound basin and the character of the drainage area, has a runoff which is probably greater per square mile of drainage area than any other moderate sized river in the United States (Van Winkle, 1914, p. 35). The total annual discharge into Puget Sound contains more than three times as much dissolved substances per unit area of drainage basin as the Mississippi, Columbia and Colorado Rivers and more than twice as much as its nearest rival, the Fraser River, among

the rivers examined. Table II gives some of the characteristics of a few North American rivers with their calculated effects on denudation. In terms of actual concentrations of dissolved substances in the water itself, rivers tributary to Puget Sound are not so impressive. For example, the Colorado and Rio Grande Rivers contain about ten times the concentration of dissolved materials as the rivers entering Puget Sound. On an areal basis, the total contribution of dissolved solids by rivers tributary to Puget Sound is greater, however, than that for any other drainage system investigated.

Some of the basic factors determining the leaching and erosion rate in the tributary drainage basins of Puget Sound have been examined and can be enumerated as follows:

- (1) A large annual precipitation with a comparatively even distribution throughout about eight months of the year permits a slow but almost continuous precolation of water underground. This accomplishes much more solution than the same amount of precipitation and runoff occurring in a short time as in a flash flood, for example. In the eastern part of the drainage basin and at higher elevations the precipitation is in the form of snow during the winter months. Late spring thawing extends the period of large runoff into the summer.
- (2) The lithological character of the drainage basin lends itself to rapid weathering. The mountainous terrain consists largely of volcanic, sedimentary and metamorphic rocks. Basalts and other eruptive rocks have extreme susceptibility to chemical



weathering. They are more easily attacked and more rapidly destroyed by chemical weathering than most rocks.

- (3) A heavy vegetal cover over much of the drainage basin provides humic acids which assist in the solution of some of the chemical constituents. The associated soil acts as a filter retaining much of the suspended material washed down from the exposed rocks.
- (4) The extreme seasonal variations in climate of the headwaters region of the drainage basin greatly enhance disintegration and decomposition of rocks by the freezing and thawing action.
- (5) Large gradients of the stream beds in the mountains are accompanied by rapid erosion. In the low coastal region these gradients are comparatively small and deposition may be occurring.

The dominating factors contributing to the high dissolved inorganic content of the rivers are (1) and (2), the particular precipitation and the lithological character of the drainage basin. It is noteworthy that the vegetation which may be a significant contributor to the solvent properties of the water is also largely responsible for the small suspended load.

Clarke (1924, p. 54) has cited the work of Bunsen (1855) on the chemical weathering potential of rain water. He shows that active gases are concentrated in rain water so that carbon dioxide and oxygen are in much higher proportion to nitrogen than they are in the atmosphere. Thus rain water has both a lower pH and greater oxidizing properties than water which has run its course on the ground for some time. The composition of air extracted from rain water at different temperatures and that of average atmospheric air is shown in Table III.

Direct solution, hydrolysis and double decomposition all aid in bringing materials into solution. Many secondary rocks, such as gypsum, enter directly into solution. Limestones may be dissolved by interaction with alkali sulfates. Evidence has shown that all the important minerals are attacked by carbonic acid (Clarke, 1924, p. 481). The effect of rain water in chemical weathering can be divided into several phases. First, the water partially dissolves the more soluble minerals containing oxides of the alkali metals ( $\text{Na}_2\text{O}$ ,  $\text{K}_2\text{O}$ ) and those of the alkaline earths ( $\text{CaO}$ ,  $\text{MgO}$ ,  $\text{BaO}$ ) (Petrijohn, 1948, p. 379) with the liberation of colloidal silica and formation of carbonates containing lime, iron, magnesium and the alkalis. The lime, magnesia, and alkali salts remain partly in solution to be washed away with much of the dissolved, colloidal, and particulate silica. Since river waters are rarely saturated in silicates, this material may continue going into solution as it is washed toward the sea. The higher pH encountered in sea water will increase the solubility of the silica (Cooper, 1952a) and more of it may go into solution. Bruevich (1953) has demonstrated that sea water is never saturated with respect to silicic acid.

High oxygen concentration generally has the effect of a precipitating agent. In rock decomposition the effect of oxidation is mainly a surface phenomenon as it has been shown that oxygen content of ground rocks decreases with depth (Clarke, 1924, p. 480). However, the carbon dioxide present in rain water is augmented by that produced in the decay of vegetative matter on the surface of the ground or in the soil. An additional factor increasing the dissolved carbon dioxide and the con-

sequent solvent properties of the runoff waters is the winter snow at the higher elevations. The mechanical disintegration of the rocks by the grinding process of glaciers, the disruptive effects of frost, and unequal expansion due to alternations of heat and cold is aided extensively by chemical weathering. Work done recently on the chemical weathering in the Cascade Mountains (Williams, 1949, p. 131) showed that the presence of a high concentration of carbon dioxide in the melt water enhances its solvent qualities. The pH of this snow water was found to be 5.91 compared to 7.08 for the water of the Snoqualmie River nearby and the corresponding concentrations of  $\text{CO}_2$  were 9.3 and 1.0 p.p.m., respectively. Williams explained that the high concentration of  $\text{CO}_2$  in the melt water is due to alternate solution and release of  $\text{CO}_2$  during the period of alternating high and low temperatures of the spring season. Water trickling through snow is near freezing or at an optimum temperature for dissolving gases such as  $\text{O}_2$  and  $\text{CO}_2$ . Carbon dioxide is absorbed by cold water and is released when the water freezes. But, being a heavy gas,  $\text{CO}_2$  settles in the snow when it is released from the water. Trickling water picks up this  $\text{CO}_2$  and carries it into the soil beneath the snow. Experimental determinations of  $\text{CO}_2$  in a column of snow in the Snoqualmie Pass area showed 0.098% compared to only 0.040% in the atmosphere of the chemical laboratories of Bagley Hall, University of Washington.

Unfortunately, there has been no work done on the dissolved organic substances in either the rivers draining into Puget Sound or in the sea water. Williams (1949, p. 134) does show, however, that the water in

the soil beneath a snow bank in the Snoqualmie Pass area contained 6.4 p.p.m. of volatile matter. No such volatile substance was present in the Snoqualmie River water. The organic content of most rivers probably is not high as the waters are not excessively discolored by the brown humic materials so characteristic of bog lakes (Van Winkle, 1914, p.37). One factor which should not be overlooked is the organic and nutrient substances contributed by salmon and other anadromous fishes which die in the streams after spawning. It would appear that in small streams with large runs this might be a very important source of nutrients and organic materials. Work being conducted currently on the fertilization of lakes in Alaska with artificial fertilizers (Edmondson, Seminar) is the direct result of the loss of a nutrient source due to the decline of a salmon run.

Data on the chemical composition of rivers tributary to Puget Sound are very fragmentary. The early work of Van Winkle (1914) still stands as the only large-scale investigation of some of the main rivers (Love, 1952). Concentrations of chemical constituents of rivers tributary to Puget Sound for which data are available along with the chemical constituents of some other rivers of North America are given in Table IV. Analyses for local rivers have been averaged giving due weight to the volume discharged by each river and the results are presented in Table V. The average concentrations of these constituents in Puget Sound and offshore are given for comparison. Table V shows that silicates, nitrates, sulfates, and iron in river water contribute measurably to the concentrations of these ions in Puget Sound water. To explain the relatively large concentration of phosphate in Puget Sound one must look elsewhere.

The chemical composition of river water gives a rough indication of the materials through which runoff waters have percolated and have acted upon. According to Van Winkle (1914, p. 37), an excess of sulfate over alkalis in Skagit River water suggests that the prevailing rocks of the basin are sedimentary and part of the strata is entirely unmetamorphosed. The content of silica of this water is considered lower than that in rivers flowing through lava formations. It is characteristic of runoff from the metamorphosed Paleozoic rocks of the headwater regions rather than that from the lower reaches. Van Winkle (1914, p. 40) also points out that the waters of Wood Creek are characterized by primary alkalinity which indicates that the prevailing rock material in the drainage basin is of igneous origin.

Two periods of high water are usual for most of the rivers of Puget Sound although in some of the shorter streams the high water periods are almost directly a function of precipitation in the form of rain. Once the ground becomes saturated by the latter part of November more than 80% of the rain precipitation becomes river runoff. In the Skagit River a late autumn flood period is common. Destructive flash floods occur when a southerly Chinook wind in the Cascade Mountains follows a heavy snowfall and is accompanied by a rainstorm. Within a period of a week the Skagit may increase from an insignificant discharge of 5,000 c.f.s. to the violent force of 75,000 c.f.s. The spring-early summer flood is a result of the melting snow in the head waters and extends over a period of two to three months with a smaller discharge and less violence. Accompanying these large fluctuations in stream flow are seasonal variations

in the dissolved constituents which occur mainly in the concentrations of chloride, sulfate, and calcium. Large variations in turbidity correspond to the fluctuations in stream flow and reflect chiefly the variations in suspended load.

#### Physical Oceanography of Puget Sound

It is not the purpose of this work to review in any comprehensive way the physical oceanography of Puget Sound but to deal only with those concepts which are important in the distribution of chemical constituents.

The two large variables in Puget Sound are the runoff and the ocean water moving in by way of Juan de Fuca Strait. Some of the more permanent factors, which can modify the oceanography and more or less determine the pattern, are the topography, geography, and coriolis force. The fact that the water is deep gives a different circulation than that in Chesapeake Bay on the Atlantic Coast. Absence of shallow sills provides for ample ventilation of the deep water and makes the basin different from Norwegian fjords. The narrow passages provide regions of intensive mixing by strong tidal currents. Other variables which are essentially superimposed on the two mentioned are the tides varying diurnally as well as fortnightly and the meteorological conditions - winds, precipitation and insolation. The effects of other factors can have only minor significance in the physical oceanography.

Puget Sound is a basin where precipitation and runoff exceed evaporation. Thus there is a net flow of low-salinity water seaward at the surface and a net flow of high-salinity water landward at depth. The currents in Puget Sound have been studied (Paquette and Barnes, 1951) using various

recording and direct-reading mechanical devices - Ekman, Price and Roberts current meters. Tidal currents and topography are the dominating influences on the deep currents in Puget Sound. Circulation of the surface water appears to be governed primarily by tides, winds and geography. This has been observed in the model of Puget Sound without recourse to wind action. Currents are strongest (up to 7 knots) at mid-channel in the narrow, constricted passages, - Deception Pass, Tacoma Narrows, and Agate Pass. They are of moderate velocity (up to 4 knots) in some of the wider channels such as Admiralty Inlet and between 1 and 2 knots at the entrance to Hood Canal, Possession Sound, and Saratoga Passage (U. S. Department of Commerce, 1947). Circulation in bays is relatively sluggish. Because of the coastline around some islands, tidal currents pass freely in one direction through one channel but are diverted into another channel on the reverse tide. A net circulation may be developed around the island. This occurs counterclockwise around Vashon Island where currents in Colvos Passage are almost always directed northward. Tidal currents moving past points and prominences such as Double Bluff and Admiralty Head cause a series of eddies which may persist for long distances and for a long time after the change of tide. Where two or more channels meet severe tide rips may occur. These rips are merely convergences of surface water. Similar phenomena may occur when wind waves oppose the tidal current. Wide-mouthed bays along a channel may contain a large eddy which forms a tide rip with the channel current.

The circulation and flushing in the inlets are governed to a large extent by the salinity of deep water inflow, the type of entrance, and

the amount of runoff. The most rapid flushing of Puget Sound occurs in the autumn when the deep water is highly saline, runoff is small and surface water is being cooled (Barnes, personal communication). Hood Canal undergoes the slowest flushing in Puget Sound because of its shallow threshold sill (37 fathoms), its great depth (90-100 fathoms), and the relatively small river effluent which it receives. Experiments on the Puget Sound Model (Barnes, Lincoln, and Hattrey, 1954, p. 13-15) have shown that an increase in the source salinity changes the water structure in the main basins of Puget Sound in about 90 days, prototype time, when equilibrium is reached. Decreasing the source salinity alters the equilibrium structure in the main basin in 100 to 166 days according to the distance from Admiralty Inlet. In Hood Canal, however, water below 70 meters changed only slightly after 166 days. This corresponds to conditions in nature where deep waters of Hood Canal are flushed out only slowly and probably only once every few years.

Two periods, as widely different as possible within the limitation of the data, have been chosen to discuss the oceanography of Puget Sound on a seasonal basis. July is a period when conditions are approaching a midsummer picture of low runoff, north-northwest winds, and high air temperature. At this time water in Juan de Fuca Strait at depth is beginning to show high salinities and low temperatures. In mid-February the area is near a peak condition of high runoff, south-southwest winds, and low air temperatures. Actual peak winter conditions in the sea water are not reached until late March or early April when the trend begins toward a summer condition. The seasonal variation in salinity, temperature and



oxygen off New Dungeness at the approaches to Puget Sound is shown in

Figure 2. It is quite evident that the surface water displays the highest and lowest salinity sometime in August, the same period of highest salinities and lowest temperatures in the deep water. The most homogeneous water mass occurs in December.

The runoff waters flow into Puget Sound over the surface of denser sea water and mix in a brackish layer as they flow toward the sea. This mixing effect entrains sea water into the fresher surface water removing a considerable amount of salt from Puget Sound. To replenish this salt water there must be a net movement of sea water into the Sound. Otherwise, the Sound waters would become progressively fresher. Observations over a twenty year period do not show this to be the case (unpublished data). Current measurements made over a three-day period in November, 1953, show the presence of a net flow seaward at the surface and a net flow landward at depth in Admiralty Inlet (Paquette, Seminar). A layer of no net motion was shown to be present at 40 meters depth. The flow of water in the surface layer showed a net outflow in excess of the deep water inflow of the order of magnitude of the discharges of the rivers emptying into Puget Sound. These observations were also important in that they showed that the current velocities into Puget Sound at depth did not decrease rapidly below the sill depth but continued at about the same magnitude (13 cm/sec. net flow, Nov. 30 to Dec. 3, 1953) to within 10 meters of the bottom.

Assuming that the water of Puget Sound is a single mixture of the water entering the Sound at depth and fresh water coming in from the rivers, it should be possible to compute the amount of fresh water in Puget Sound at a particular time based on salinity. It would be necessary to know the

average salinity  $S_A$  of the Sound water and the average salinity  $S_B$  of the sea water entering the Sound. Then the percentage of fresh water,  $F\%$   $= \frac{S_B - S_A}{S_B} \times 100$  (Ketchum, 1950, p. 304). As a first approximation, the average salinity of Puget Sound was obtained by subdividing the whole Sound into four sectors of different oceanographic conditions and choosing a representative station for each. By evaluating the average salinity at each station and taking into consideration the volume of each sector, an average salinity was computed. The sectors and representative stations are given in Table VI with the corresponding salinities. The salinity of water entering Puget Sound was determined by averaging the salinity below 40 meters (depth of no net motion) at Port Townsend. Choice of the base salinity for such computations is the most critical, but it is considered that Port Townsend should be as representative as possible. Percentage of fresh water in July is shown to be greater than it is in February. This is somewhat contrary to normal opinion as it is generally believed that fresh water is removed more rapidly during the summer months of large stratification than it is in winter of intensive mixing. However, the seasonal variation of the source salinity strongly influences the flushing rate. Moreover, prevailing summer winds are north-northwesterly (Harris, 1954, Tyler, 1952, p. 24) and they will tend to retain the fresh water in the Sound. Southerly winter winds help to drive the fresh water out of the Sound. The salinity structures at various stations for July and February are shown in Figure 3. It is worthy of note that the fresh water is mixed to much greater depth in winter than it is in summer as shown by the halocline. It might be

argued that a better choice of stations for the base salinity would give more realistic values for the amount of fresh water in summer and winter. Salinities averaged from the Pillar Point Station in Juan de Fuca Strait gave a difference between summer and winter volumes of fresh water which was even more pronounced (Table VI). It would not be valid to evaluate a source salinity from stations further into Admiralty Inlet as mixing decreases the salinity of the deep water. There is a possibility that the two-layer flow system breaks down during the winter months of little stratification and intensive wind mixing. In such a case bulk exchange, as suggested by Fleming (2nd Pacific Northwest Oceanographic Conference, 1953), would occur. This implies that water is exchanged by the tide over the whole depth where the fresh water is distributed evenly vertically rather than confined to an upper layer. Thus a certain amount of the fresh water in the deep layer would greatly reduce the calculated percentage of fresh water in Puget Sound. Unless the oceanographic processes occurring in summer and winter are vastly different, however, the figures computed for the fresh water should be reasonable. Certain refinements in method used for the computation might improve the accuracy. The largest error stems from neglect of the change in volume between equal intervals of depth from the surface to the bottom. Such a volume correction would increase the calculated amount of fresh water.

The vertical distribution of properties in summer and winter is shown in Figures 4 and 5 for a section from Pillar Point to Devil's Head. The most striking feature is the contrast in the distributions from summer to winter. In July the water is very strongly stratified with low salinities,

high temperatures in the surface waters of Puget Sound and high salinities, low temperatures in the deep water of Juan de Fuca Strait. The range in salinity is almost 8.5 ‰ and in temperature 9.5° C. The winter picture shows great homogeneity with relatively high salinity in the surface water of Puget Sound. Temperature variations at this time are practically non-existent. The range in temperature is less than 1.0° C from Devil's Head to Pillar Point and the corresponding range in salinity is 4.5 ‰. Circulation can be inferred from the density distribution where the dense water flows toward the basin of Puget Sound at depth and the light surface water is forced seaward at the surface. The dissolved oxygen confirms this circulation, the low concentration moving with the deep water from the Pacific Ocean into the Puget Sound basin.

T-S diagram can be a useful tool for characterizing water masses in inshore coastal areas as well as those offshore. In Figure 6 the line of stations from Pillar Point to Devil's Head is represented by temperature-salinity relationships. The curves for the Juan de Fuca stations show almost a linear relationship during the summer. A discontinuity appears in going from stations in Juan de Fuca Strait to those in Puget Sound. This discontinuity shows essentially a change in the water mass from the dense, high-salinity, low-temperature Juan de Fuca water to the light, low-salinity, low-temperature Puget Sound water. There is some evidence in the T-S curves for water off Point Jefferson that at about 75 m there is a lag behind the water at maximum depth in the warming effect. This would indicate a more rapid circulation in the deep water than at intermediate depths, which seems reasonable if there is to be

a layer of no net motion. February T-S curves show a general contraction in range of salinity, temperature, and density from the July picture.

Differentiation of water masses becomes more difficult due to the general homogeneity of the water. The curves appear more continuous and it can be said only that Juan de Fuca water lies in the denser part of the curves and Puget Sound water is in the low density section of the T-S curves.

It is noteworthy that the mixed water falls on the same section of the T-S curves densitywise at about  $\sigma_t = 23.5$  both summer and winter. The southern mixed waters of the Strait of Georgia have a density of about  $\sigma_t = 24$ . This may have certain significance in the overall behaviour of the system. Some further work must be done on the energy and mixing relationships. Contrary to deep sea areas where mixing occurs along isopycnals, here the mixing is across  $\sigma_t$ -lines with a large energy expenditure.

#### Chemical Oceanography of Puget Sound

The nutrients of Puget Sound must be regarded as non-conservative properties, they are affected not only by advection and diffusion but also by biological activity. The advective forces have already been discussed under the section of Physical Oceanography. Diffusion can be treated only on a quantitative mathematical basis which will not be attempted here. From a preliminary analysis of the problem of vertical eddy diffusion in Admiralty Inlet, the coefficient of vertical mixing increased from the surface to 40 meters (depth of no net motion) and then decreased toward the bottom (Paquette, Siminar). This would suggest a maximum

vertical mixing occurring at a depth of no net motion with little or no vertical mixing at the surface and bottom. Such a condition checks well with the actual physical picture where the change in properties at the surface and depth is due largely to horizontal advection and that at 40 to 75 meters is a result of mainly turbulent mixing.

#### Phosphate Distribution

The distribution of Phosphate as it occurred horizontally and vertically at the approaches to Juan de Fuca Strait, July 2 - 16, 1952, is shown in Figure 7. A very pronounced surface gradient in phosphate from 0.5 to 2.1  $\mu\text{g} - \text{st/l}$  is exhibited at the approaches to Juan de Fuca Strait. In vertical section the slope of the isophors from deep oceanic water to surface Juan de Fuca water is very pronounced. This may be regarded as a typical summer phosphate distribution which is similar to that obtained by Iglerud, Robinson, and Thompson (1936, p. 16-17). A suitable winter distribution for phosphate is not available, but a later April survey showed concentrations of phosphate at the surface of the entrance to Juan de Fuca Strait, only slightly more than 0.5  $\mu\text{g} - \text{st/l}$ . Such evidence seems to be quite conclusive that deep waters off southern Vancouver Island rise to the surface in summer bringing high concentrations of nutrients. No similar process appears to exist in this region in winter. There is little question that deep water is being forced to the surface at the entrance to Juan de Fuca Strait during the summer months. The main argument appears to be in the mechanism by which this process occurs. Is it a case of a horizontal divergence of currents, a

seasonal tilting of the isopycnals suggested by Flemming (Seminar, 1952), capitalizing as suggested by Cooper (1952b) for the English Channel or an actual case of wind-generated upwelling? It is probably a combination of factors which cause this enrichment of surface waters, - winds, surface outflow due to runoff, topography and tidal currents. The effect appears to be local and is not evident off the northern end of Vancouver Island. Nevertheless, it is important inasmuch as it provides the main source of nutrients for the inshore waterways of Juan de Fuca Strait, Puget Sound and the Strait of Georgia. In this paper the term "upwelling" is used although it may not be applied in the normal sense of the word.

Distribution of phosphate from Pillar Point, Juan de Fuca Strait, to Devil's Head, Puget Sound, is shown for July and February in Figures 4 and 5. High phosphate concentrations in the deep water of Juan de Fuca Strait and low concentrations in the surface waters of Puget Sound are very conspicuous in July. The picture is reversed in February with a low concentration in Juan de Fuca Strait particularly at the surface and a relatively homogeneous water mass of high phosphate concentration in Puget Sound. These distributions of phosphate correspond to the distribution of density and oxygen which are products of advection, diffusion and in the case of oxygen, also biological activity.

The phosphate picture as it is affected by advection and diffusion is depicted on phosphate -  $\sigma_t$  diagrams (Figures 8 and 9). Phosphate -  $\sigma_t$  relationships have been plotted for each station from Pillar Point to Devil's Head. Basically, two groupings of points are prominent. In July the high phosphate, high density water occurs in Juan de Fuca Strait and low density, low phosphate water occurs in Puget Sound. The system appears to be

continuous, or nearly so, from the linearity of the points taken from deep Juan de Fuca water to surface Puget Sound water. However, the February picture is very different. Two groupings still occur, but the water in Juan de Fuca Strait is of high density and low phosphate. In contrast, the water of Puget Sound is characterized by low density and high phosphate. Moreover the system is no longer continuous as surface waters. Waters of Juan de Fuca Strait are of low density and low phosphate breaking the continuity from Puget Sound surface waters high in phosphate. This low winter surface phosphate concentration in Juan de Fuca Strait can be attributed in part to dilution from the Fraser River and local streams. However, the amount of dilution of the strait water by fresh water should be proportional to the salinity change. The phosphate decrease is actually much greater and may be due to some intrusion of low-salinity, low-phosphate water near the surface from the western end of Juan de Fuca Strait. This would necessitate some sinking to an intermediate depth of the out-flowing surface water from eastern Juan de Fuca Strait. Such a flow pattern has not yet been demonstrated. Another point of interest is the erratic fluctuation of phosphate concentration with depth at most Puget Sound stations in February. This can be seen more clearly in Figure 10 showing the profiles of dissolved phosphate in winter and summer.

The biological activity as it affects phosphate distribution is illustrated by the phosphate-dissolved-oxygen curves plotted in Figures 11 and 12. It can be regarded generally that water becomes saturated with oxygen at the surface and that any changes at depth, depletion or supersaturation, are due to biological activity. Near the surface,



photosynthesis by phytoplankton utilizes carbon dioxide, nutrients and sunshine to produce carbohydrates and oxygen. At depth, where light is insufficient for photosynthesis, the respiration of animals depletes the oxygen concentration. Bacterial activity near the bottom aids in the decomposition of organic matter with the utilization of available oxygen and the release of nutrients. Thus high phosphate concentrations are associated generally with low dissolved oxygen content and low phosphates occur where the dissolved oxygen content is high. Figures 11 and 12 show the relationship of phosphate concentration to dissolved oxygen content at stations extending from Pillar Point to Devil's Head in July and February. During the summer, low dissolved oxygen concentration and high phosphate content occur in the deep Juan de Fuca water. This is in accord with the biological history of the water which has been depleted of oxygen and enriched in dissolved phosphate during its tenure near the bottom outside of Juan de Fuca Strait. The surface water of Puget Sound is low in phosphate and high in dissolved oxygen which likewise agrees with the biological processes occurring at this time. Most of the surface Juan de Fuca water and deep Puget Sound water assumes some intermediate value in oxygen content and phosphate concentration. The February picture shows a very close grouping of points with high oxygen, high phosphate concentrations in Puget Sound and low oxygen, low phosphate concentrations in Juan de Fuca Strait. Obviously biological activity plays only a minor role in the phosphate distribution in winter. The major influences are advective and diffusive processes.

Certain conclusions might be drawn from the foregoing treatment.

Phosphates can be used as an independent check on water movements in the Puget Sound area. Horizontal advection and biological activity are dominant processes in the distribution of phosphates in summer. Vertical turbulent mixing appears to take over in winter.

#### Phosphate Budget

In order to determine the annual budget of phosphate in Puget Sound, all the possible factors contributing and removing phosphate must be considered. A simple equation can be written to express the changes of total phosphate occurring in the Sound over the period of a year.

$$Po + O_d + R + I + P + E + O + F + F + (N + C) \quad (1)$$

In this equation, Po represents the inorganic dissolved phosphate at the beginning of the year, P that at the end of the year, Oo is the organic phosphate at the beginning of the year, O that at the end of the year, R is the annual contribution of the rivers, I is the annual influx from upwelled waters and E is the phosphate added by pollution. Withdrawing of phosphate from the system is represented by N the annual efflux of phosphate to surface water, F the fishing activity of man and birds, P the flux of phosphate in the plankton and netton, B precipitation due to biological activity, and C chemical precipitation. The last two terms are grouped together and should be determinable from the sediments.

Rivers as it has been shown already, contribute very little phosphate and will be neglected in the first approximation. The main source of phosphate in the surface water from Juan de Fuca Strait. This phosphate is added by deep currents moving into Puget Sound during the summer months of upwelling conditions. Some of the phosphate accumulated during the

summer months is flushed out of Puget Sound by the seaward flow of brackish water at the surface during the large runoff period in winter. Pollution contributes a considerable quantity of phosphate in a year, but its significance can only be measured in terms of the difference between the natural influx and efflux of phosphate. Photosynthesis of phytoplankton removed a substantial quantity of inorganic phosphate during the summer and concentrates it in organic form in the plant and animal life. Some of this phosphate is lost from the Sound when animal life moves out or is removed by fishing. A certain fraction of the planktonic organisms settling to the bottom after death may not be completely decomposed and form part of the organic material in the sediments. An additional biological factor which may serve to remove phosphates is the benthic fauna. Loss of phosphate in the water may occur by chemical precipitation of calcium phosphate or some combined phosphate compound when the solubility product of the ionic concentrations is exceeded. This loss cannot be overlooked as no determinations of phosphates in the sediments have yet been made. Such precipitation could possibly occur in Dabob Bay, Lynch Cove and the southern reaches of the Sound where the highest phosphate concentrations (up to  $5 \mu\text{g-at/l}$ ) are encountered.

An estimate of the relative magnitude of the terms in equation (1) should be made before any quantitative evaluations are attempted. This will obviate painstaking calculations in those terms which are ultimately insignificant. In the case at hand, the dominating factors appear to be the natural influx and efflux of phosphate with the water. To arrive at some figure for a balance or deficit in phosphorus at the end of a year on

the basis of water exchange, it is necessary to know the volume of water which flows into and out of Puget Sound in the course of a year and the average phosphate concentration in each water mass. If the difference between influx and efflux of phosphate is large, then the contribution of the other terms is very minor. On the other hand, a very close balance in the two terms would increase the relative weight of the other terms. A net addition of phosphate to Puget Sound, as determined by this method, would mean either an increase in the phosphate concentration of the waters of Puget Sound at the end of a year and/or an accumulation of phosphate in the sediments resulting from biological and chemical precipitation.

Current measurements made in Admiralty Inlet ( $48^{\circ}01'N$ ;  $122^{\circ}37'W$ ) over a three-day period, Nov. 30 to Dec. 3, 1953, were employed to calculate the inflow of Juan de Fuca water and outflow of surface water. It was assumed that the mechanism for water exchange through Admiralty Inlet is unaltered throughout the year and that the period of measurements represents average conditions. Observations at other seasons of the year will be necessary to check the validity of this assumption. Also, the exchange through Deception Pass was neglected. The cross-sectional area of Admiralty Inlet ( $3.43 \times 10^5 m^2$ ) is nearly 100 times that of Deception Pass ( $4.31 \times 10^3 m^2$ ) so that, in the first approximation, this introduces only a small error. The volumes calculated on an annual basis were  $4.97 \times 10^9$  cubic meters (77.8 cubic nautical miles) for the inflow and  $5.41 \times 10^9$  cubic meters (84.7 cu.n.mi.) for the outflow. Phosphate concentrations below 40 meters at Port Townsend were averaged for July, August, September and November, 1953, and February, 1954, to give a mean phosphate concentration of

2.16  $\mu\text{g-at/l}$  in the inflowing waters. Similarly, a mean of 2.06  $\mu\text{g-at/l}$  was obtained for the outflowing water (by averaging the phosphate concentration in the upper 40 meters at Port Townsend. The total weight of phosphate phosphorus added was computed to be  $33.2 \times 10^6 \text{ kg}$  ( $36.6 \times 10^3 \text{ tons}$ ), and the total removed was  $34.4 \times 10^6 \text{ kg}$  ( $38.0 \times 10^3 \text{ tons}$ ). The difference of  $1.2 \times 10^6 \text{ kg}$  should be the net phosphorus removed from the Sound in a year's period. On the basis of this calculation alone, the phosphate content of Puget Sound should be less at the end of the year than at the beginning. One large error in this evaluation might be in the average phosphate concentrations used as they were only based on five months' observations.

The monthly data for phosphates off Port Townsend for the period 1932-1942 were examined and it was observed that the difference between phosphate concentration in inflowing and outflowing water was greater for those years than that calculated for 1953-54. An average outflowing concentration of 1.82  $\mu\text{g-at/l}$  and outflowing concentration of 1.67  $\mu\text{g-at/l}$  was computed for the year 1939. This gives a total annual influx of  $278 \times 10^5 \text{ kg}$  ( $30.7 \times 10^3 \text{ tons}$ ) and efflux of  $279 \times 10^5 \text{ kg}$  ( $30.8 \times 10^3 \text{ tons}$ ) using the 1953 figures for water flow. A close balance is achieved.

The first consideration for errors in the foregoing calculations is in the volume inflow and outflow of water. Although an absolute error in this calculation might be quite large, of the order of 15% (Paquette, personal communication), the relative error is small. The difference between outflowing and inflowing volume is the major error-determining factor and this is governed by the river discharges which can be determined quite accurately. Provided the outflowing volume is several times

greater than the discharge of the rivers an error in the volume calculations will make only a small change in the phosphate budget. An error in the choice of average phosphate values, however, may be very significant. To illustrate this point a simple equation for phosphate exchange through Admiralty Inlet can be written,

$$V_o \times C_1 = N(V_o - V_R) C_2 \quad (2)$$

$V_o$  is the volume outflow,  $V_R$  is the volume discharge of the rivers,  $V_o - V_R$  is the volume inflow,  $C_1$  and  $C_2$  are the concentrations of phosphate in the outflowing and inflowing waters, respectively, and  $N$  is the ratio of the annual phosphorus carried out to that brought in, that is,  $\frac{P}{I}$ . This equation is exact for a water volume and phosphate balance at the entrance to Puget Sound when all other influencing factors are ignored. Rearranging, and solving for  $N$ , the equation becomes

$$N = \frac{V_o \frac{C_1}{C_2}}{V_o - V_R}$$

The right-hand side can be divided through by  $V_o$ , numerator and denominator, giving

$$N = \frac{\frac{C_1}{C_2}}{1 - \frac{V_R}{V_o}} \quad (3)$$

This equation is a hyperbolic form and can be graphed as shown in Figure 13. The curve for positive values of  $V_o$  and  $N$  shows that when the outflow  $V_o$  is greater than four times the river discharge, the curve approaches the line  $N = \frac{C_1}{C_2}$  asymptotically. Little error is introduced in the value of  $N$  by errors in  $V_o$  beyond this point. However, in the region of the curve  $V_o < 2 V_R$  small errors in the volume outflow will make large errors in  $N$ .

Since the outflow of water is in the neighborhood of 12 times the river discharge, the value of  $N$  is little affected by an error of 15% in the water outflow. This can be seen from (3) where if  $V_o = 84$  cu.n.mi. and  $V_R = 7$  cu.n.mi.,  $N = 1.09 \frac{C_1}{C_2}$ . If an error of 20% is introduced into  $V_o$  to give 67 cu.n.mi. and  $V_R$  is again 7 cu.n.mi.,  $N = 1.12 \frac{C_1}{C_2}$ . This gives an error of 2.8% in  $N$  assuming  $\frac{C_1}{C_2}$  is nearly 1. On the other hand, an error in  $\frac{C_1}{C_2}$  by 10% may be very significant in the final result. Suppose actual  $C_1 = 2.0$   $\mu\text{g-at./l}$  and  $C_2 = 2.1$  which gives  $\frac{C_1}{C_2} = 0.950$  and  $N = 1.037$  using the true value of outflow. Then  $C_2$  is taken as 2.3  $\mu\text{g-at./l}$  giving an error of 9.5% in inflowing phosphate concentration. The value of  $N = \frac{.870}{.917} = 0.949$  which is an 8.4% error in  $N$ . These errors, of course, are much larger when based on the difference in overall phosphate. Hence it is important to be able to determine an accurate value for outflowing and inflowing phosphate concentrations.

Because the natural influx and efflux of phosphates in Puget Sound appear to maintain a very critical balance, interference from outside factors can be effective in shifting this balance. Sewage discharged into Puget Sound is roughly that from about a million people. Various authors give different values for phosphorus concentrations in sewage. Armstrong and Miall (1946, p. 43) give 17,000 tons of rock phosphate per year for 5,000,000 people. This works out to about 680 tons of phosphorus per million people assuming the rock phosphate to be  $\text{Ca}_3(\text{PO}_4)_2$ . Sawyer (1952, p. 771) gives a value of 1.2 lb. phosphorus per capita per year made in a survey at Madison, Wis., (1942-1944), but states that this figure can be reasonably doubled at present due to the increased use of synthetic

detergents containing about 23.4% phosphorus. If it can be assumed that the population in the Puget Sound area obeys the general trend in the increased discharge of phosphorus, a value of 2 lbs. phosphorus per capita per year should be reasonable. This gives a total of  $10^5$  tons ( $9 \times 10^5$  kg) of phosphorus contributed by sewage per year. Although such a quantity may be insignificant in a large, well-flushed, open seaway, it may be quite consequential in Puget Sound. Eutrophication in lakes as a result of sewage is common and has been reported for certain of the shallow, constricted fiords of Schleswig-Holstein (Kändler, 1953, p. 199). Any excess of phosphate in Puget Sound detected in the deep water and in the sediments in future years may be largely due to pollution.

The fisheries can be regarded as removing a certain amount of phosphate from the water annually. Commercial fishery landings in Puget Sound total about 50,000 tons per year (Washington State Commercial Fishing Statistics, 1952, p. 24). The sport fishery may remove 10% as much as the commercial catch and an equal amount will be allowed for removal by birds, which is probably too large. A total of 60,000 tons of fish can be considered as taken out of Puget Sound per year although a large percentage of the commercial catch is from outside the Sound waters. Hawk, et al (1945, p. 1242) gives 0.286% as the phosphorus content of canned salmon. For 60,000 tons of fish, predominantly salmon, 172 tons of phosphorus are removed. It is probable that only about 1/10 of the fish caught feed in Puget Sound. The total phosphorus removal by various fisheries does not likely exceed 50 tons ( $4.5 \times 10^4$  kg) which is quite small compared to the other factors. Withdrawal of phosphate from Puget Sound waters by kelp



and seaweed harvesting is probably insignificant as no established kelp industry exists in the area.

There is no way at present to evaluate the flux of phosphorus in the plankton and nekton. It undoubtedly results in a loss of phosphorus from the sound over a year's period by the drift seaward of planktonic organisms in the surface waters. Assume that the upper 40 meters of water contain  $0.5 \mu\text{g-at/l}$  of phosphorus in the plankton for six months of the year and that this plankton moves out with the outflowing water. Then the loss of phosphorus in this form amounts to  $41.7 \times 10^5 \text{ kg}$  or  $4.6 \times 10^3$  tons. This figure may be as much as ten times too large from the choice of maximum values of organic phosphorus concentration and volume of outflow. But in a system which is closely balanced in its phosphate budget, the loss of phosphorus in the plankton may have some bearing.

It may be argued that phosphate data used here are inorganic phosphate determinations and that the organic phosphate may be present in large concentrations. Hansen and Robinson (1953, p. 35) have shown that organic phosphate may reach concentrations up to  $1.0 \mu\text{g-at/l}$  compared to  $2.5 \mu\text{g-at/l}$  of inorganic phosphate. On an annual basis it is probably valid to assume that the dissolved organic phosphate maintains a close balance in the water exchange, as it is fairly evenly distributed in the water column. The large withdrawal would be the particulate organic phosphate in the plankton. Until more data are available on organic and total phosphate, little can be said positively on the net overall effect due to neglect of the organic phosphate.

Equation (1) can now be reduced to only a few terms, with reasonable

confidence,

$$I + p \approx R + P + (B + C) \quad (4)$$

No experimental data are available to determine  $(B + C)$  directly from the sediments. It could conceivably be of the same order of magnitude as  $p$ , that is, about  $10^3$  tons per year. If this were evenly distributed in the bottom sediments it would amount to 0.34 grams per square meter. On the basis of a total annual deposition of sediment of  $3 \times 10^6$  tons the phosphorus would amount to .033% or .076% of  $P_2O_5$ .

A graphical representation of the relative magnitude of each of the terms in equation (1) for the phosphate budget is shown in Figure 14. Before more quantitative determinations can be made, measurements of organic and total phosphate will be required as well as more complete data on the seasonal volume outflow and inflow and the average phosphate concentrations.

#### Organic Production in Puget Sound from Phosphate Depletion

Assuming that the removal of phosphate by advective processes is very slow from February to July compared to depletion by plankton photosynthesis and that very little phosphate is added by the deep water from Juan de Fuca Strait during this time, one can make an estimate of the minimum organic production. Regeneration and reuse of the phosphate during the interval is not taken into account, and this further reduces the calculated production figure. Point Jefferson was chosen as a representative station for the main basin of Puget Sound. The average phosphate concentration was determined for February and July by mechanical integration of the phosphate curves (Figure 10) from the surface to a maximum depth of 270 m.

with a planimeter. Although minimum values are taken for the summer preceding the available winter data, it is believed the error should be small as the maximum winter phosphates do not vary much from year to year. A winter average phosphate maximum at Point Jefferson is  $2.33 \mu\text{g-at/l}$ ; the summer minimum is  $2.01 \mu\text{g-at/l}$ . The difference of  $0.32 \mu\text{g-at/l}$  is assumed as phosphate used for photosynthesis. For equivalents of  $1 \mu\text{gP} = 90.0 \text{ mg dry plankton} = 41.6 \text{ mg carbon}$  (Sverdrup, et al., 1946, p. 929), the production per square meter per year is calculated at 243 gm. dry plankton or 111 gm carbon. If this production is put on a comparative basis with other regions of the world (see Table VII) it is moderate to low.

The validity of using the whole depth of 270 m. as a basis for organic production from phosphate depletion may be questioned inasmuch as the euphotic zone does not extend so deeply. Replenishment at the surface would necessarily rely on diffusion of nutrients from depth which is not considered in the calculations ordinarily. Recalculation on the basis of 30 m depth of euphotic zone gives an annual production even smaller than previously with 30 gm carbon per square meter. Plankton production in the Sound is much higher than this figure would indicate, and it can only be concluded that phosphates are continually replenished from depth.

The figures calculated here are low minima for the annual production as they take into consideration only the early plankton peak of the year. However, even if the production calculated were doubled, the production potential in nutrients is certainly not being utilized. Light, temperature and other factors must be limiting the phytoplankton synthesis. Another point to consider is that Point Jefferson is only an average station for mid-channel regions. Much higher plankton populations have been

observed in the shoaler, sheltered embayments. For example, plankton tows of equal duration were taken recently (April 24, 1954) in the open Sound waters as well as in Port Madison. From a qualitative visual comparison of settling volumes, the Port Madison hauls contained about twice as much plankton as the hauls from the open Sound.

#### Seasonal and Long-Term Variations in Phosphate

The seasonal variation of phosphate concentration at different levels off Point Jefferson is shown in Figure 15. Concentrations of phosphate increase at all levels from July to February with an intervening peak in October. Generally speaking, seasonal inorganic phosphate variation in Puget Sound undergoes a low in summer and a high in winter. The summer low is due to plankton activity, whereas the winter high results from a late-summer inflow of high-phosphate waters and regeneration of nutrients.

A regular seasonal pattern is apparent in Juan de Fuca Strait for the season 1953-1954, with a high phosphate content in summer and a low in winter. However, one must be cautious in accepting this as a regular seasonal picture. Analysis of data taken on a 10 year period, 1932-1942, does not suggest an annual recurrence of high phosphate in summer and low phosphate in winter in Juan de Fuca Strait. Although salinity, temperature and density data show, on the average, a period of summer upwelling, the extent of this process may vary from year to year. In certain years high-phosphate waters may not be brought to the surface, or biological factors may control the inorganic phosphate concentration in Juan de Fuca Strait. A large phytoplankton bloom may deplete much of the summer phosphate in

certain years of favorable conditions. The annual picture of low phosphate concentration in summer and high concentration in winter suggested for Puget Sound, on the other hand, appears to repeat from year to year when checked on a 10 year basis.

Long term fluctuations in phosphate in both areas are not large. Certainly the long-term trends in phosphate concentration, which have occurred in the English Channel (Russell, 1955), have not appeared in Juan de Fuca Strait and Puget Sound in the period of available observations. The ten-year variation in phosphate in the upper 25 m. in July is shown in Figure 16 for Pillar Point and Point Jefferson.

#### Silicate Distribution

The distribution of silicates is primarily determined by the runoff and phytoplankton activity. Rivers carry a much higher concentration in silicates than normally found in sea water (see Table V). A large diatom bloom may deplete the silicate content to a low concentration. The section from Pillar Point to Devil's Head in Figure 4 shows the July silicate distribution. High silicate concentrations occur off the Nisqually River estuary, but low silicate water occupies the surface in the region south of Seattle where a large diatom bloom has probably occurred. Unfortunately, there are no synoptic data to show the winter distribution, but spot data for the winter months show that silicates are generally in high concentration. Some silicates are added to the Puget Sound system by deep waters coming in through Juan de Fuca Strait. These silicate concentrations are usually of only average value.

Seasonal variation of silicates in the upper 30 m. is shown in Figure 17 for both Pillar Point and Point Jefferson during the year 1939.

### Nitrates

Generally, the nitrate concentrations are higher in the coastal areas than they are farther offshore. Some nitrate is contributed by rivers as shown in Table V, but the concentration is small. The vertical distribution in Puget Sound is characterized by a peak concentration at some intermediate depth of about 100 m. and then drops off towards the bottom. Typical examples for stations in Puget Sound, Juan de Fuca Strait and the open Pacific Ocean appear in Figure 18.

The ratio of nitrate to phosphate by atoms, 15 to 1, proposed as "normal" by Cooper (1938) and shown by Sverdrup *et al.* (1946, p. 243) to hold generally for the oceans, is somewhat high for Puget Sound waters. Aside from much scatter in the points, Figure 19 shows that for stations following the usual trend, an average ratio for  $\frac{N}{P}$  of 10 to 1 is closer. This deviation from the normal is attributed to either biological processes, which may regenerate the nitrates at a slower rate than phosphates, or to a higher ratio of phosphate to nitrate in the source water. The latter alternative is not satisfied by the river water, which has some nitrate but is almost completely devoid of phosphate. The increased phosphate content of sewage, however, gives a ratio of 10 to 1 for the atoms of nitrogen to phosphorus (Sawyer, 1952, p. 769). Friday Harbor data taken over a period of several years, 1931-1935 (Thieler and Thompson, 1937, p. 49) show an average ratio of 12.7 for  $\frac{NO_3-N}{PO_4-P}$  in mg-atoms. Obviously, the ratio

approaches the normal as one goes seaward. This is in accord with the data obtained by Hakestraw in the Gulf of Maine where the ratio is lower and more variable than in the open ocean outside the Gulf.

Too many conclusions drawn on the basis of the nitrate determinations may be misleading because the method and analysis for nitrate have been only roughly quantitative. However, results reported by Chow and Robinson (1953, p. 10) employing a sensitive polarographic method for nitrate analysis have shown that the previous data are not seriously in error.

### Nitrites

The nitrite form of nitrogen is the lower oxidation state found in non-reducing environments and tends to be somewhat unstable. It is generally found only inshore and near the surface in the warm waters. The reduction of nitrates to nitrites apparently occurs by the action of denitrifying bacteria (Hann and Thompson, 1941, p. 17). Because of the apparent temperature dependence of nitrites, the seasonal variation shows high concentrations in summer and low values in winter in Puget Sound. A typical seasonal variation of nitrites in the upper 30 m. is shown in Figure 20.

Little can be said concerning the relationship of phytoplankton activity to the seasonal picture of nitrites except that phytoplankton maxima are followed by increased nitrite concentrations. An inverse relationship exists between nitrite and phosphate concentrations. Varying nitrite content of sea water reflects an index of the oxidation of the nitrogen organic compounds to nitrate, which in turn re-enters the

nitrogen cycle of the sea as nutrient salts usable by the phytoplankton population. The ratio of  $\frac{\text{NO}_2\text{-N}}{\text{PO}_4\text{-P}}$  in  $\mu\text{g-atoms}$  shows a consistency for about seven months of the year, April through October, with an average of about 0.2. (Pflüger and Thompson, 1937-38, p. 48).

Upwelling generally brings up low nitrite water as seen for stations at Pillar Point where the bottom water seldom had any determinable nitrite. Rivers may contribute some nitrite depending on the amount of organic nitrogen and the oxidation state of the water.

#### Other Chemical Constituents

Aluminum occurs in substantial quantity in sea water. The overall average content of waters in the San Juan Island area according to Haendler and Thompson (1939, p. 15) is  $20 \mu\text{g-at/l}$ . Monthly averages exhibited high concentrations in late spring and early summer and low concentrations in winter. Some evidence was given for a relationship of aluminum concentration with biological activity. In the offshore Pacific water there was a slight increase in aluminum at the depth approaching 1000 m where high iron and low oxygen values were found. Offshore concentrations were generally higher ( $15\text{-}65 \mu\text{g-at/l}$ ) than those inshore ( $6\text{-}16 \mu\text{g-at/l}$ ), but no correlation could be made with land drainage as no aluminum data were given for river water.

Ammonia concentration is low in almost all waters of Puget Sound, the San Juan Islands and Juan de Fuca Strait. An exception can be made for the more stagnant basins of Hood Canal and East Sound. A maximum concentration of  $7.6 \mu\text{g-at/l}$  was found at depth in East Sound; the remaining values were less than  $1.8 \mu\text{g-at/l}$ . (Robinson and Wirth, 1934, p. 19).



This lack of ammonia nitrogen indicates an absence of highly reducing conditions and ~~good circulation~~ <sup>stagnation</sup> of water.

Boron content of ocean waters is slightly higher (0.42 mg-at/l) than that of inshore waters (Haro Strait, 0.38 mg-at/l, but the boron/chloride ratio remains nearly constant (Igalarud, Thompson, and Zwicker, 1938, p. 54). Organic and other complex forms of boron have not been reported. These may be significant as marine plants and animals appear to concentrate boron. Algae from the San Juans varied in boron from 4.2 to 14.9 mg-at/kg dry weight basis.

Bromine occurs in concentrations of 0.057 ‰ in the surface waters of Puget Sound at Point No Point and Port Townsend (Thompson and Korpi, 1942, p. 35). Concentrations increase with depth to about 0.059 ‰ at 100 meters. The bromine-chlorinity ratio ( $\frac{Br}{Cl} \frac{\text{‰}}{\text{‰}}$ ) is remarkably constant for all waters examined being .0034. Consequently, in the more saline water off the coast of Washington (47° 09' N, 125° 10' W) the bromine concentration at the surface reaches 0.062 ‰.

Calcium concentrations in San Juan Island water are considerably lower (9 mg-at/l) than in the Gulf of Alaska (10.3 mg-at/l) but higher than in the surface Strait of Georgia water (7.7 mg-at/l). The Ca/Cl ratio is nearly constant ranging from 0.0214 to 0.0216 for Ca in mg/kg or .535 to .540 where Cl is in mg-at/l. (Thompson and Wright, 1930, p. 919). A certain amount of calcium is added by rivers, but the concentration in fresh water is much smaller than it is in the sea. Thus dilution by land drainage decreases the calcium concentration in Puget Sound. The difference in calcium concentration between fresh water and sea water is reflected in the larger percentage of calcium in the shells of marine pelecypods than in

the shells of fresh water calcareous organisms.

Copper in the sea water of the local area has been studied intensively by Chow and Thompson (1952, 1954a). They obtained an average concentration of 0.023  $\mu\text{g-at/l}$  in all samples analyzed in the San Juan Islands. A definite seasonal trend was indicated with an autumn minimum of 0.016  $\mu\text{g-at/l}$ . The concentration of copper varied directly with the amount of fresh water from the Fraser River in the area and inversely with the density, phosphates, and silicates. Offshore Pacific stations gave slightly lower values of copper, from 0.016 to 0.020  $\mu\text{g-at/l}$ , compared to the average inshore values. At Point Jefferson in Puget Sound the concentration was near the overall average, 0.020  $\mu\text{g-at/l}$ . Near Tacoma, however, there was about 1.5 times as much copper as normal with about 0.033  $\mu\text{g-at/l}$ . This increase in concentration was attributed largely to the tailings discharged from the smelters of Tacoma. Some of the lake water (Lake Washington, Lake Union) contributing to Puget Sound waters was analyzed and found to have copper concentrations of 0.070  $\mu\text{g-at/l}$ , nearly four times as great as average sea water. Even larger concentrations of copper have been detected in some of the northern rivers such as the Fraser and Komatiko (Thompson, personal communication). This strongly suggests that runoff waters in the Pacific Northwest flow through copper-bearing ores and add measurable quantities of copper to the sea water. It has been suggested that biological processes concentrate copper (Chow and Thompson, 1954a). In an euxinic environment as found in the upper reaches of East Sound, copper is precipitated evidently as copper sulfide by the hydrogen sulfide present. On exposure to high air temperatures during

the summer low tides, the copper sulfide is oxidized to copper sulfate releasing relatively large copper ion concentrations into the water. Up to  $0.046 \mu\text{g-at/l}$  of copper occur in the water at the head of East Sound and  $590 \mu\text{g-at/kg}$  in the sediments.

Iron has been regarded for some time as one of the minor constituents in sea water which acts as a growth factor in phytoplankton synthesis (Oren, 1931; Harvey, 1937). In the Friday Harbor area a decrease in the iron content of the water occurs in the spring months. (Thompson and Bremer, 1932, p. 292). This seasonal trend is attributed to the spring bloom of diatoms. In East Sound where the plankton production is large, no iron was detected in the summer months. In Juan de Fuca Strait the concentration ranged from  $0.66$  at the surface to  $5.00 \mu\text{g-at/l}$  at  $300 \text{ m}$  for the summer of 1931. For corresponding depths here Strait waters contained  $0.75$  and  $2.06 \mu\text{g-at/l}$  and San Juan Channel waters contained  $0.54$  and  $1.52 \mu\text{g-at/l}$ .

Magnesium, aside from its commercial extraction from sea water, is of interest biochemically in that it forms the central atom of the complex chlorophyll molecule. However, being one of the major constituents in sea water, it is never a limiting factor to phytoplankton growth. Rivers discharging into Puget Sound contribute only small amounts of magnesium (Table V) and generally dilute the concentrations in the sea water. Friday Harbor surface values showed an average concentration of  $46 \mu\text{g-at/l}$  which is lower than the Gulf of Alaska value of  $30 \mu\text{g-at/l}$ . The average magnesium chlorinity ratio is nearly constant at  $\frac{\text{Mg}}{\text{Cl}} \frac{\text{g/1000}}{\text{g/1000}} = 0.067$  or  $2.7$  when Mg is in  $\mu\text{g-at}$ . This ratio also holds quite closely in diluted estuary waters.

The calcium-magnesium ratio is likewise nearly a constant at 0.321 by weight or 0.195 by atoms. (Thompson and Wright, 1930, p. 919).

Manganese is present in very small concentration in sea water, and it has been regarded also as a growth factor. (Harvey, 1950). According to Thompson and Wilson (1935, p. 236), concentration is almost doubled by the presence of plankton in a sample of water from San Juan Channel. Unfiltered samples contained 0.20 ug-at/l while filtered ones contained only 0.11 ug-at/l of manganese per liter. Surface water from Hood Canal at the mouth of the Liliwamp River contained only 0.05 ug-at/l. Plankton contain high concentrations of manganese with about 0.07% or 12.7 mg-at/kg on the basis of ash weight. Bottom samples contained remarkably high concentrations of manganese for certain areas sampled. Parts of Hood Canal showed an average percentage of 0.28 or 50.9 mg-at per kilogram of dry mud. A sample off Shingle Island, southeast Alaska, gave analysis of 0.25% or 4.5 mg-at/kg of dry mud. Commencement Bay off Tacoma gave only 0.07% or 12.7 mg-at/kg. Most of the high concentrations occurred in diatomaceous muds. The apparent constancy of results agrees well with the results obtained from the analysis of phytoplankton. (Thompson and Wilson, 1935, pp. 237-8).

Radium in sea water and sediments has been studied with considerable interest by several investigators, because of the stimulus given to radiochemistry by prominent discoveries early in the century. In the San Juan Archipelago waters radioactivity increases from the surface to the bottom (Devaputra, Thompson and Utterback, 1932, p. 363). Compared to Gulf of Alaska waters, the average radioactivity of these waters is lower, but is higher

than that of California offshore waters. The latest determinations of the radium content of San Juan waters by methods more refined than those used earlier give concentrations of  $6 \times 10^{-17}$  g.Ra/c.c. of water (Evans, Kip, and Moberg, 1938). Much research has been done on the radium content of sediments in the Pacific Northwest (Utterback and Sanderson, 1937, 1941, 1948).

The average concentration of radium in Puget Sound sediments taken on the basis of 11 stations is  $0.37 \times 10^{-12}$  g.Ra/gm. This concentration is comparable to the Ra content of glacial drift. A high Ra concentration was found in the sediment at the mouth of the Fraser River,  $0.64 \times 10^{-12}$  g.Ra/gm. The drainage basin of the Fraser River, which is predominantly granitic, has a Ra content three times as great as the rocks of the southern portion of Vancouver Island and the northern portion of the Olympic Peninsula which are chiefly sandstone and basalt. Generally the Ra content of the sediment is related to the Ra content of the land from which the sediment was derived. (Utterback and Sanderson, 1937-8, pp. 189-191). Offshore samples of the northeast Pacific (Piggott, 1933) show a larger Ra content ( $7.6 \times 10^{-12}$  g.Ra/g), but this large discrepancy may be due to difference in technique of analysis. Ra content of samples from glacier-fed inlets in southeast Alaska was approximately twice that of the offshore samples (Sanderson and Utterback, 1941, p. 137).

Strontium is present in highest concentration of the minor constituents in sea water. It is near the threshold of being a major constituent. In sea water sufficiently far from dilution effects of fresh water the strontium-chlorinity ratio varies only slightly. Recent work by Chow and

Thompson (1954b) shows that water in the Friday Harbor area has a range in strontium content of 72  $\mu\text{g-at/l}$  to 88  $\mu\text{g-at/l}$ . In Pacific Ocean water off the Washington coast the range is from 87 to 99  $\mu\text{g-at/l}$ . The average strontium content of sea water with a chlorinity of 19.35 ‰ is 95  $\mu\text{g-at/l}$ . Fresh water contains only traces of strontium outside the range of sensitivity of the flame photometric technique employed for analysis. The function of strontium in marine organisms is unknown, but work being conducted currently (Chow, Seminar) shows that different organisms utilize strontium in different ratios to calcium.

Sulfur occurs in sea water chiefly as sulfate, one of the eight major constituent ions. According to Thompson, Lang and Anderson (1927, p. 287) concentrations of sulfate in Puget Sound vary from 20.5 to 25.0  $\text{mg-at/l}$ . Water in the San Juan Archipelago reaches a maximum of 26.4  $\text{mg-at/l}$  and that in the north Pacific, on the Alaskan coast, varies from 25.2 to 26.6  $\text{mg-at/l}$  at the surface. The deep water has a higher sulfate concentration with 28.3  $\text{mg-at/l}$  at 110 meters. River water has a low sulfate content compared to sea water but has a high sulfate-chlorinity ratio. A concentration of 0.185  $\text{mg-at/l}$  was reported for the Skagit River which gives a sulfate-chlorinity ratio of 95.0 with the sulfate in  $\text{mg-at/l}$ . For Puget Sound the ratio is only 1.48. Hence the proportionality constant of sulfate to chlorinity is disturbed when the sea water is diluted by more than an equal volume of fresh water. Adsorption of the sulfate ion on colloidal particles carried by river water may lower the ratio. (Thompson, Lang, and Anderson, 1927, p. 281). Biological activity generally reduces the sulfate to sulfide in euxinic environments where stagnation has

occurred and oxygen has been depleted completely by bacteria. On exposure to the atmosphere or to water with high oxygen content, the sulfide may be oxidized back to sulfate or elementary sulfur.

Titanium is present in sea water in extremely small concentrations. It has been detected both spectrographically and spectro-photometrically but occurs only to the extent of 0.04  $\mu\text{g-at Ti/l}$  in Puget Sound. In diatoms as much as 0.0021 to 0.032% Ti on dry weight basis has been found. Sea muds contain appreciable quantities of Ti and a sample taken from East Sound gave 0.20% titanium in the dried sediment. (Griel and Robinson, 1952, pp. 176-178).

The following other constituents have been detected in or near Puget Sound water: fluoride, lithium, potassium, gold, dissolved nitrogen and isotopic water. These are reviewed elsewhere (Puget Sound Literature Survey, Volume III, 1954).

#### Suggestions for Future Work

1. Waters from all the various rivers should be analyzed for their chemical content to provide a more complete and more accurate picture of the chemistry of runoff water in Puget Sound.
2. The upwelling off the northwestern Washington coast has yet to be definitely established by an intensive oceanographic study.
3. The phosphate budget should be checked more carefully on a month-to-month basis throughout the year to give a more accurate seasonal trend.
4. Nitrate distribution should be analyzed carefully to determine any similarity with that of phosphate. The seasonal variations of nitrites and silicates in Puget Sound need to be investigated more thoroughly.
5. Year-to-year variations in the nutrient salts in both Puget Sound and Juan de Fuca Strait should be studied to determine any long-term cycles.

Much data on these are available from 1932 to 1942.

6. Different areas in Puget Sound such as Hood Canal, Possession Sound and the southern section below Tacoma Narrows should be treated independently on an annual budget basis to provide a better overall understanding.

7. A careful examination should be made of the bottom waters to study the relationship between the dissolved oxygen and phosphate concentrations. This should determine changes due to biological activity and those due to advection and diffusion.

8. Careful chemical analysis of the sediments would be of value particularly for determination of phosphorus, copper, iron and manganese content.

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TABLE 1 Comparison of Annual Maxima and Minima for Some Dissolved Constituents in Various Marine Regions-----  
(Average in Depth 0 - 25 M.)

REGION	Phosphate Max.	$\mu\text{g-at/l}$ Min.	Silicate Max.	$\mu\text{g-at/l}$ Min.	Nitrate Max.	$\mu\text{g-at/l}$ Min.	Nitrite Max.	$\mu\text{g-at/l}$ Min.	Literature Source
Puget Sound (47° 44' N 122° 25' W)	2.4	1.5	61	24	29	11	.03	.65	Present Work
Strait of Georgia (49° 15' N 123° 47' W)	2.0	0.4	62	22	27	6.0	0.30	0.05	Tully and Dodimead, 1954
Juan de Fuca Strait (48° 18' N 124° 03' W)	2.1	1.4	55	19	16	5.0	.57	.03	Present Work
Friday Harbor <sup>1</sup>	3.3	.8	80	33	37	4	.75	.03	Phifer and Thompson, 1937-38, P. 57-58
Olga, East Sound	2.2	.25	49	28	12	5	.68	.09	Present Work
Bering Sea <sup>2</sup>	2.0	0.3	70	5	-	-	.3	0	Barnes and Thompson, 1938, P. 79-83
Barents Sea	0.63	0	-	-	12.5	1	-	-	Sverdrup et al., 1946 P. 939
Gulf of Maine	1.	0.2	-	-	12	2	-	-	Sverdrup et al., 1946 P. 939
English Channel	0.55	0	4	0	7	0	-	-	Sverdrup et al., 1946 P. 939
Fjords of Schles <sup>3</sup> Wig Holstein	10.	.3	-	-	-	-	7.1	0	Kandler, 1953, P. 196
Antarctic Ocean (South Georgia)	1.7	0.9	30	5	-	-	-	-	Sverdrup et al., 1946, P. 939

TABLE 1 (Continued)

REGION	Phosphate Max.	$\mu\text{g-at/l}$ Min.	Silicate Max.	$\mu\text{g-at/l}$ Min.	Nitrate Max.	$\mu\text{g-at/l}$ Min.	Nitrite Max.	$\mu\text{g-at/l}$ Min.	Literature Source
Northeast Pacific Ocean <sup>4</sup>	1.1	.03	-	-	-	-	0.4	0	Goodman and Thompson, 1940, P. 27-30
Northwest Pacific Ocean <sup>2</sup>	1.5	.05	-	-	-	-	-	-	Graham and Moberg, 1944
Off Washington Coast 46° N. 127° W.	.23	-	2	-	3.1	-	0	-	Present Work
Southern Calif. 32° 05' N. 124° 55' W.	.63	.31	-	-	-	-	-	-	Marine Life Research Program, 1950.

1 Extreme Surface Values

3 Average for Upper 10 M.

2, 4, 5 Max, and Min. Represent Regional Variation in Summer

TABLE 11 - CHARACTERISTICS OF SOME NORTH AMERICAN RIVERS

RIVER	Sampling Location	Drainage Basin Area (Square Miles)	Mean Annual Discharge (Acre Feet) <sup>6</sup>	Dissolved Substances (p.p.m.)	Suspended Substances (p.p.m.)	Total Annual Dissolved Material (Tons)
Mississippi	New Orleans	1,245,000	$434 \times 10^6$	166	1,400	$97.8 \times 10^6$
Columbia	Cascade Locks	239,600	$129 \times 10^6$	97	40	$17 \times 10^6$
Colorado	Yuma	200,000	$16 \times 10^6$	707	8,460	$15.3 \times 10^6$
Rio Grande	El Paso	38,600	$0.86 \times 10^6$	699	14,140	$.82 \times 10^6$
Fraser	New Westminster	85,600	$88 \times 10^6$	69	73	$8.23 \times 10^6$
Skagit	Sedro Wooley	3,191	$12 \times 10^6$	48	19	$0.78 \times 10^6$
Cedar	Ravensdale	149	$.63 \times 10^6$	49	4.2	$4.21 \times 10^4$
Green	Hot Springs	385	$.85 \times 10^6$	55	7.0	$6.37 \times 10^4$
Wood Creek <sup>2</sup>	Everett			86	13	
Snohomish <sup>3</sup>	Snohomish	1,734	$8.68 \times 10^6$	86	13	$1.0 \times 10^6$
Duwamish <sup>4</sup>	Near Auburn	488	$1.05 \times 10^6$	55	7.0	$7.9 \times 10^4$
Total Puget <sup>5</sup> Sound Rivers	Average	11,077	$37.2 \times 10^6$	63	15	$3.7 \times 10^6$

1 - Gauged at San Marcial, N. Mexico

2 - Drainage area and discharge not available

3 - Suspended and dissolved substances based on Wood Creek data

4 - Suspended and dissolved substances based on Green River data

5 - Averaged from available data

6 - 1 acre-foot = 43,540 cubic feet

TABLE 11 - CHARACTERISTICS OF SOME NORTH AMERICAN RIVERS (CONTINUED)

RIVER	Total Annual Sediment Deposited (Tons)	Sediment per Sq. Mi. of Drainage Basin (Tons)	Dissolved Substances per Sq. Mi. of Drain- age Basin (Tons)	Total Dissolved and Suspended Material per Sq. Mi. Drainage Basin (Tons)
Mississippi	$500 \times 10^6$	401	78.5	479.
Columbia	$7 \times 10^6$	29.2	71	100
Colorado	$184 \times 10^6$	920	76.5	996
Rio Grande <sup>1</sup>	$16.5 \times 10^6$	427	21.2	448
Fraser	$10 \times 10^6$	116.9	96.1	213
Skagit	$0.3 \times 10^6$	94.1	244	338
Cedar	3610	24.2	282	306
Green	8100	21	165	186
Wood Creek <sup>2</sup>				
Snohomish <sup>3</sup>	$.15 \times 10^6$	88.4	576	664
Duwamish <sup>4</sup>	$1.0 \times 10^4$	20.6	162	182
Total Puget Sound Rivers	$.76 \times 10^6$	68.4	289	357

TABLE 11 - CHARACTERISTICS OF SOME NORTH AMERICAN RIVERS (CONTINUED) - 3

RIVER

Mississippi	Dole, 1909, p.77; Holle, 1952, p. 111; Twenhofel, 1950, p.226.
Columbia	Van Winkle, 1914, p. 89, 98; Clarke, 1924, p. 89.
Colorado	Stabler, 1911, p. 101; Twenhofel, 1950, p. 223-4.
Rio Grande	Stabler, 1911, p. 101; Twenhofel, 1950, p. 226.
Fraser	Johnston, 1921, p. 23, 25.
Skagit	Van Winkle, 1914, p. 38; Clarke, 1924, p. 90.
Cedar	Van Winkle, 1914, p. 44.
Green	Van Winkle, 1914, p. 46.
Wood Creek	Van Winkle, 1914, p. 40.
Snohomish	Van Winkle, 1914, p. 40.
Duwanish	Van Winkle, 1914, p. 46.
Total Puget Sound Waters	Calculated.

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TABLE 111 - Composition of Air Extracted from Rainwater at Different Temperatures and of Atmospheric Air. (From Clarke, 1924, p. 54).

ELEMENT	Air From Rainwater at Different Temperatures					Average Atmospheric Air
	<u>0° C.</u>	<u>5° C.</u>	<u>10° C.</u>	<u>15° C.</u>	<u>20° C.</u>	
Oxygen	33.88	33.97	34.05	34.12	34.17	21.00
Carbon Dioxide	2.92	2.68	2.46	2.26	2.14	0.03
Nitrogen	63.20	63.35	63.49	63.62	63.69	78.00
Argon						0.97
Total	100.00	100.00	100.00	100.00	100.00	100.00

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TABLE IV - CONSTITUENTS OF SOME NORTH AMERICAN RIVERS (ANNUAL MEAN IN P.P.M. UNLESS OTHERWISE STATED)

RIVER	LOCATION	Years Measure- ments.	Turbidity	Suspended Matter	Coeff. of Fineness	Silica (SiO <sub>2</sub> )	Iron (Fe) (Fe <sub>2</sub> O <sub>3</sub> )	Calcium (Ca)	Magnesium (Mg)	Sodium and Potassium (Na, K)	Carbonate Radical (CO <sub>3</sub> )	Bicarbonate Radical (HCO <sub>3</sub> )	Sulfate Radical (SO <sub>4</sub> )
Mississippi	New Orleans	1905-06		1,400		11.7	0.22	34	8.95	13.8	58.0		25.5
Columbia	Cascade Locks	1911-12	27	40	1.97	14	0.06	17	3.9	8.9	0.0	69	12
Colorado	Yuma	1905		8,460				92	23.3	113.	2.0	233	184
Rio Grande	Courchesne near El Paso	1905-07		14,140				105	18.2	112	0.7	238	210
Fraser	New Westminster	1919-20		73		9.5	0.31	11.9	2.1	5.5	20.8		13.2
Skagit	Sedro Wooley	1910-11	12	19	1.31	9.4	0.08	7.9	1.7	3.6	0.0	29	8.2
Cedar	Ravensdale "	"	5	4.2	0.74	13.0	0.02	6.7	1.4	3.6	0.0	28	5.7
Green	Hot Springs	1910 (7 mo.)	6	7.0	1.10	17.0	0.04	6.0	1.3	5.6	0.0	28	5.9
Wood Creek	Everett	1910-11	10	13.0	1.15	25.	0.01	8.6	4.5	7.6	0.0	51	7.8
Snoqualmie	Snoqualmie Pass	1947	Slight	3.1		11.2		(CaO) 5.7	(MgO) Trace	(Na <sub>2</sub> O) 8.0	0.0	29.2	(SO <sub>3</sub> ) 4.0
Puget Sound Rivers	Average			15.		10.5	0.08	7.6	1.6	3.9	0.0	29	7.8

1 Based on chemical data for Skagit, Cedar and Green Rivers and assuming that the Green River data are representative of the Duwamish River.



TABLE IV - CONSTITUENTS OF SOME NORTH AMERICAN RIVERS (ANNUAL MEAN IN P.P.M. UNLESS OTHERWISE STATED) \*\* (CONTINUED - 2)

RIVER	Nitrate Radicle (NO <sub>3</sub> )	Chlorine (Cl)	Dissolved Solids	pH	CO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	REFERENCE
Mississippi	2.66	10.3	166			0.75	Dole, 1909, p. 77
<b>Columbia</b>	0.48	3.2	97				Van Winkle, 1914, p. 89
Colorado	0.7	127	707				Stabler, 1911, p.28
Rio Grande	0.5	105	699				Stabler, 1911, p. 101
Fraser	0.3	4.4	69			(Al) 0.96	Johnston, 1921, p. 25
Skagit	0.24	0.9	48				Van Winkle, 1914, p. 38
Cedar	0.20	1.2	49				Van Winkle, 1914, p. 44
Green	0.17	1.3	55				Van Winkle, 1914, p. 46
Wood Creek	0.39	2.9	86				Van Winkle, 1914, p. 40
Snoqualmie		2.0	29.1	7.08	1.0	(FeAl) <sub>2</sub> O <sub>3</sub> 4.2	Williams, 1949, p. 134
Puget Sound Rivers <sup>1</sup>	0.23	1.0	63				Calculated

<sup>1</sup> Based on chemical data for Skagit, Cedar and Green Rivers and assuming that the Green River data are representative of the Duwamish River.

TABLE V. Relative Concentrations of Various Chemical Constituents in Rivers Discharging into Puget Sound and in Sea Water in Puget Sound and Offshore (in  $\mu\text{g-at/l}$  unless stated otherwise).

AREA	Phosphate	Silicate	Nitrate	Nitrite	Bicarbonate	Calcium	Chloride	Copper	Iron	Magnesium	Manganese	Sodium and Potassium	Strontium	Sulfate
Puget Sound Rivers	Trace	165	3.7	?	475	190 <sup>a</sup>	28.2	0.070	1.43 <sup>a</sup>	66 <sup>a</sup>	0.05 <sup>a</sup>	3.9	Trace	81
Puget Sound Water	2.0	42	20	.3		$9 \times 10^3$	$4.62 \times 10^5$	0.020	0.7	$46 \times 10^3$	0.11	$9.47 \times 10^3$	80 <sup>a</sup>	22
Offshore Pacific Ocean	0.3	2	3	0	2350 <sup>c</sup>	$10.3 \times 10^3$	$4.95 \times 10^5$	0.018		$50 \times 10^3$	0.18	$10.8 \times 10^3$	95	26

a. Friday Harbor Data From San Juan Channel.

b. From Mouth of Liliwaup River, Hood Canal.

c. Average for the Oceans.

TABLE VI. Computation of Fresh Water in Puget Sound, July 1953 and February 1954.

## AVERAGE SALINITIES AT VARIOUS STATIONS, S

DATE	Port Townsend	Port Jefferson	Camano Head	Pleasant Harbor	Devils Head	Pillar Point
	$S_B$	$S_1$	$S_2$	$S_3$	$S_4$	$S_B$
July 18-22 1953	30.20	30.10	29.54	29.85	29.31	33.53
Feb. 15-19 1954	29.90	29.18	28.86	28.92	29.01	31.38
Volume of Section	V	15.51	4.58	3.92	2.49(nmi <sup>3</sup> )	

Fraction of Total Volume	f	.585	.173	.148	.094	
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CONTRIBUTION OF EACH SECTION (fs) TO  
AVERAGE SALINITY OF PUGET SOUND

DATE	Ave. Sal. Puget Sound	% Fresh Water in Puget Sound	Fresh Water Volume (n.mi) <sup>3</sup>	No. Days Discharge of Puget Sound Rivers (Using Annual Mean Discharge).
	$S_A = \sum fs$	$\frac{S_B - S_A}{S_B} \times 100$		
July 18-22 1953	29.89 ‰	4.29%	1.112	56.6
Feb. 15-19 1954	28.99 ‰	3.04%	0.805	41.0
FRESH WATER IN PUGET SOUND BASED ON PILLAR POINT SALINITY				
July 18-22 1954	29.89	10.85	2.88	146.5
Feb. 15-19 1954	28.99	7.62	2.02	102.8

TABLE VII. Organic Production Computed From Phosphate Depletion.  
 Puget Sound Compared to Other Areas.  
 (Mostly from Sverdrup, et. al, 1946, p. 938 and Buch, 1952, p. 51)

LOCATION	PRODUCTION Carbon gm/m <sup>2</sup> /year	LITERATURE SOURCE
Point Jefferson <sup>1</sup> Puget Sound	30-111	Present Work.
Dry Tortugas	27	Sverdrup, et. al. 1946, p. 938.
English Channel	84	Atkins, 1923.
Barents Sea	170-330	Kreps and Verjbinskaya, 1930.
Long Island Sound <sup>3</sup>	138-350	Riley, 1941.
Gulf of Maine <sup>3</sup>	270	Riley, 1941.
Sound of Elsinore, Denmark	110	Steeman Nielsen, 1937.
Hangö (The Baltic) <sup>4</sup>	24	Buch and Gripenburg, 1935.

1 Minimal quantity from February to July

2 For six months

3 For whole year with nutrients used several times

4 Minimal quantity from 21 March to 21 April during rapid diatom outburst from beginning to its maximum.

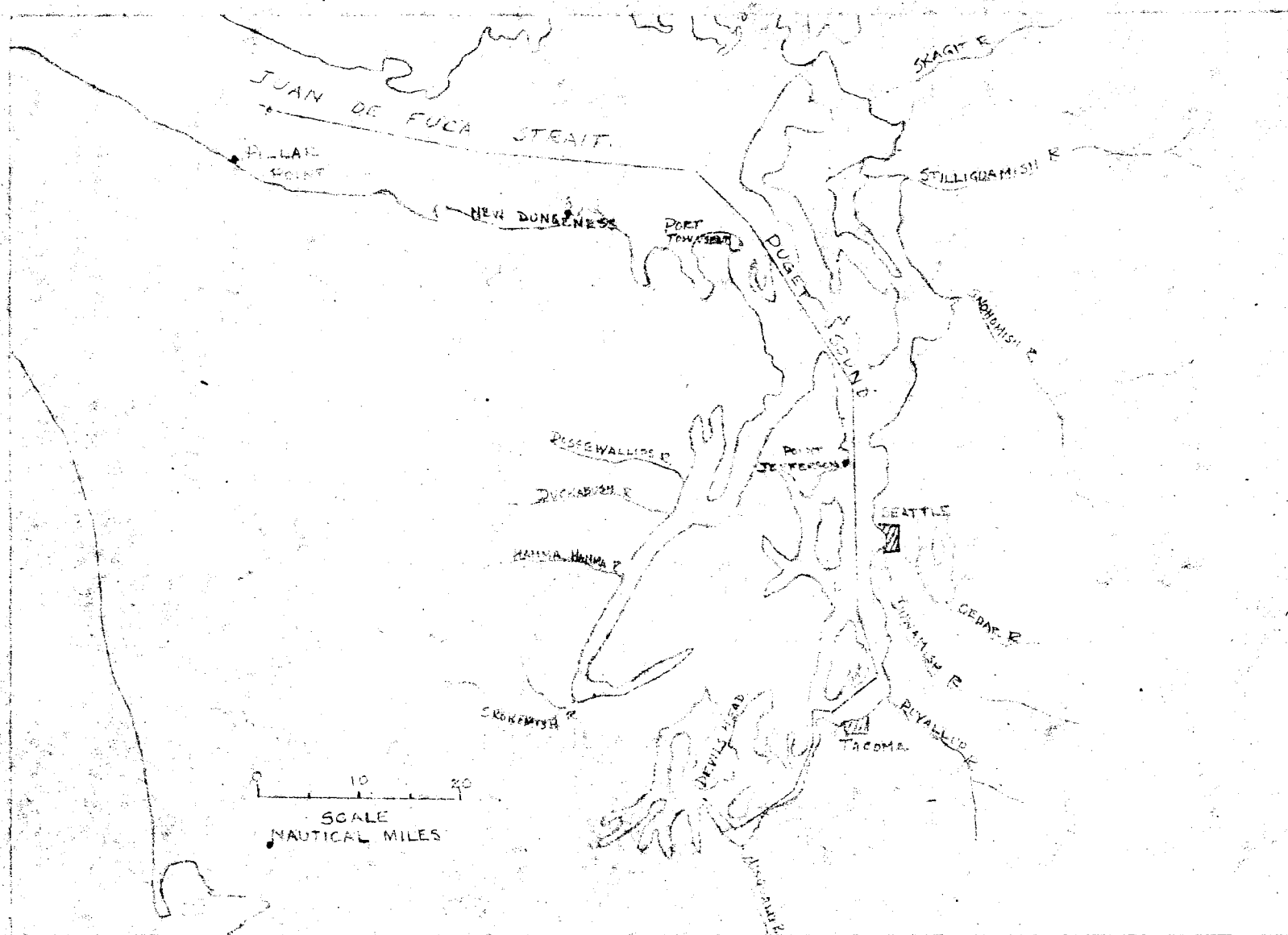


FIG. 1 - CHART OF PUGET SOUND AND PART OF JUAN DE FUCA STRAIT  
SHOWING THE LINE OF STATIONS FROM PILLAR POINT TO DEVILS HEAD

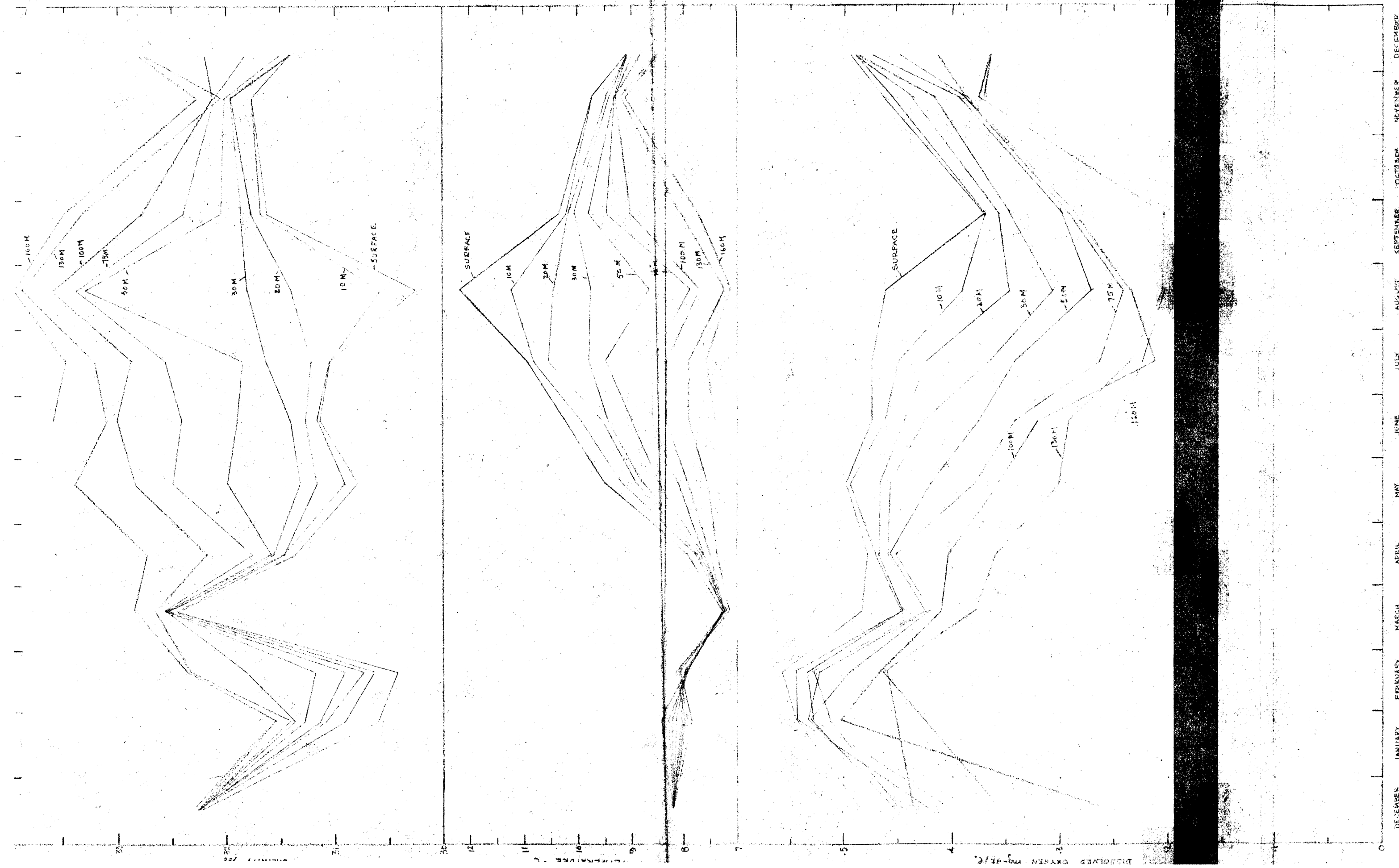


FIG. 2. SEASONAL CYCLE OF SALINITY, TEMPERATURE AND DISSOLVED OXYGEN AT NEW DUNGENESS (48°16' N, 123°04' W) 1953

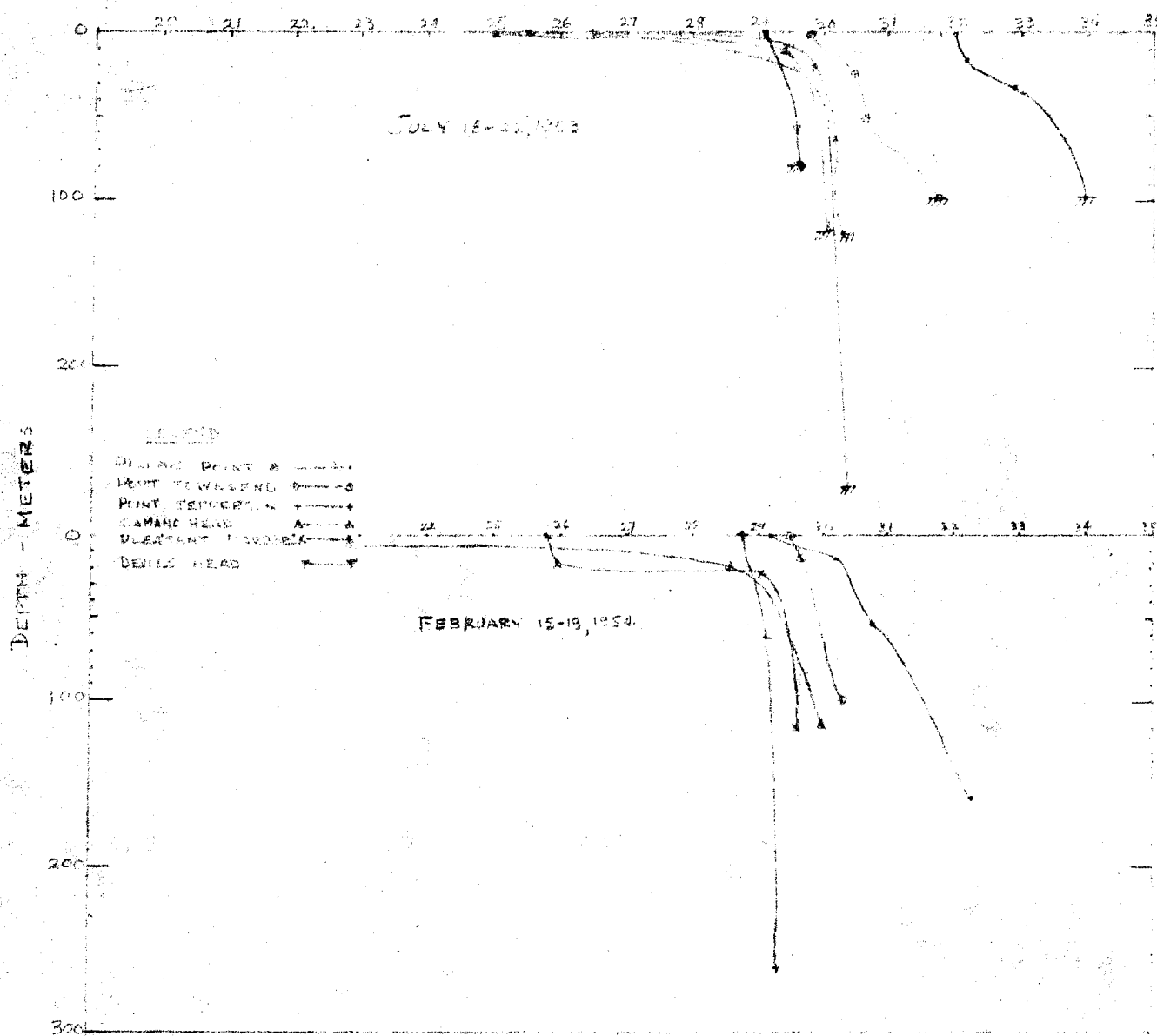


FIG. 3 - SALINITY STRUCTURE AT VARIOUS STATIONS, JULY 1953, AND FEBRUARY 1954.

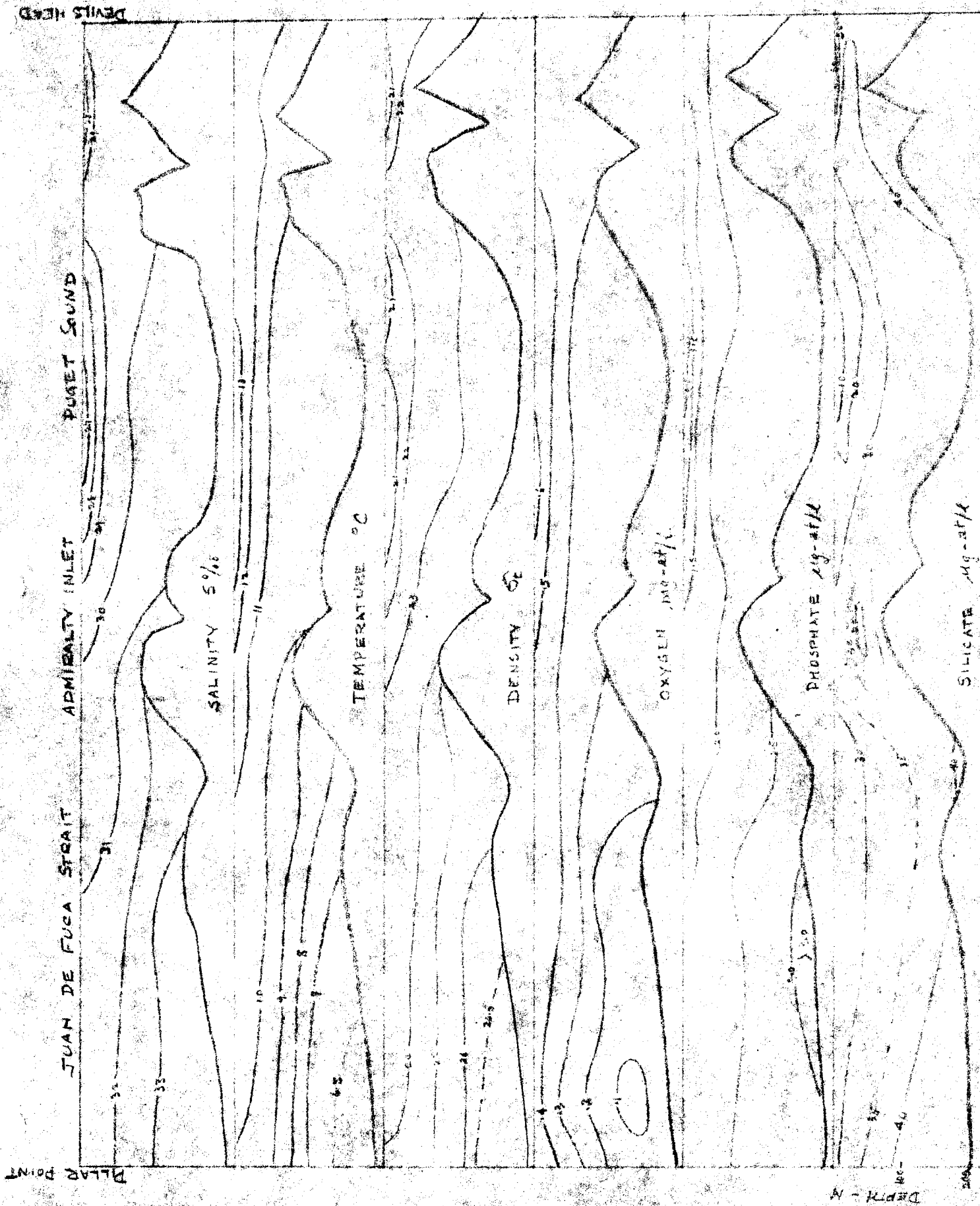


FIG. 4 - DISTRIBUTION OF PROPERTIES IN THE JUAN DE FUCA STRAIT - PUGET SOUND SYSTEM, JULY 1981



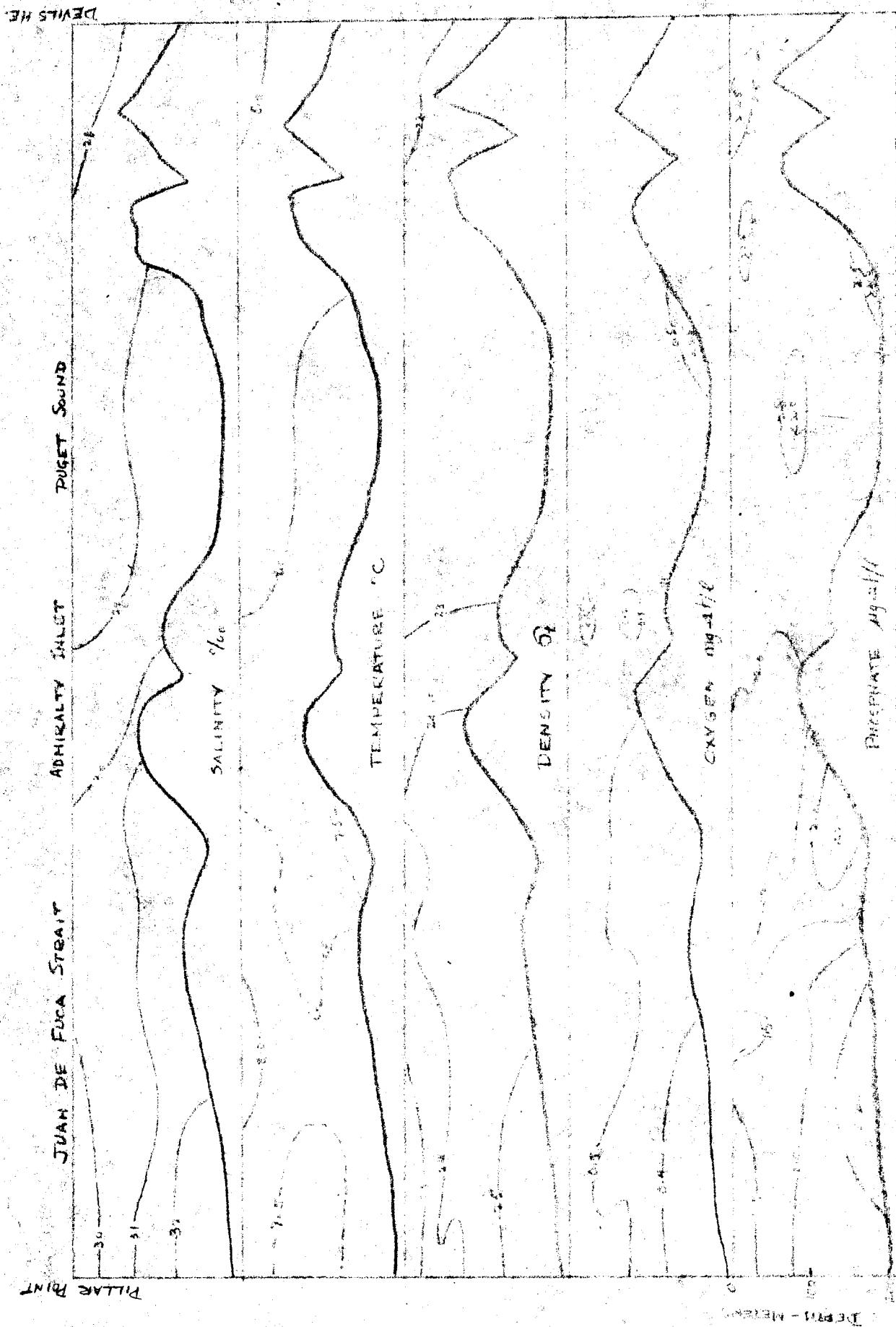


FIG. 4 - DISTRIBUTION OF PROPERTIES IN THE JUAN DE FUCA STRAIT - PUGET SOUND SYSTEM, FEB. 1954

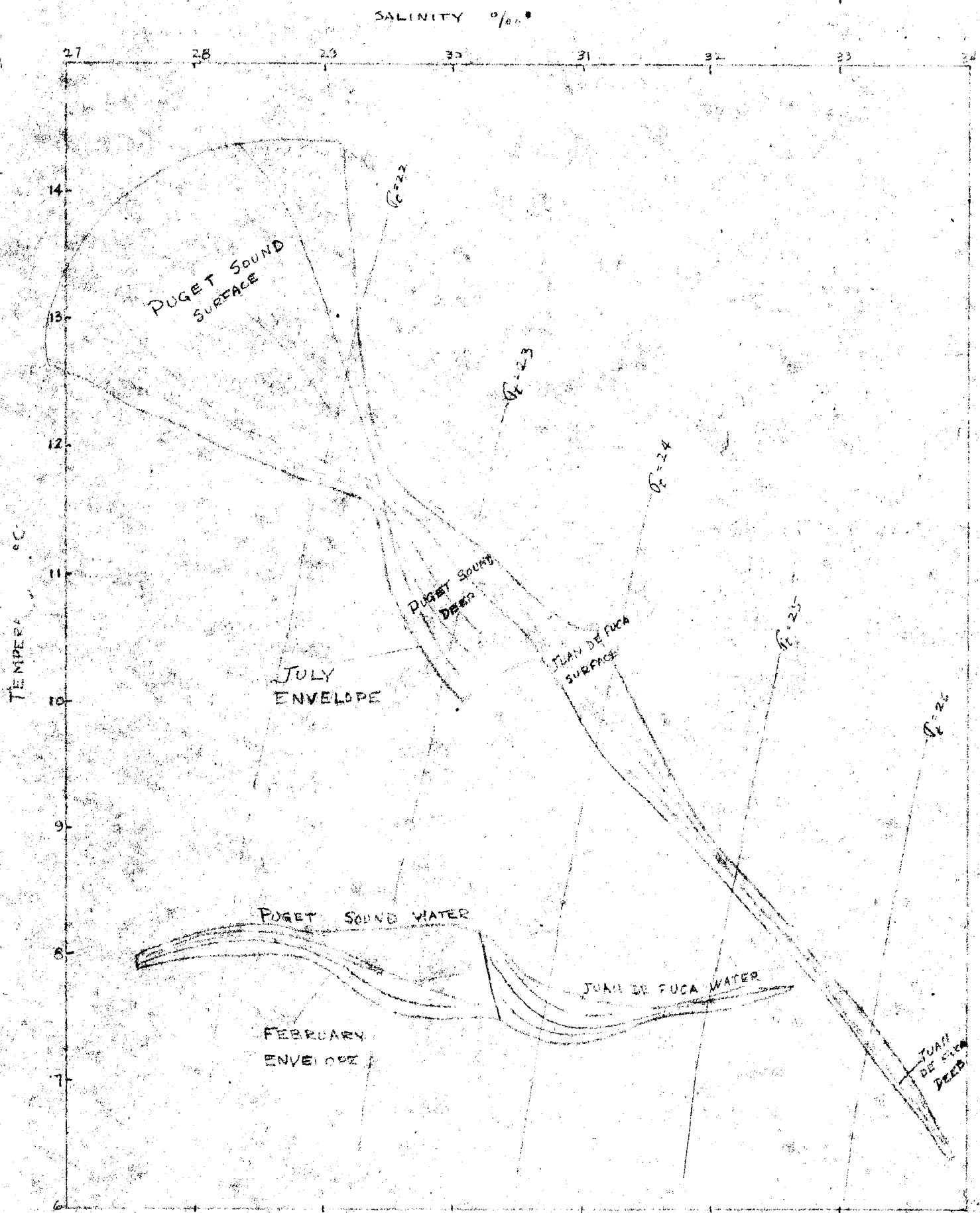
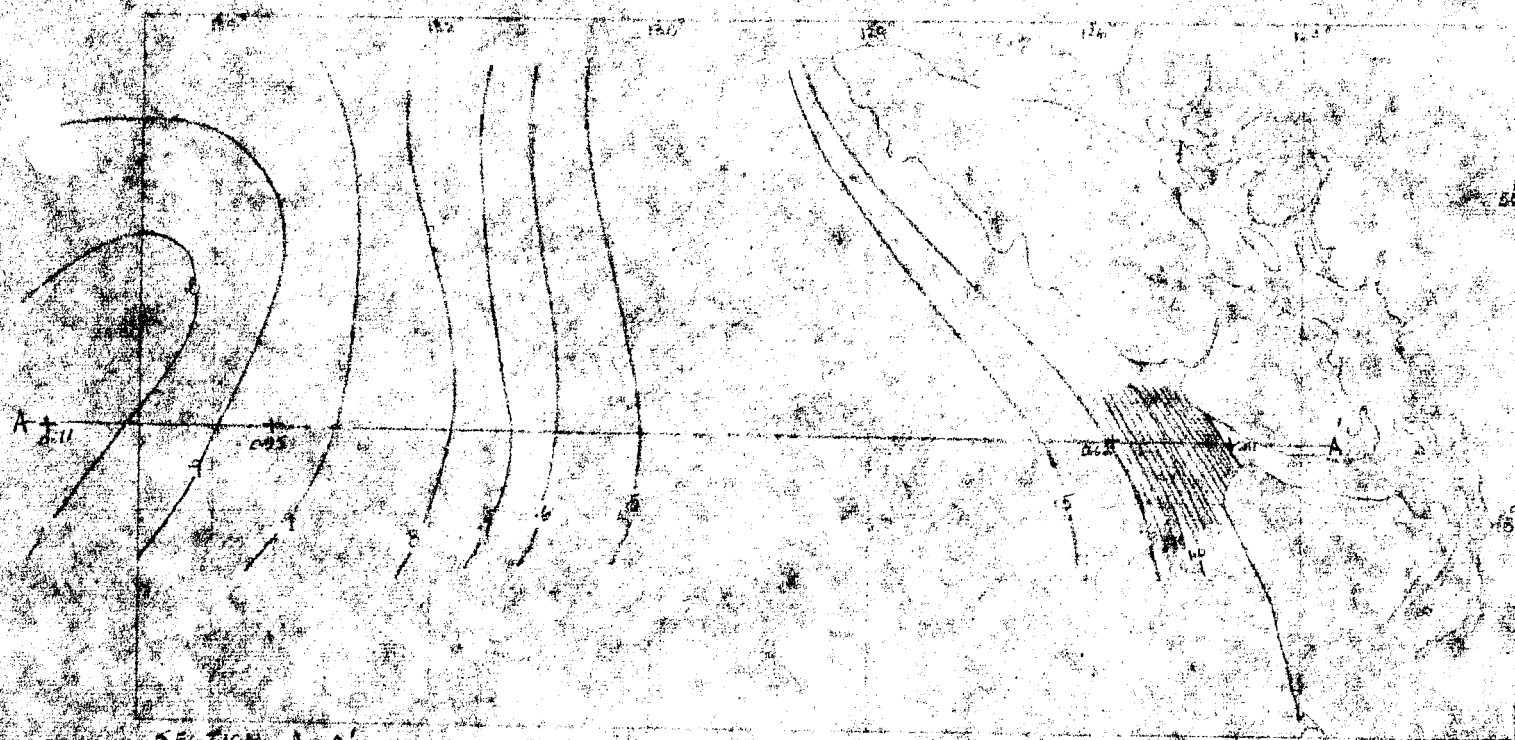


FIG. 6 - T-S RELATIONSHIPS FOR JUAN DE FUCA STRAIT - PUGET SOUND



SECTION A-A'

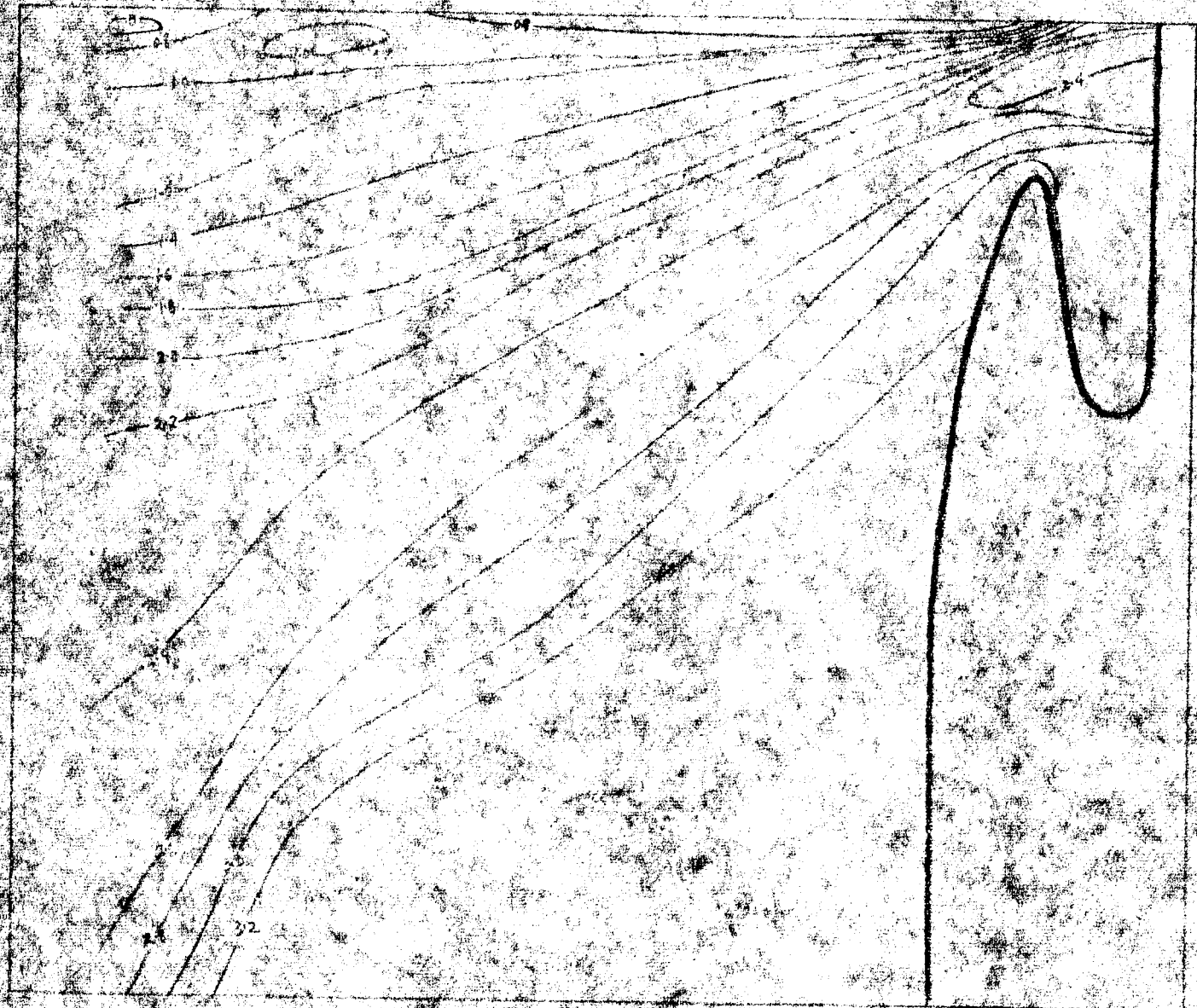


FIG. 1. SURFACE AND VERTICAL DISTRIBUTION OF PHOSPHATE IN  $\mu\text{gm}/\text{l}$  AT THE APPROACHES TO JUAN DE FUCA STRAIT, JULY 1962.

PHOSPHATE -  $\mu\text{g} \cdot \text{L}^{-1}$

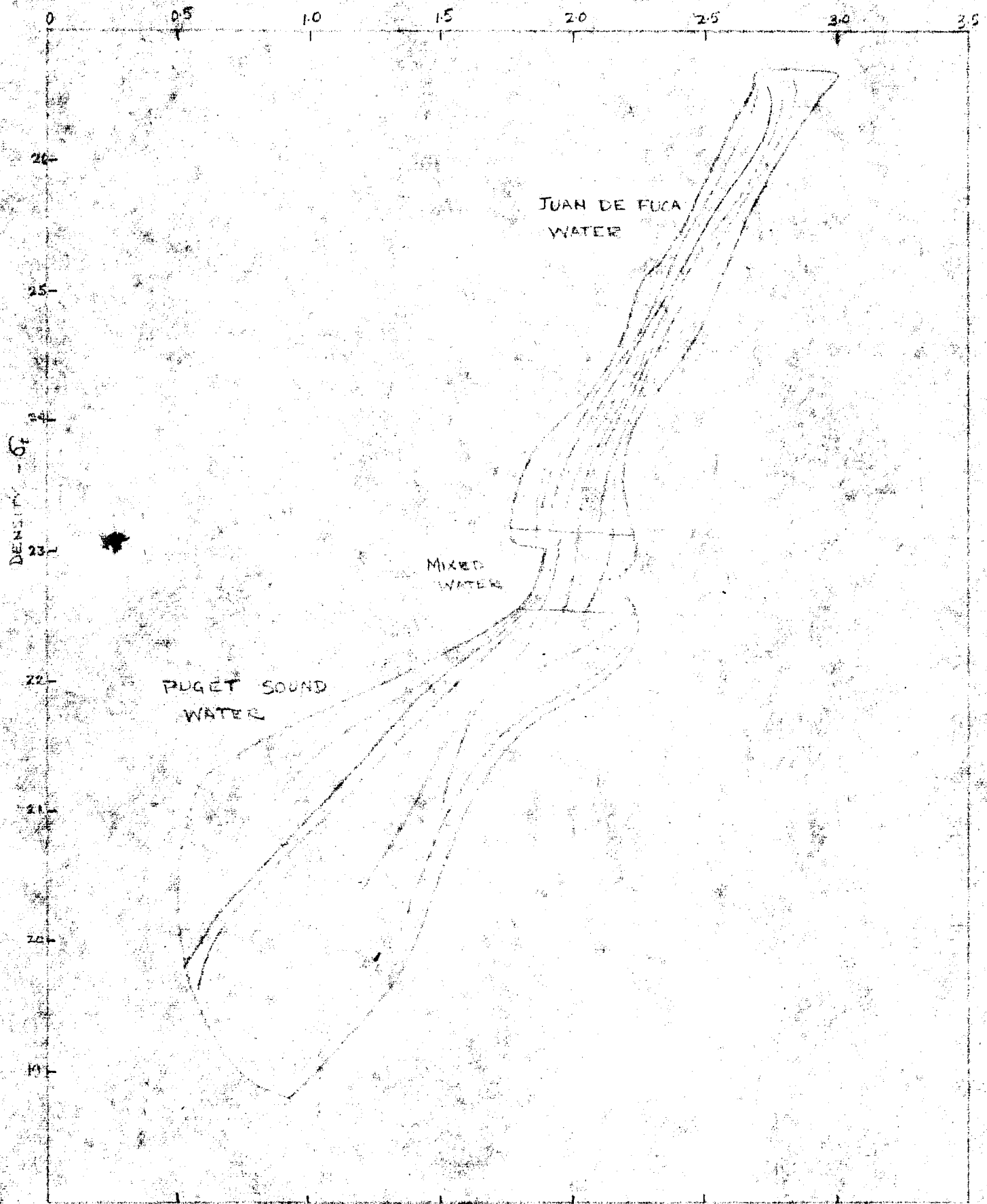


FIG. 2 - PHOSPHATE-DENSITY RELATIONSHIP FOR THE WATERS OF JUAN DE FUCA STRAIT AND PUGET SOUND, JULY 1983.

PHOSPHATE -  $\mu\text{g-at/l}$

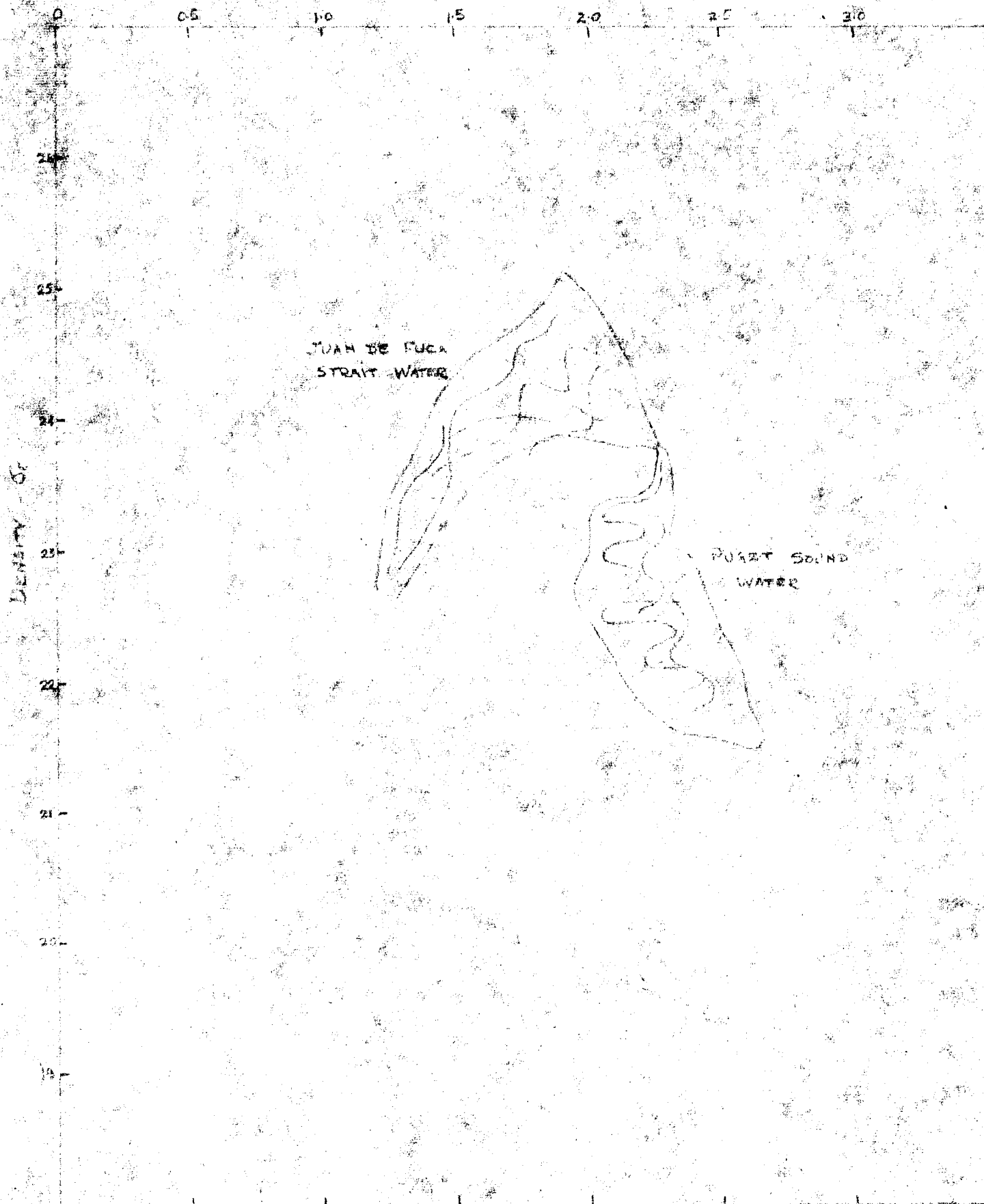


FIG. 9 - PHOSPHATE - DENSITY RELATIONSHIP FOR THE WATERS OF JUAN DE FUCA AND PUGET SOUND, FEBRUARY 1954.

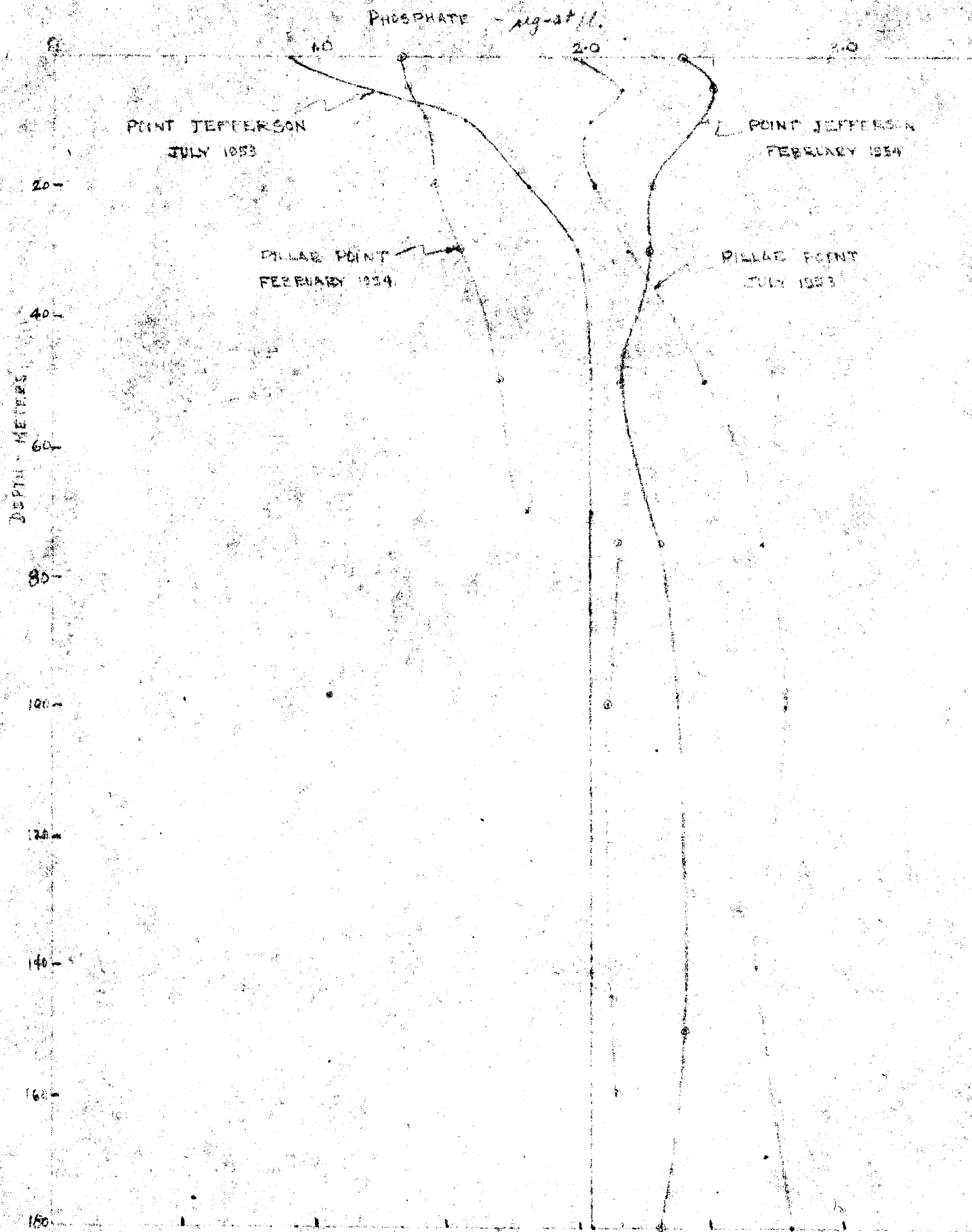


FIGURE - PHOSPHATE PROFILES AT PILLAR POINT AND POINT JEFFERSON  
FOR JULY 1953 AND FEBRUARY 1954

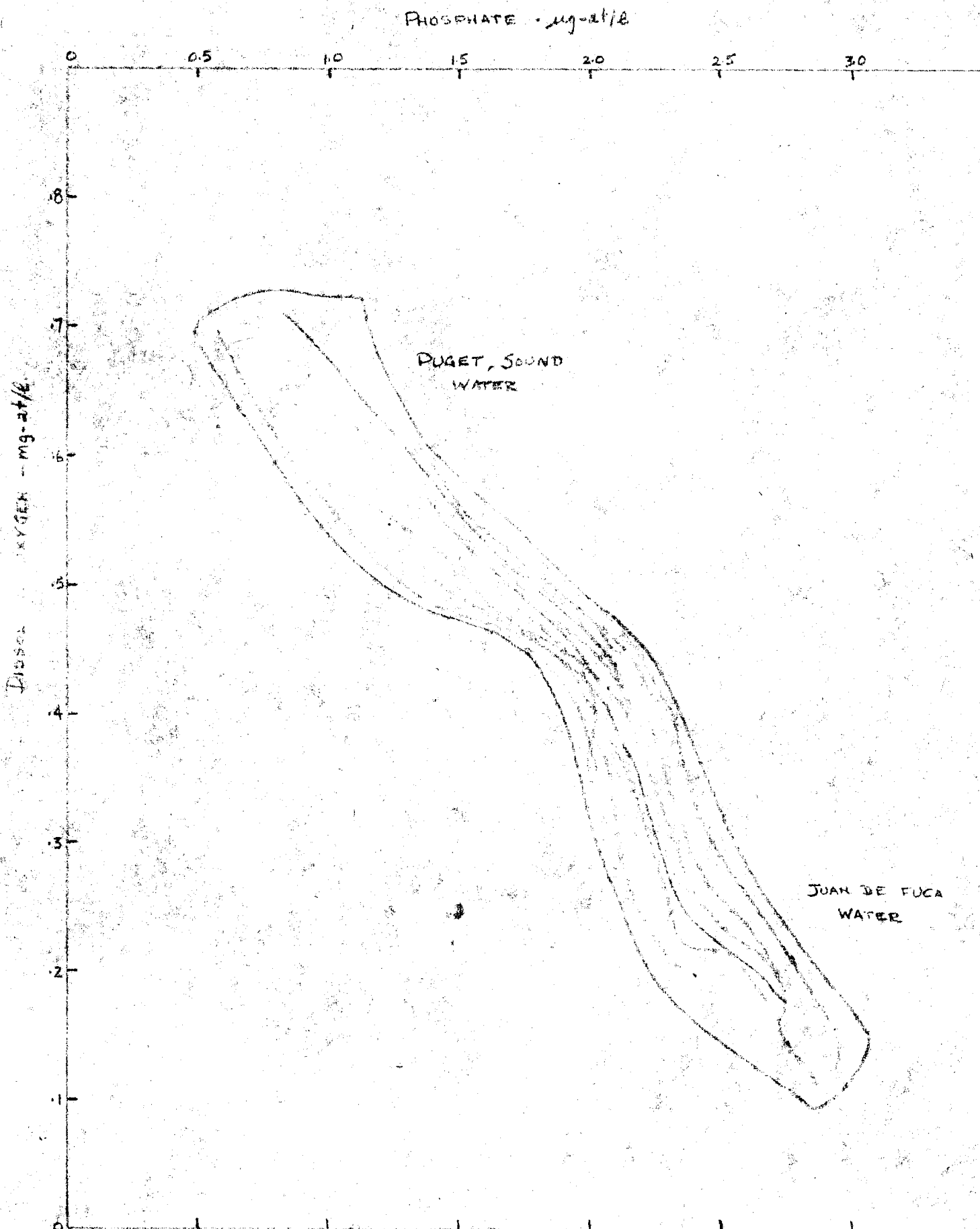


FIG. II - PHOSPHATE - OXYGEN RELATIONSHIPS FOR THE WATERS OF JUAN DE FUCA STRAIT AND PUGET SOUND, JULY 1963

PHOSPHATE -  $\mu\text{g-at/l}$

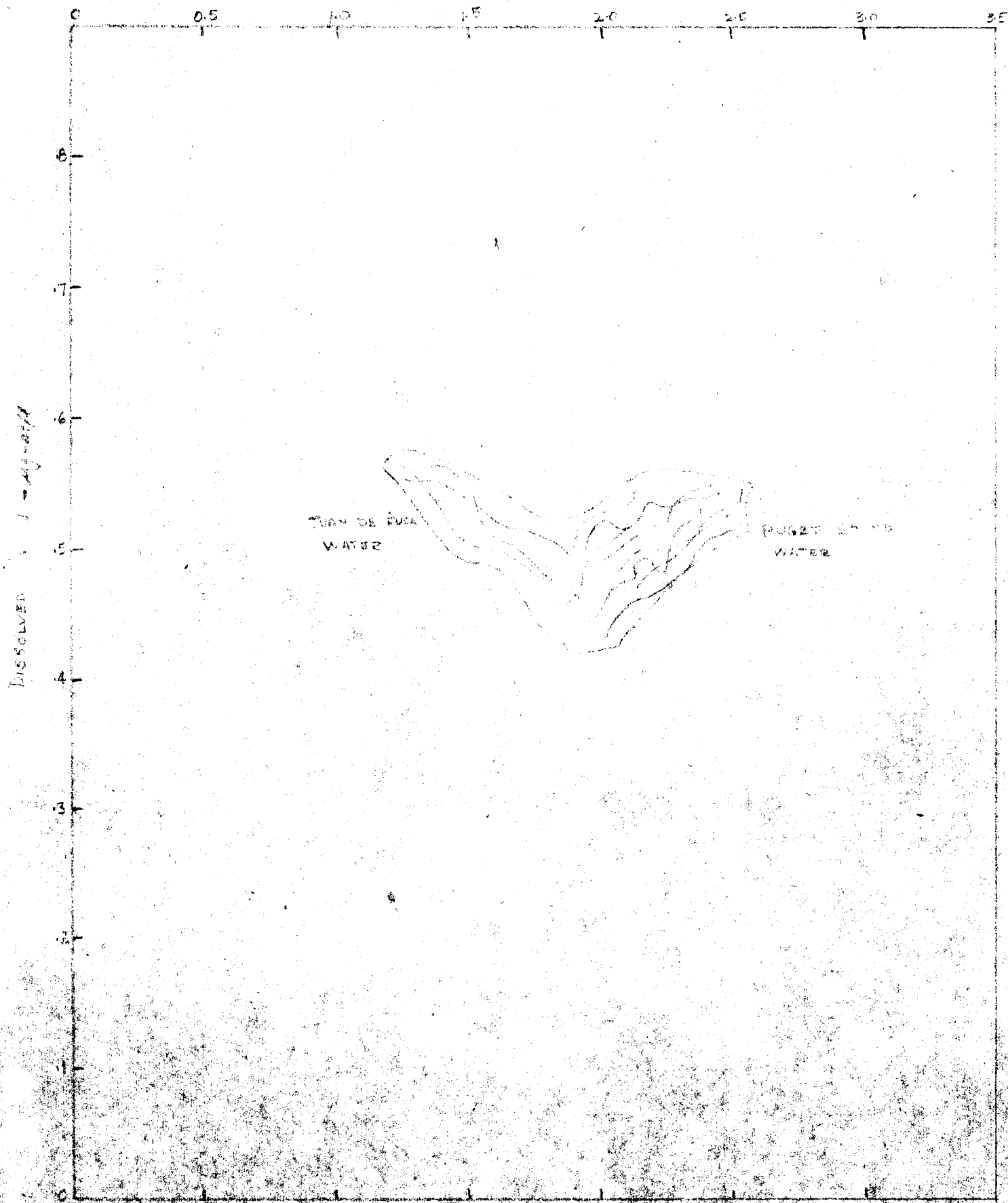
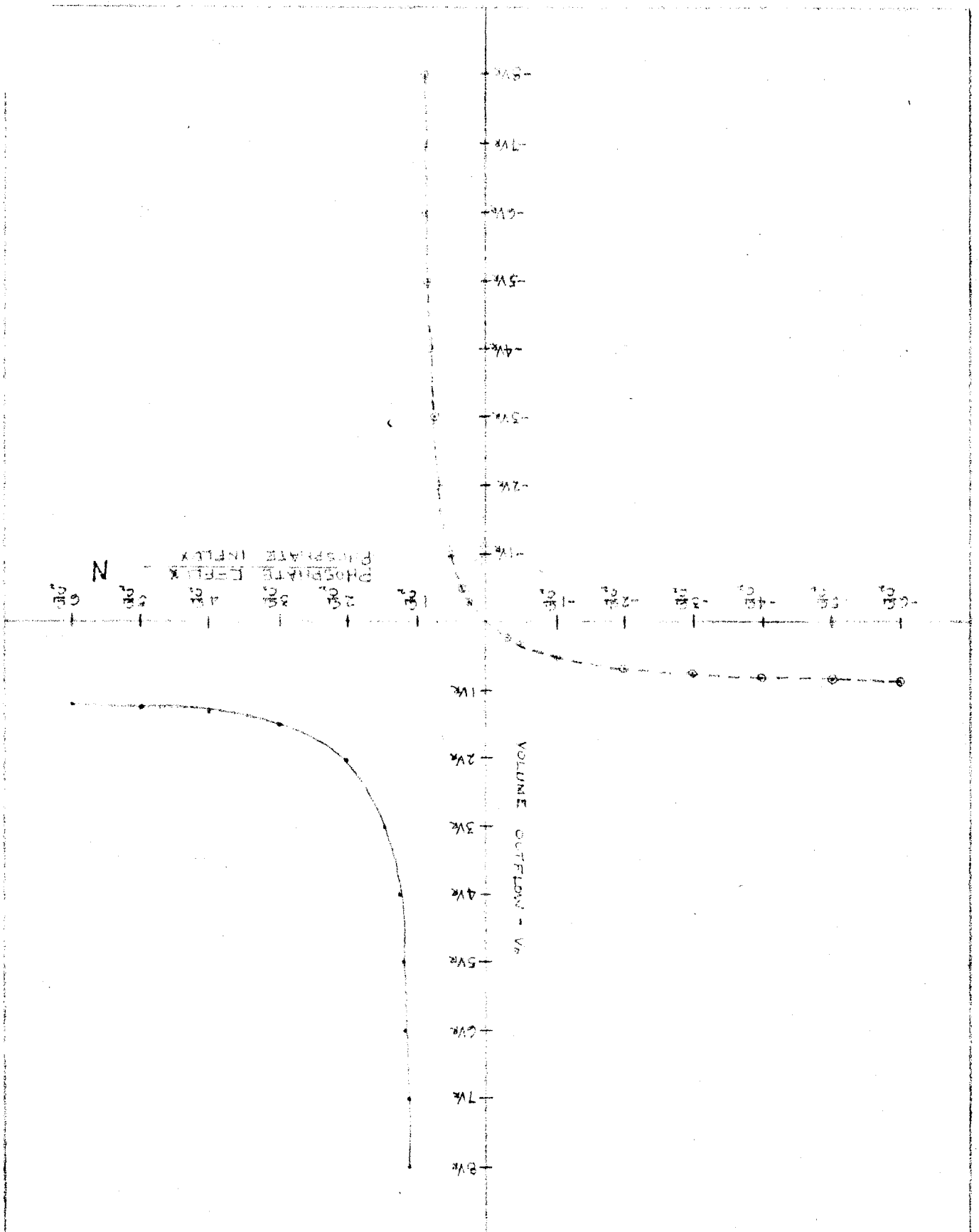


FIG. 12 - PHOSPHATE - OXYGEN RELATIONSHIP FOR THE WATERS OF JUAN DE FUCA STRAIT AND PUGET SOUND, FEBRUARY 1954.



FIG. 13 - PLOT OF EQUATION  $N = \frac{1}{\frac{1}{V_R} - \frac{1}{V_0}}$  (SEE TEXT FOR EXPLANATION OF TERMS)



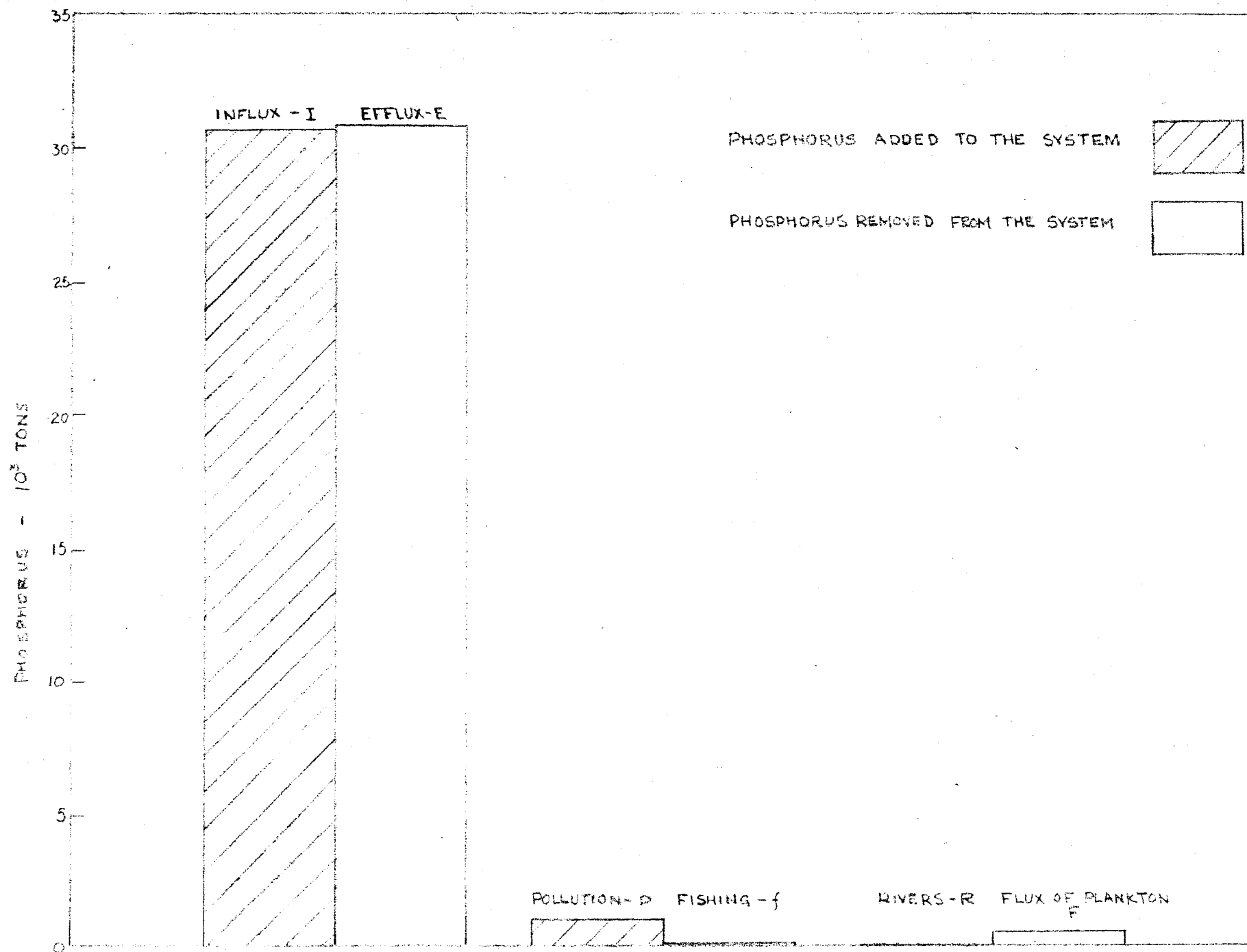


FIG. 14 - GRAPHICAL ILLUSTRATION OF THE MAGNITUDE OF THE VARIOUS TERMS IN THE PHOSPHATE - BUDGET EQUATION.

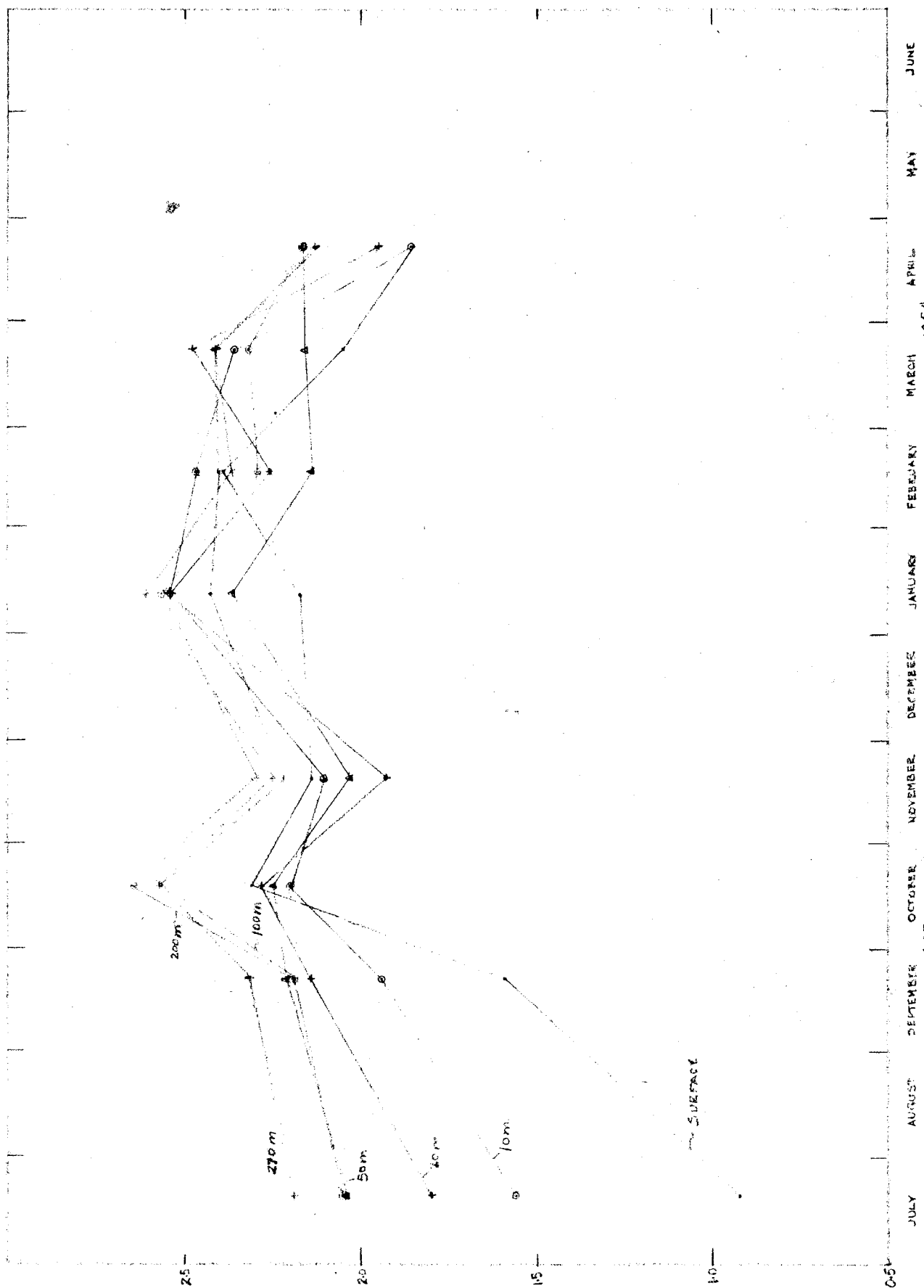


FIG.15 - SEASONAL VARIATION OF PHOSPHATE OFF POINT JEFFERSON, 1953-1954

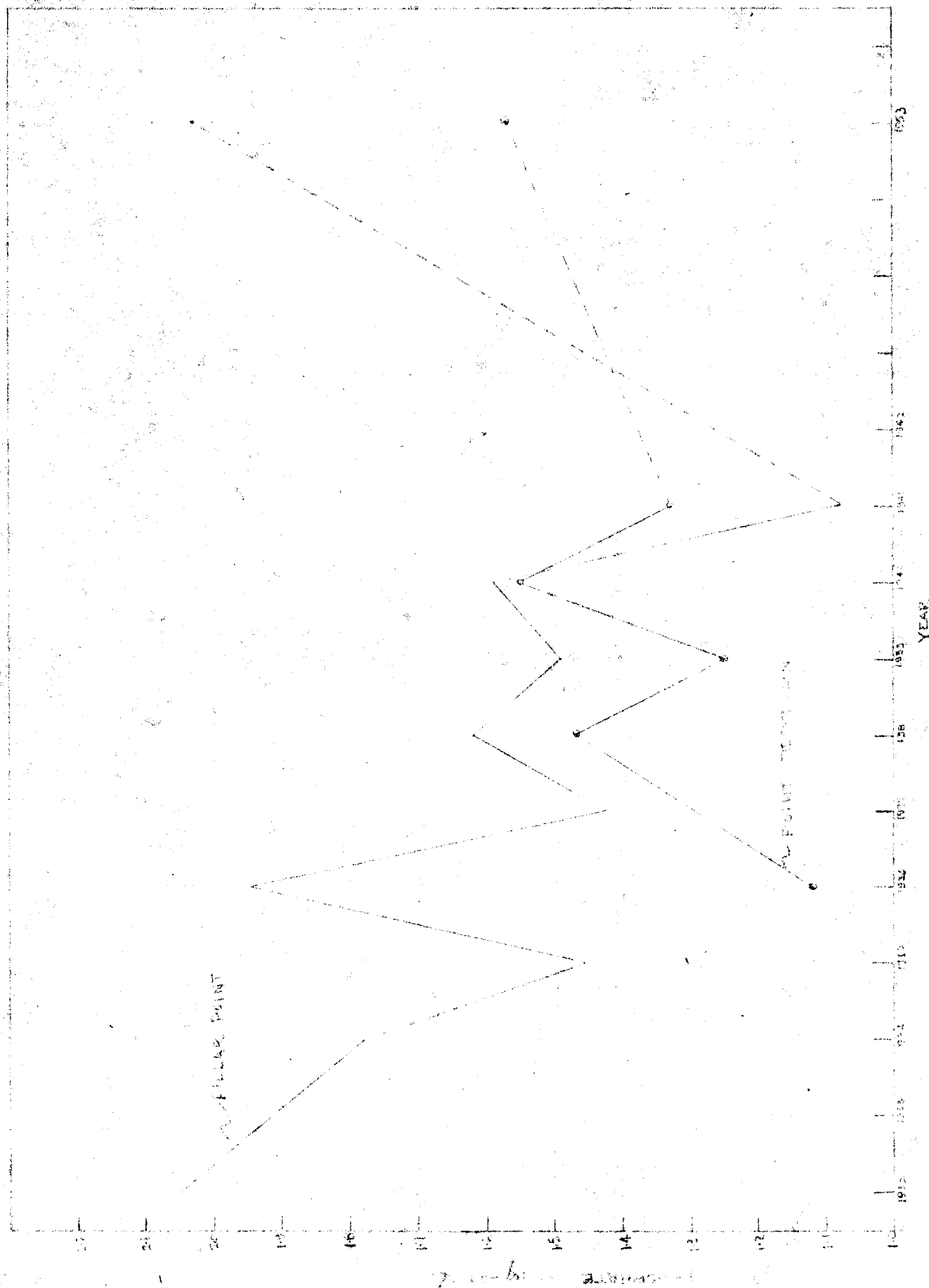


FIG. 6 - LONG TERM VARIATION IN BIRD DENSITIES IN THE UPPER SON OFF PILLAR POINT AND POINT ROBINSON FOR JULY.

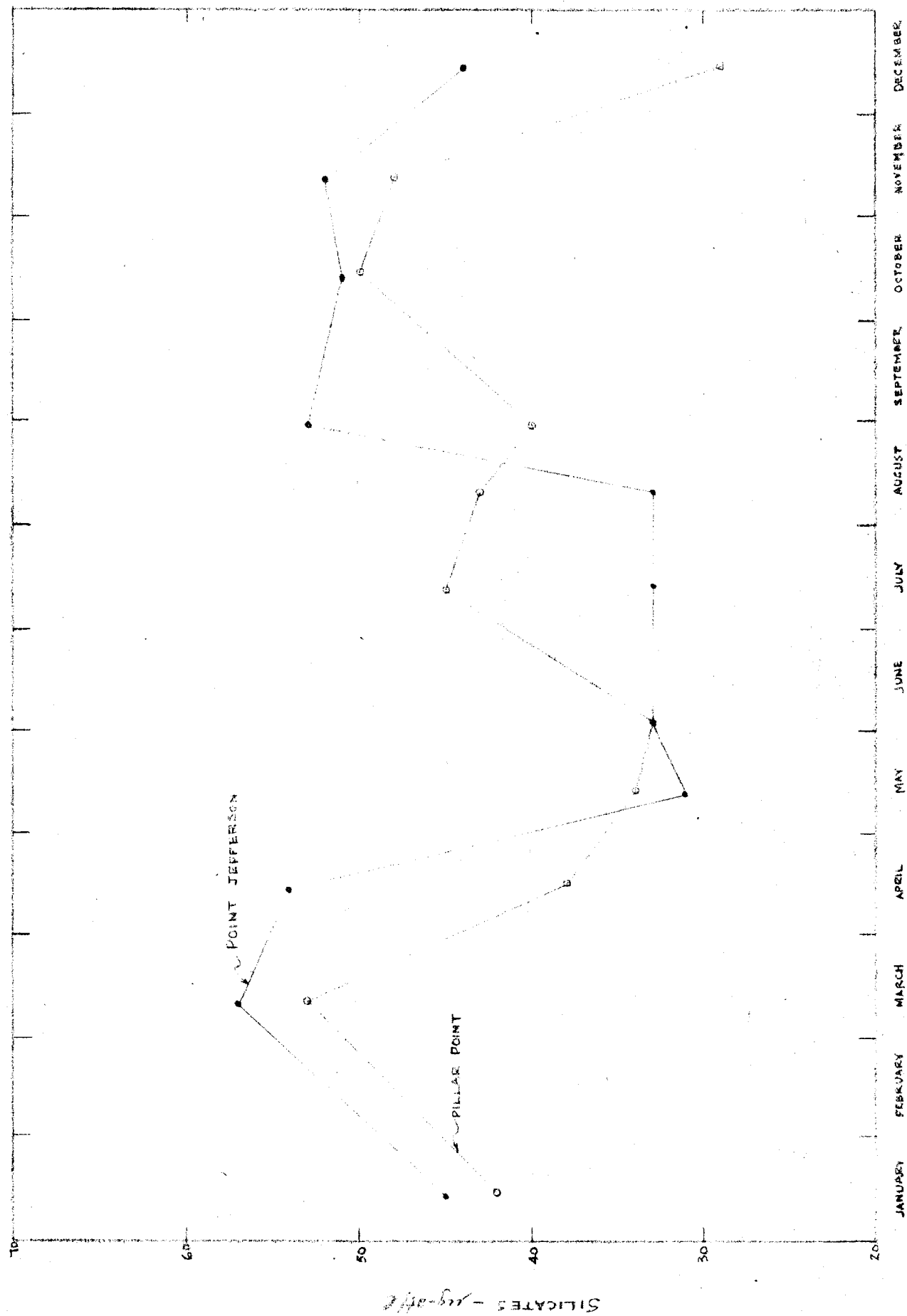


FIG. 17 - SEASONAL VARIATION OF SILICATES IN THE UPPER 30 M. OFF PILLAR POINT AND POINT JEFFERSON, 1939.

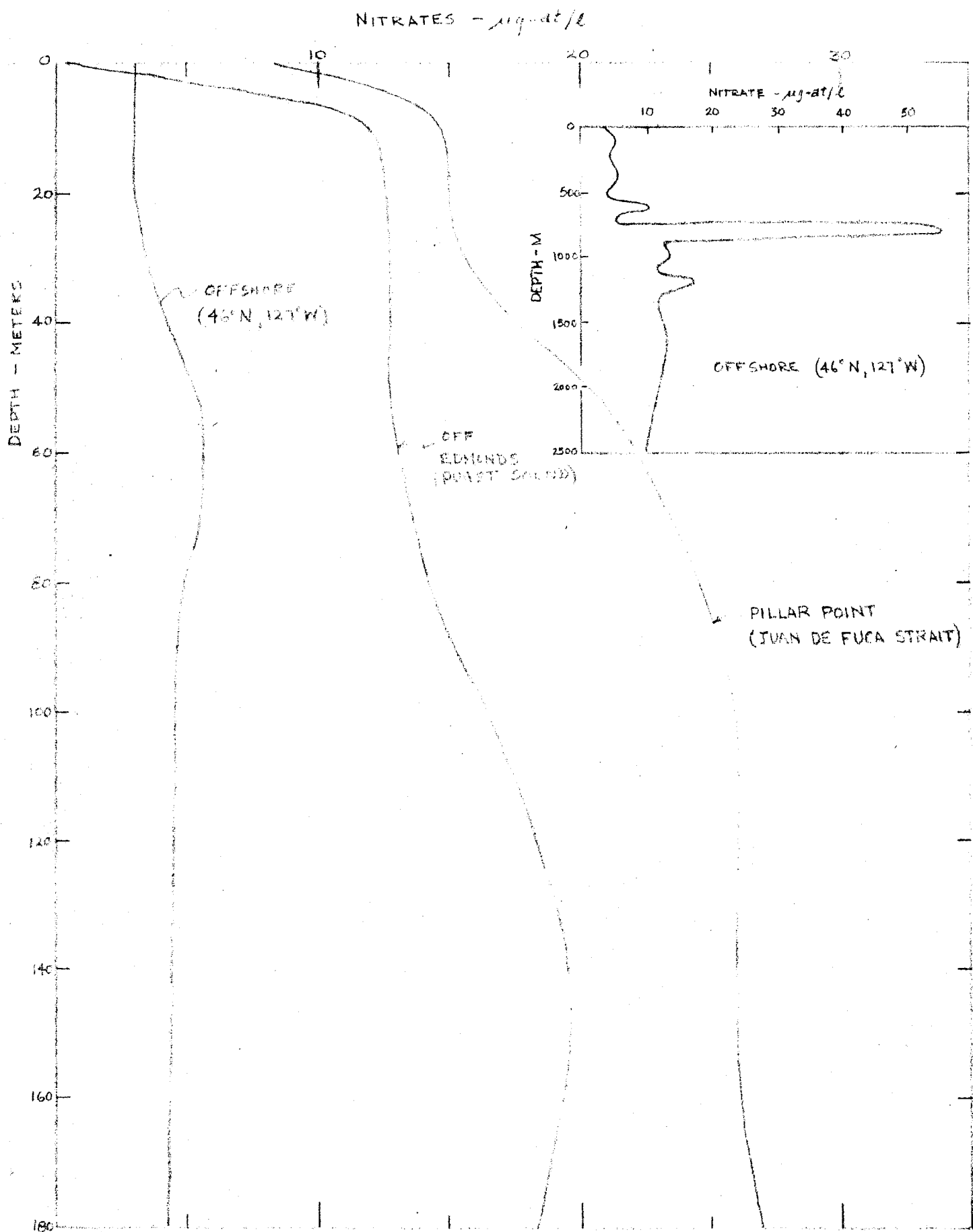


FIG. 18 - VERTICAL DISTRIBUTION OF NITRATE IN PUGET SOUND, JUAN DE FUCA STRAIT AND OFFSHORE IN JULY.

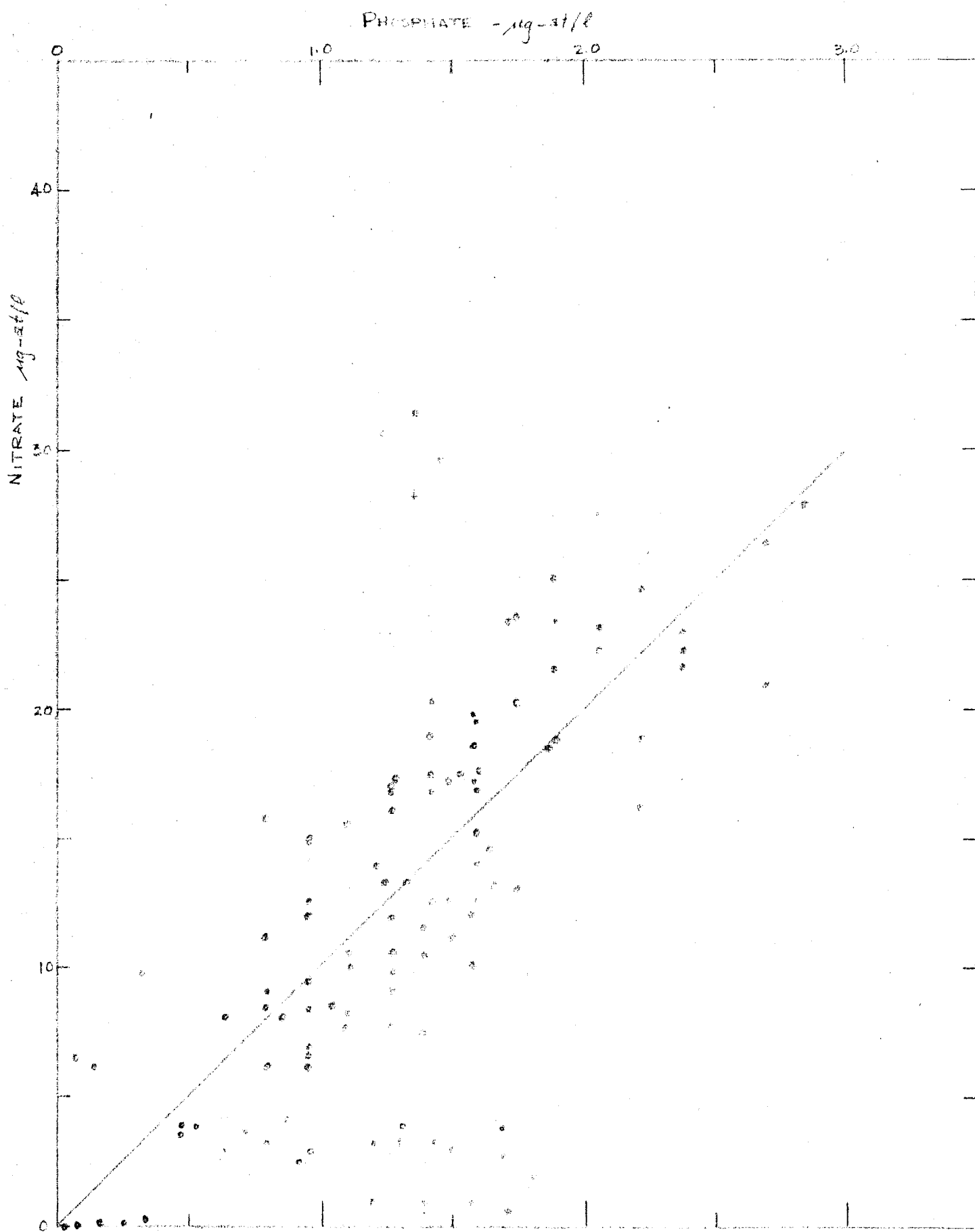


FIG. 19. - RELATIONSHIP BETWEEN PHOSPHATE AND NITRATE CONCENTRATIONS IN PUGET SOUND

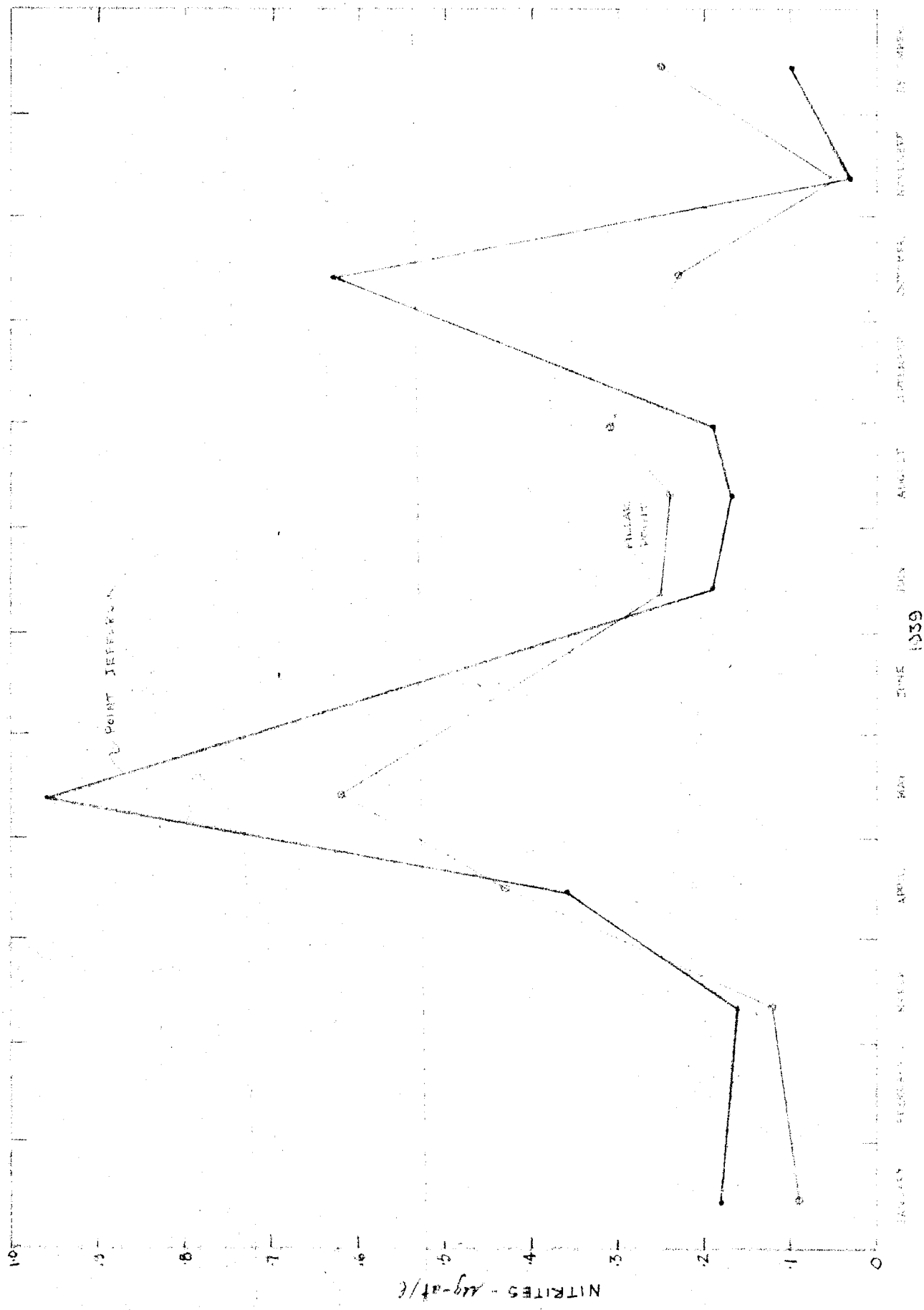


FIG. 20 - SEASONAL VARIATION OF NITRITES IN THE UPPER 30M. BELLING POINT AND POINT JEFFERSON, 1939.