Measurement of Salt-Wedge Excursion Distance in the Duwamish River Estuary, Seattle, Washington, by Means of the Dissolved-Oxygen Gradient

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1873-D

Prepared in cooperation with the Municipality of Metropolitan Seattle

Measurement of Salt-Wedge Excursion Distance in the Duwamish River Estuary, Seattle, Washington, by Means of the Dissolved-Oxygen Gradient

By W. A. DAWSON *and* L. J. TILLEY

ENVIRONMENTAL QUALITY

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1873-D

Prepared in cooperation with the Municipality of Metropolitan Seattle

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1972

UNITED STATES DEPARTMENT OF THE INTERIOR

ROGERS C. B. MORTON, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

Library of Congress catalog-card No. 72-600252

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 25 cents (paper cover)
Stock Number 2401-2166

CONTENTS

ILLUSTRATIONS

ENVIRONMENTAL QUALITY

MEASUREMENT OF SALT-WEDGE EXCURSION DISTANCE IN THE DUWAMISH RIVER ESTUARY, SEATTLE, WASHINGTON, BY MEANS OF THE DISSOLVED-OXYGEN GRADIENT

By W. A. DAWSON and L. J. TILLEY

ABSTRACT

The Duwamish River estuary has been the object of a series of comprehensive studies undertaken to predict the effects of the changing character of waste-water inputs on the water quality of the estuary. This report discusses the fresh- and salt-water relations of the estuary. The distance that the salt-water wedge in the estuary moves upstream and downstream with the tide is measured by a method that utilizes the persistence of the longitudinal gradient of dissolved oxygen in the salt water of the wedges. The method, though unorthodox, can serve as an independent check on any other measurements of tidal-excursion distance. Typical values obtained were a 1-kilometer excursion for a 1.3-meter tide range and a 3-kilometer excursion for a 3-meter tide range. This method of tracing the water movement seems to work because of two unusual aspects of the Duwamish River estuary: (1) the channel configuration is simple and well-suited to synoptic measurement and (2) the physical properties of the entering salt water are nearly constant.

INTRODUCTION

The Duwamish River estuary at Seattle, Wash., like many estuaries in urban areas, is undergoing a change in the patterns of its waste-water inputs. The effects of this change are being intensively studied. An understanding of how water moves in and through the estuary and its rates of movement is fundamental to the study.

Salt water enters from Puget Sound at depth at the mouth of the estuary, which is split by Harbor Island (fig. 1), and fresh water enters from the Green River at the head. Within the estuary these two inputs are mixed, and the mixed water leaves the estuary in a surface layer. Relating salt- and fresh-water input to the mixed-water output requires a determination of the ratio of salt to fresh water in the output mix as well as a measure of the output volume. Although the rate of fresh-water input can be and is measured continuously, the total output from the estuary and the salt-water input have been measured only at the mouth of the estuary during intensive short-term studies of directional flow rates. Therefore, a better understanding of how the quality of water in the estuary will be affected by changing waste loads requires improved measurements not only of the total movement of water through the estuary but also of the short term variations in the factors that control water movement. The most important factor, the tide, controls both the level of the water and the differential rate of movement of the upper, seaward-moving, layer of mixed water and the lower, landward-moving, layer of sea water. This report demonstrates the stability and persistence of the lower layer and describes its tidal behavior.

All continuous records of water-quality parameters for the deeper salt-water layer have indicated that the longitudinal movement of salt water was a tidal oscillation, or excursion.

The writers apparently were the first to assume that this small estuary—13 kilometers (7 miles) long with a 3-meter (12-ft.) tide and a fresh-water inflow rate between 300m^3/min (200 cfs) and 20,000m^3/min (12,000 cfs)—would have a persistent deeper salt-water layer; therefore, no previous attempts were made to measure systematically the movement of such a layer. As this presentation demonstrates, the assumption was valid. This analysis uses dissolved oxygen (DO), a water parameter not usually regarded as stable enough to serve as a tracer of water movement, to measure the movement of the salt-water layer.

Use of DO to trace the movement of the salt-water layer seems to work because of two unusual aspects of the Duwamish River estuary: (1) its configuration is simple and well suited to synoptic measurement and (2) the physical properties of the entering salt water are nearly constant year-round, at least in comparison with the water of the overlying layers. This second aspect permits both a ready identification of salt-water-input distribution in the estuary and a comparison of synoptic measurements made in different seasons. The constancy of the Duwamish salt-water input stems from some properties of its parent water body, Puget Sound, and the Sound's relationship to the Pacific Ocean. These aspects are discussed briefly in subsequent sections of this report.

This report is part of a comprehensive cooperative study of the Duwamish River estuary made by the U.S. Geological Survey and the Municipality of Metropolitan Seattle (Metro). The data on which the analysis is based were gathered during a study of algal growth in the river and estuary, one phase of the cooperative study.

DESCRIPTION OF THE ESTUARY

Prior to 1908, the Duwamish River was fed by the White, Black, and Green Rivers. In 1908, the White River was permanently diverted from the Green at Auburn (beyond the area shown in fig. 1). In 1916, the lowering of the level of Lake Washington reduced the Black River, which drained the lake, to a slough and since then the Black River, which joins the Green to form the Duwamish at river km 19, has supplied little water to the Duwamish. The Green River is now the main source of the Duwamish.

Because tidal rise and fall is observed above the mouth of the Black River, the Duwamish may be regarded as a river that is estuarine and tidal over its entire length (fig. 1). The estuary is quite narrow in proportion to its length, and along most of its length its banks are fairly straight and nearly parallel; only a few shallow, blind side channels are all that remain of old undredged meanders. The estuary is maintained as a navigational channel by dredging up to river km 10.0. At this point a wide space of deep water is created by the turning movements of the dredges. At river km 12.0, a bedrock ledge crosses the river and produces an 18-inch drop in the water surface at extreme low tides. This location, opposite a drive-in theater (fig. 1), is the effective present limit of navigation on the estuary at low tide.

The Duwamish River estuary is two-layered from its mouth at Elliott Bay (fig. 1) to a distance upstream that varies with the amount of fresh water entering its head from the Green River. The lower layer has a salinity within a part per thousand of that of Elliott Bay. The salinity of the upper layer increases downstream, starting with a value at the head equal to that of the Green River.

Green River water temperatures follow the usual annual cycle from around 6°C (Celsius) in winter to 24°C in summer. Because even the coldest river water is always less dense than the saline Puget Sound water, the fresh water overrides the salt

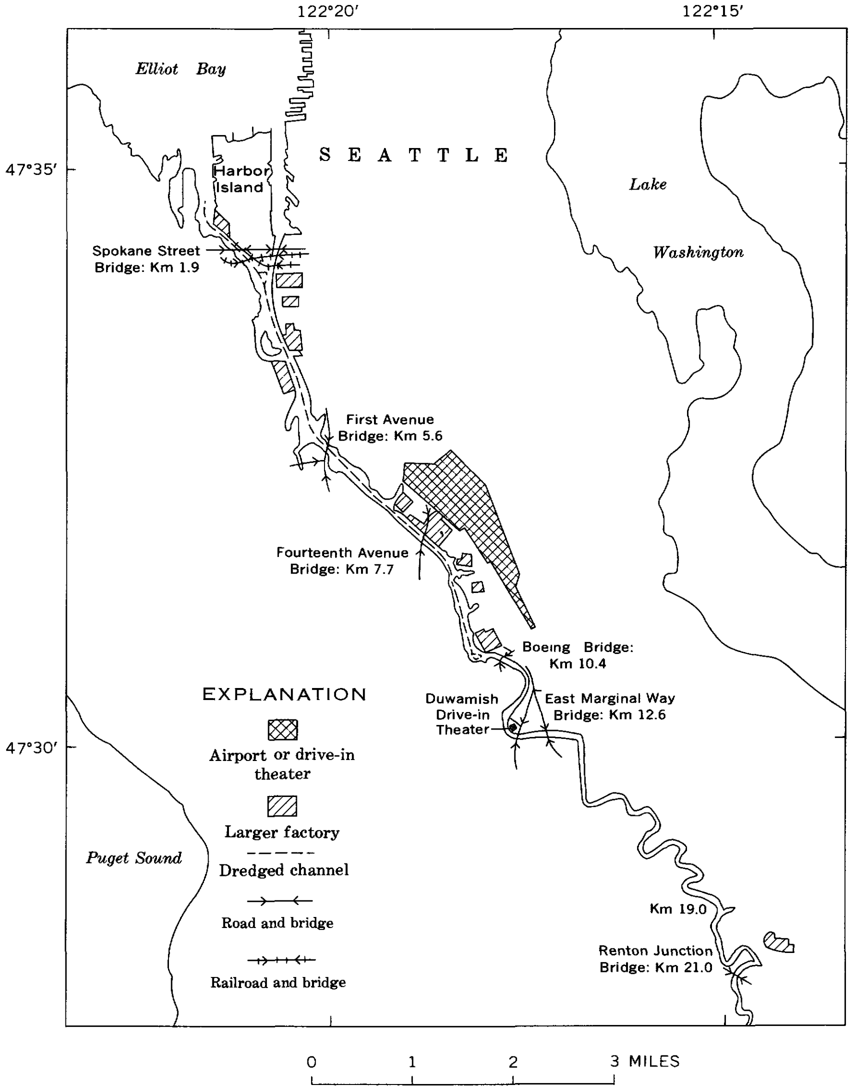


FIGURE 1.—Duwamish River estuary.

water and moves seaward on top of it. The overriding upper layer of river water on its way seaward erodes and entrains the salt water below. The lower layer of nearly unmixed sea water is called a salt wedge because of its shape in side view (figs. 4–6). The wedge tapers upstream, the bottom of the wedge having the steeper gradient. The toe of the salt wedge is most often near river km 12.0. Even at the mouth of the estuary, the salinity of the deeper water is always greater than the salinity of the water at the surface. This condition is true for all river stages, winter and summer, and the salt wedge must be considered a permanent feature of the estuary (figs. 4–6).

The discharge of the Green River varies annually from sporadic peak flows of 20,000 m^3/min (cubic meters per minute) and more to dry-weather minimums of 300–400 m^3/min. High flows usually occur during the winter and spring concurrent with lowland rains and thawing of snow in the upper reaches of the Green River in the Cascade Range, and more predictably in May, June, or early July, during the main snowmelt period. From mid-July through September the flow of the Green River tends to be well below 1,000 m^3/min.

Stoner (1967) compared the record from a continuous water-quality monitoring station at river km 12.6 with the hydrograph from the nearest Green River gaging station (at river km 21.0). The comparison of water quality with rate of inflow showed that the salt water that is mixed upward from the salt wedge into the river water will be moved upstream on a rising tide, reaching a point somewhere above the location of the monitor when the fresh-water inflow rate is less than 1,060 m^3/min. Salt water never appears at this monitor station when inflow is greater than 1,700 m^3/min (fig. 6*A*).

Data from a second automatic water-quality monitor at river km 7.7 show that the salt wedge itself is displaced downstream below this point at very high rates of fresh-water inflow. However, this displacement is not shown in figures 4–6, for they do not depict longitudinal salinity distribution for this rate of inflow.

As the overriding upper layer erodes the surface of the salt wedge, the wedge contributes salt to the river water above but is not itself significantly diluted in return. Some salt water is mixed upward all the way to the surface, but only negligible amounts of fresh water find their way downward into the wedge during the net upstream advection of the salt-wedge water. During low river flows the vertical salinity gradient is diffuse, and a higher concentration of salt is present in the upper layer of river water in the estuary than during high flows. If the salt wedge at high flow is compared with that at low flow (figs. 6*A*, *B*), the initial impression might be that more mixing occurs at low rates of flow; however, figures 6*A* and *B* should not be so interpreted because they do not show the differing rates of flow and, hence, differing residence times.

PROPERTIES AND CIRCULATION OF PUGET SOUND WATER

One of the better definitions of an estuary is "a semienclosed body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage" (Pritchard, 1967, p. 4). Fitting the Duwamish River estuary to this definition requires that Puget Sound be its "open sea." The Sound is, in fact, an estuary in its own right and is part of a larger estuarine system as well (fig. 2) ; it is also well suited for treatment as a seaward

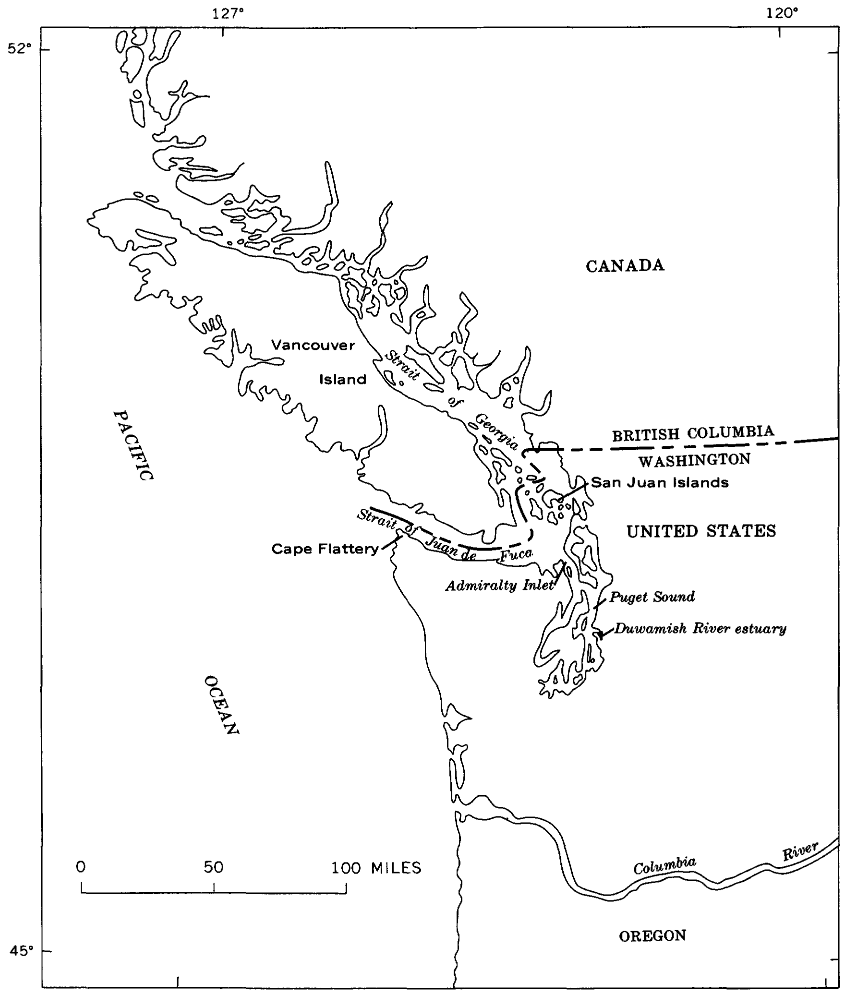


FIGURE 2.—Location of study area relative to Puget Sound and to Straits of Juan de Fuca and Georgia.

estuarine boundary. Although its surface-to-volume ratio is small among the world's estuaries, Puget Sound is far from being a fjordlike system with pronounced and persistent stratification. Owing to its bottom configuration—a succession of deep (75–100 m) sills and constrictions alternating with large deeper (200–300 m) basins—and to the large (2–4 m) tidal range, its waters are thoroughly mixed. The fresh-water inputs are relatively small and scattered, and the Sound's large volume provides enough thermal inertia so that seasonal variations in temperature are quite small (fig. 3). Refined oceanographic tech-

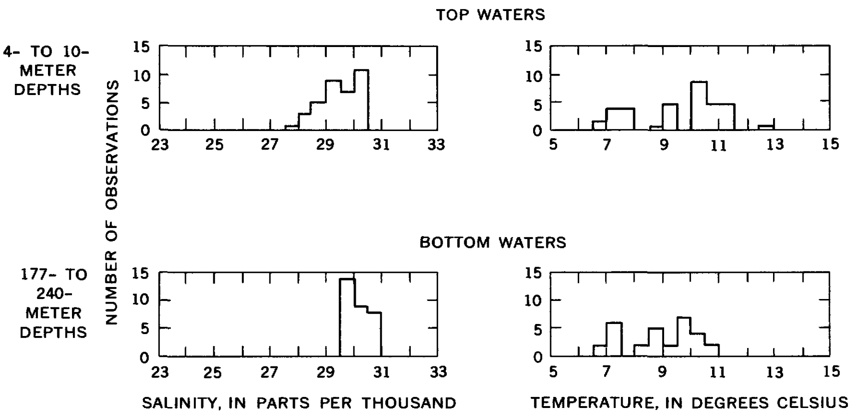


FIGURE 3.—Comparison of salinity and temperature ranges for top and bottom waters of Puget Sound off Seattle, as measured at indicated depths January 1956–December 1957. Data from Collias and Barnes (1964), who give salinities as accurate to 0.01 ppt (parts per thousand) and temperatures to 0.01°C.

niques of thermometry and salinity measurement are required to detect the stratification that does exist.

The source of Puget Sound water is another factor which helps to account for the constancy of its physical properties. Puget Sound and the Straits of Georgia and Juan de Fuca (fig. 2) form one large estuarine system that has a net transport of mixed salt water and land drainage outward at the surface and an inward flow of denser, more saline, sea water at depth (Waldichuk, 1957). The Strait of Juan de Fuca is quite deep (200–300 m) at Cape Flattery on the ocean end; the bottom shoals gently and continuously inward toward the land. Herlinvaux and Tully (1961) showed that the inward flow of ocean water in this superestuary is drawn from depths of 100–200 meters below the surface of the Pacific Ocean. At these depths the water is not subject to seasonal thermal fluctuations and also has been away from the surface so long that it is considerably undersaturated in DO. This water finally surfaces in Admiralty Inlet (and in the channels between the San Juan Islands), where the strength of the tidal currents acting against the deep-lying sills is great enough to produce top-to-bottom mixing at half-tide.

In brief, the salt-wedge water of the Duwamish River estuary comes from a rather large water body which is notable for the stability of its temperature and salt content. As a result, although new salt water constantly feeds in at the mouth of the estuary, the salt-wedge water even as far upstream as river km 7.7 has nearly the same salinity the year around.

The measurements of salinity (figs. 7*A–C*) were made in every month, at every time of day, and at every stage of the tide. Because of the constancy of its physical properties, Puget Sound water is (for purposes of analysis) a far more easily measurable input to an estuarine system than are many coastal waters.

Surface waters leave Puget Sound before contact with the atmosphere brings them to saturation with DO. For example, in 1957 surface waters of central Puget Sound were saturated with DO only about 24 percent of the time; water at a depth of 5 meters in the central Sound was saturated only 17 percent of the time, and water at 10 meters was saturated only 11 percent of the time. When saturation did occur—only in late spring and early summer—the high degree of oversaturation pointed to phytoplankton "blooms" as the source of oxygen rather than gas exchange at the water-air interface (Collias and Barnes, 1964).

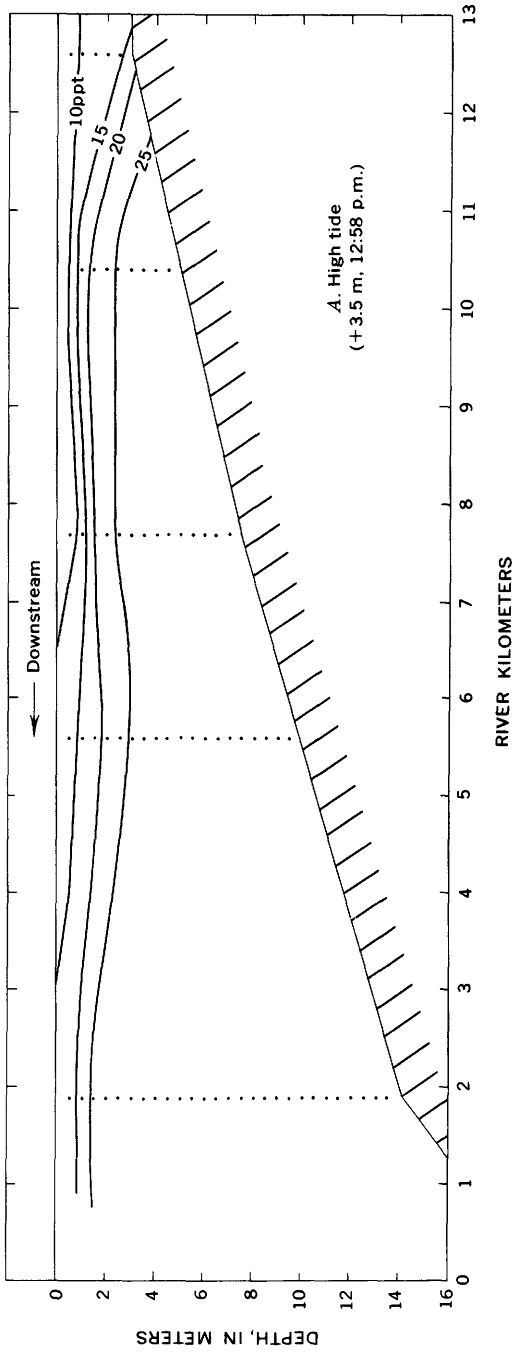
EFFECTS OF TIDES

Puget Sound tides are driven by the astronomically timed tide wave of the northern Pacnfic Ocean and are strongly influenced by resonance properties of the various basins and inlets of the Sound. Long-term measurements of the rise and fall of the tide at a few points on the Sound and shorter-term measurements at many other points have yielded sufficient data to permit publication of predicted tidal heights for any future time. Data on the tidal currents in the Sound also have been measured but in far less detail, and currents predicted from those data (with reference to times of high and low water) are valid only for the central Puget Sound basins. Diurnal inequality (the tendency for succeeding highs and lows to vary greatly) is strong. Mean tidal ranges increase from 1.5 meters (5 ft) on Juan de Fuca Strait to 3 meters (10 ft) in the inlets at the head of the Sound. Diurnal ranges (the difference between mean higher high and mean lower low tide) increase from 2 meters (7 ft) to 5 meters (16 ft) between the Strait and the head of the Sound (U.S. Coast and Geodetic Survey, 1952, 1967a, b).

The Duwamish tides, on the other hand, are hydraulic in the sense that they are driven by the difference between tidal stage of the Sound at the estuary mouth and river stage at the head. When the water level at the mouth is higher than the water levels in the remainder of the estuary, Puget Sound water flows in, raising water levels in the estuary. At these levels the water in turn brakes and accelerates the flow velocity of the river. For most small estuaries the tidal phenomena are of this hydraulic type; that is, the effect of the tide on the estuarine circulation and the amount of tidal water entering the estuary are rigidly controlled on the one hand by the volume and configuration of the estuary basin—its length, width, taper, and geographic position—and on the other hand by the entering streamflow. Some hydraulic tides are predictable, as, for example, in straits between large islands and the mainland, where the hydraulic heads producing the tides will be largely a function of differences in phase (arrival times) of the astronomic tides at the ends of the strait. But the hydraulic tide of the Duwamish River estuary, as for any small estuary, will be only as predictable as the entering streamflow.

If the tidal range on the Duwamish River estuary were near zero, the volumes of water in the estuary, in the salt wedge, and in the outgoing layer of mixed fresh and salt water would be relatively easy to measure. On such a tideless estuary changes in the position and volume of the wedge would follow changes in the rate of inflow of fresh water from the river, and when the discharge of the river was not changing rapidly, ample time would be available for making vertical profiles of the salinity distribution in the estuary.

In the presence of a strong tide with a pronounced diurnal inequality, however, the problem of mapping the wedge is more complex. The wedge position fluctuates constantly and its shape probably changes with the tide (figs. 4, 5). The period of time


10ppt
15
20
25
A. High tide
(+3.5 m, 12:58 p.m.)
Downstream
RIVER KILOMETERS
DEPTH, IN METERS
0 1 2 3 4 5 6 7 8 9 10 11 12 13
0 2 4 6 8 10 12 14 16

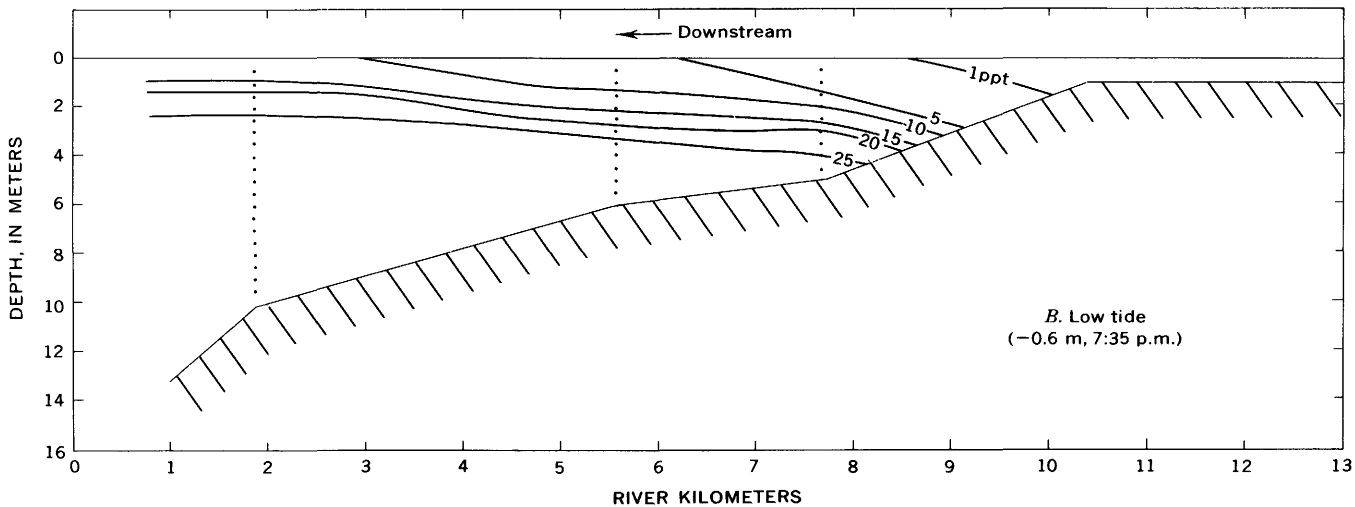
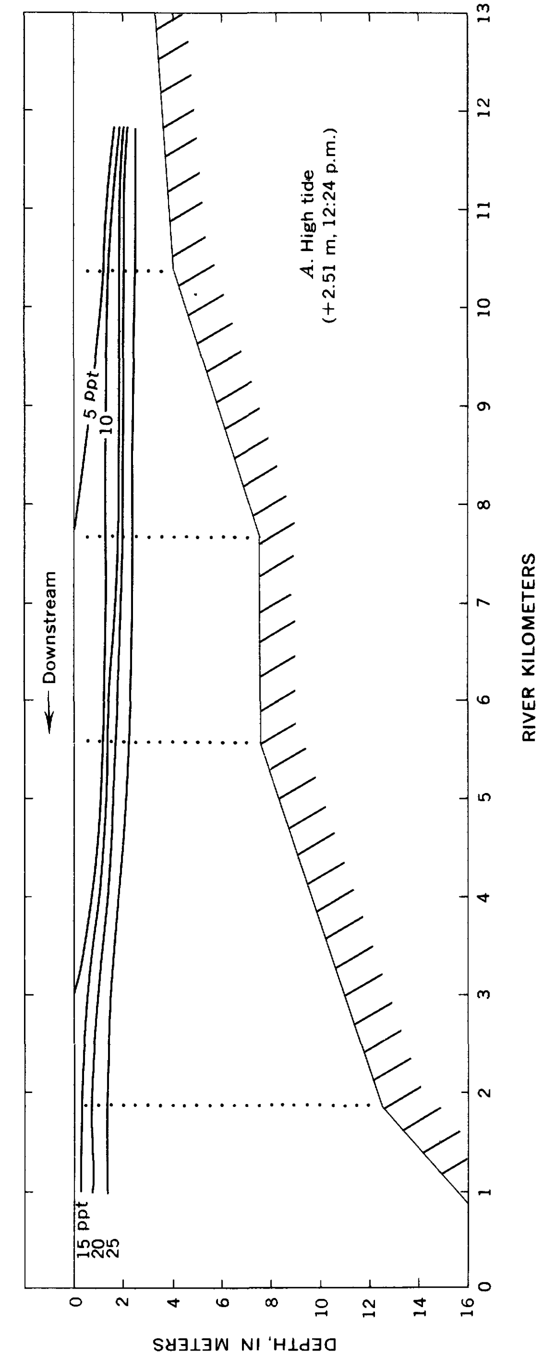


FIGURE 4.—Schematic longitudinal profiles of estuary showing distribution of salinity on a large-range tide (4.1 m) at high and at low tides, July 25, 1968. Numbered line represents depth distribution of salinity value given in parts per thousand. Dots indicate points of individual measurements, which were made at half-meter depth intervals. Fresh-water inflow rate was 665 m^3/min.


A. High tide
(+2.51 m, 12:24 p.m.)
Downstream
5 ppt
10
15 ppt
20
25
DEPTH, IN METERS
RIVER KILOMETERS
0
2
4
6
8
10
12
14
16
0
1
2
3
4
5
6
7
8
9
10
11
12
13

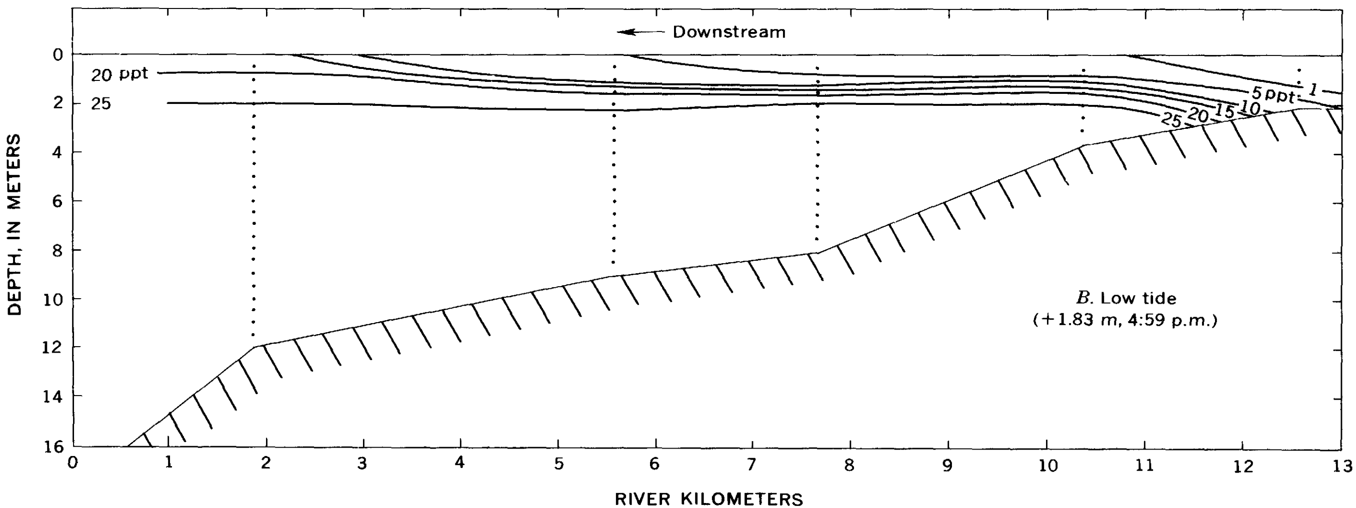


FIGURE 5.—Schematic longitudinal profiles of estuary showing distribution of salinity on a small-range tide (0.68 m) at high and at low tides, August 15, 1968. Numbered line represents depth distribution of salinity value given in parts per thousand. Dots indicate points of individual measurements, which were made at half-meter depth intervals. Fresh-water inflow rate was 655 m^3/min.

when the wedge is not changing shape or position too rapidly to be mapped is limited to an hour or two near the turn of the tide. With at most 2 hours available for measuring vertical profiles along 15 km of estuary, the choices of parameters and points to measure had to be made carefully—for example, the number of DO measurements had to be limited to two at each site selected, although 10 measurements per site would have been preferable.

Flow reversal, observed even at river km 12.6 (Stoner, 1967, p. 253) and certainly for some distance above, indicates that the tidal-height fluctuations along the estuary are by no means attributable only to a pileup of fresh water as the instantaneous flow rates in the lower part of the estuary approach zero on a rising tide. Instead, the increase in water volume during a rising tide is contributed partly by salt water and partly by fresh. Not only has the salt wedge itself been observed to move upstream (fig. 4), but the mixed water on top of the wedge also flows upstream for short periods as well. There must be, of course, for each rising tide at low rates of river flow a moving point somewhere between km 12.6 and km 21.0 (where reversal has never been observed) where the river-flow velocity is zero. During high rates of fresh-water inflow, the movement of the upper-layer waters through the entire estuary probably is downstream at all stages of the tide (fig. 6*A*).

BIOLOGICAL PHENOMENA AND HYDRODYNAMICS

There is ample ground for belief that all biological phenomena in the estuary water are strongly influenced by the shift from a nonreversing (continuously outward) flow pattern during high river flow to a reversing pattern during low flow. Welch (1969) related both the "blooms" of phytoplankton (algae in suspension) and the low DO concentrations in the salt wedge to low-flow conditions and consequent increased retention times for both upper-layer water and salt-wedge water. Although he lacked the supporting evidence of retention-time estimates, he was able to show that the timing of the "blooms" was related to minimum tidal ranges and that the gradual decline in fresh-water inflow from midsummer to early autumn was closely matched by correspondingly lower minimum DO concentrations in the salt-wedge water. The relation between water movement and DO concentration was described by Welch (1969, p. 43) as follows:

Concentrations of DO in the saline-water wedge decrease during late summer apparently because retention time of that water increases as discharge and consequent flushing rate decrease. Water in the part of the wedge that is farthest upstream has been retained in the estuary for the longest time without reaeration. ***There is a net upstream movement of bottom water, and ***the only escape for that water is through mixing and entrainment within the brackish surface-water layer. As retention time of the bottom water increases, the DO concentration decreases because the BOD [biochemical oxygen demand] has a longer time to act.

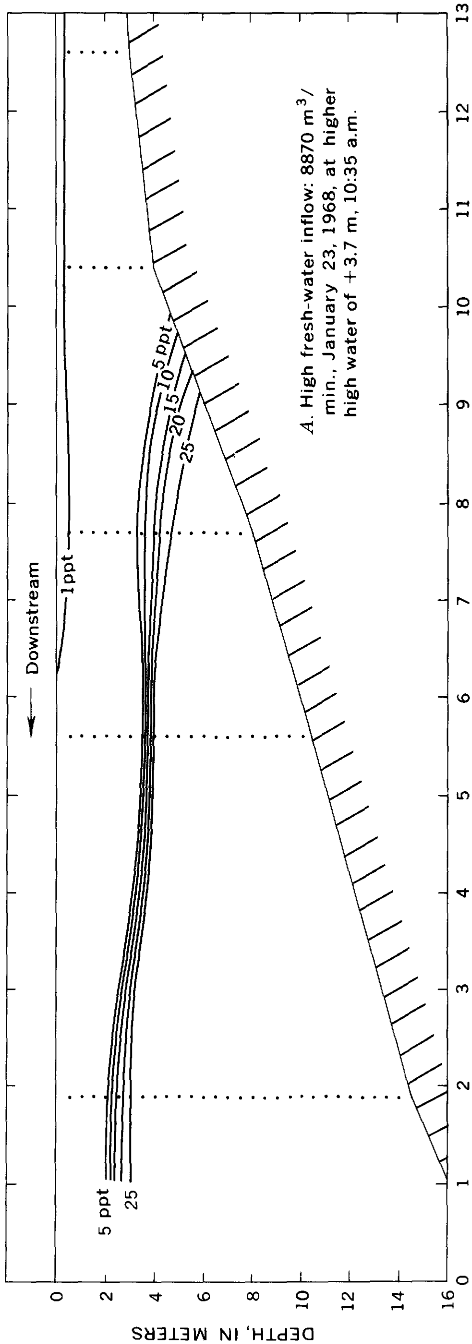
Without more detailed knowledge of the rate of this tidally pulsed upstream flow, it becomes nearly impossible to make useful interpretations of any measurements of biochemical DO consumption.

Upper-layer retention times are obviously more directly related to fresh-water inflow rate than are the retention times of the salt-wedge water; the relation is probably a continuous function. It is equally obvious that the onset and growth of flow reversal in the upper layer with declining river flow could cause an abrupt increase in retention time. Although figures 6*A*, *B* show a much greater volume of fresh water in the estuary at high rates of inflow than at low rates, they do not show the different rates of flow of the water through the estuary and therefore cannot be used to determine retention time.

MEASUREMENT OF SALT-WEDGE EXCURSION BASED ON DISSOLVED-OXYGEN GRADIENTS

One possible approach to measurement of wedge excursion distance might be to locate the toe of the wedge at different times during the tidal cycle. Spot probing with a salinometer can do this quite easily. Nevertheless, this approach was not pursued because the toe of the wedge is likely to be the most unstable part —the smallest volume fraction and the most vulnerable to entrainment and mixing.

Measuring the excursion distance of the submerged salt-wedge water by the method here described requires only that some property of the wedge water be distributed in a longitudinal gradient which is both steep enough and persistent enough to define displacement. As a careful comparison of the centroid values of figure 7*A–C* will show, the salt-wedge salinities have a definite tendency to decline in an upstream direction



A. High fresh-water inflow: 8870 m^3/min., January 23, 1968, at higher high water of +3.7 m, 10:35 a.m.

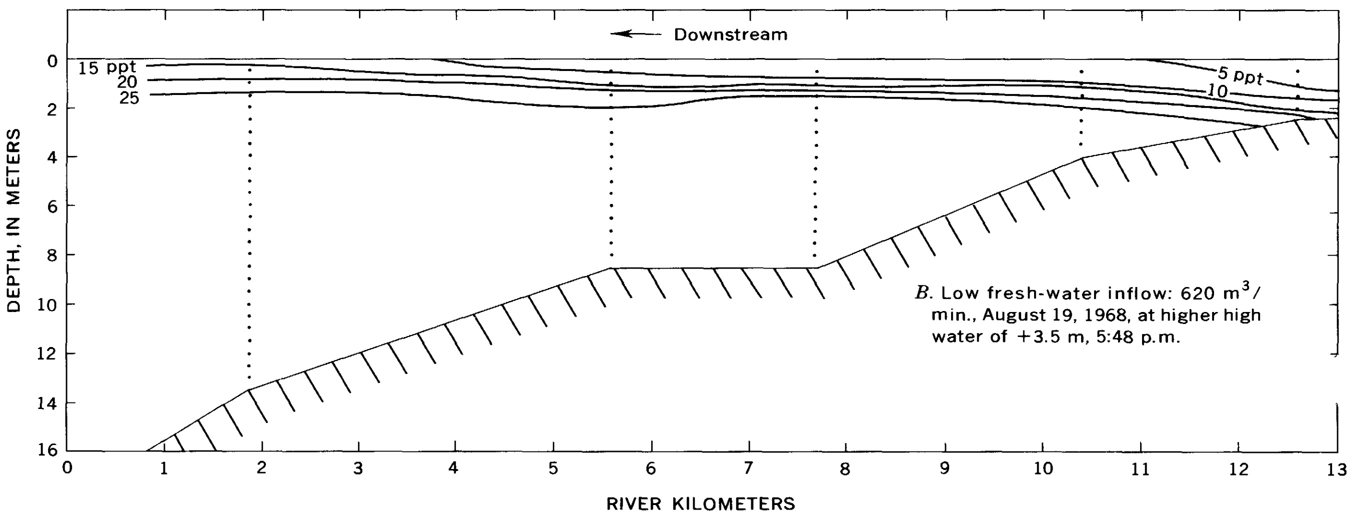


FIGURE 6.—Schematic longitudinal profile of estuary showing distribution of salinity at high and low rates of fresh-water inflow at high tide. Numbered line represents depth distribution of salinity value given in parts per thousand. Dots indicate points of individual measurements, which were made at half-meter depth intervals.

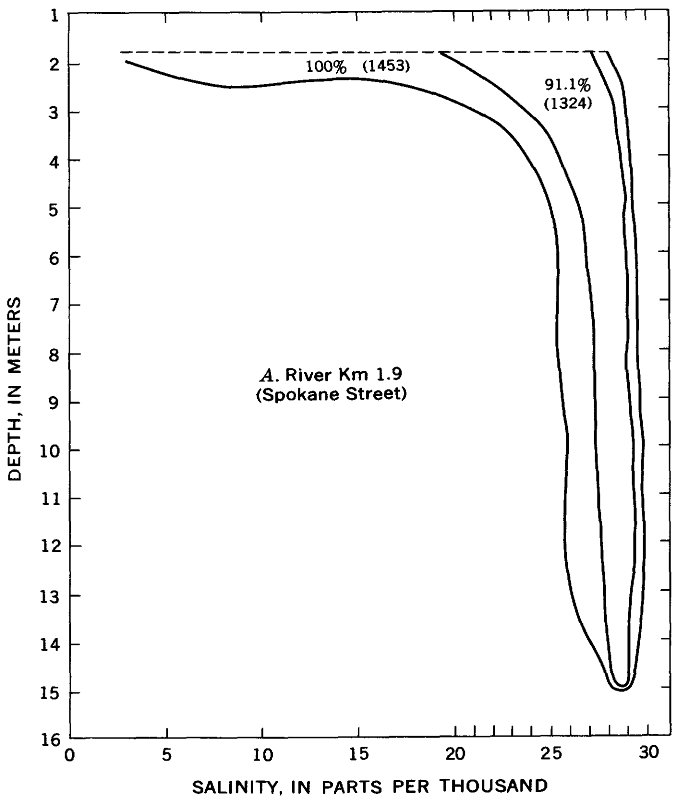


FIGURE 7.—Salinities in the salt wedge (below 2-m depth) at three stations upstream from the mouth of the estuary. Number outside parentheses shows percentage of measurements that fall within outlined area. Number within parentheses shows number of plotted measurements represented by outlined areas.

at a rate of about 0.2 ppt (part per thousand) per km. Although this gradient has the required steepness, the scatter of the salinity values (fig. 7) weakens their usefulness as an index of the position of the wedge in the estuary. The same is true of temperatures (not shown). The individual points around which the envelope lines of figure 7 were constructed represent synoptic data measured with a portable instrument to a precision of 0.1 ppt. Continuous salinity data from fixed-position recorders have the same (or better) precision; so the possibility exists that a systematic examination of continuously recorded salinities might indeed yield usable estimates of excursion distance.

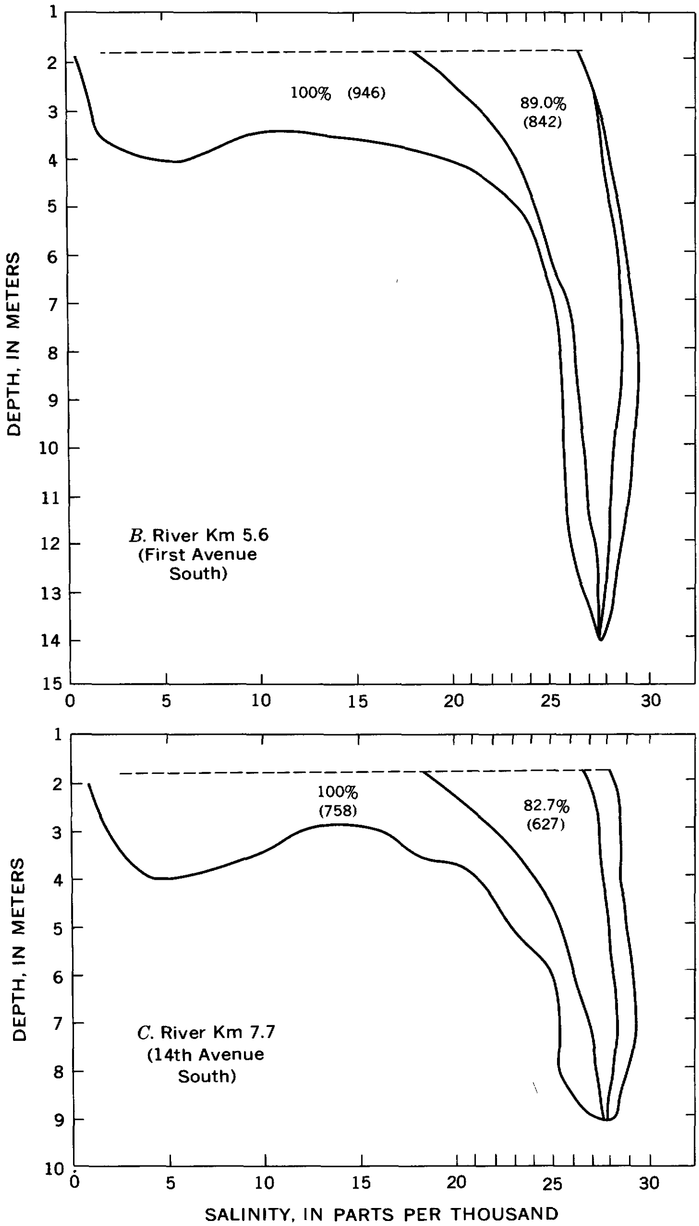


FIGURE 7.—Continued.

The rate of decline of DO in an upstream direction along the length of the wedge was found to vary less from periods of low to high rates of fresh-water inflow (fig. 8) than was expected

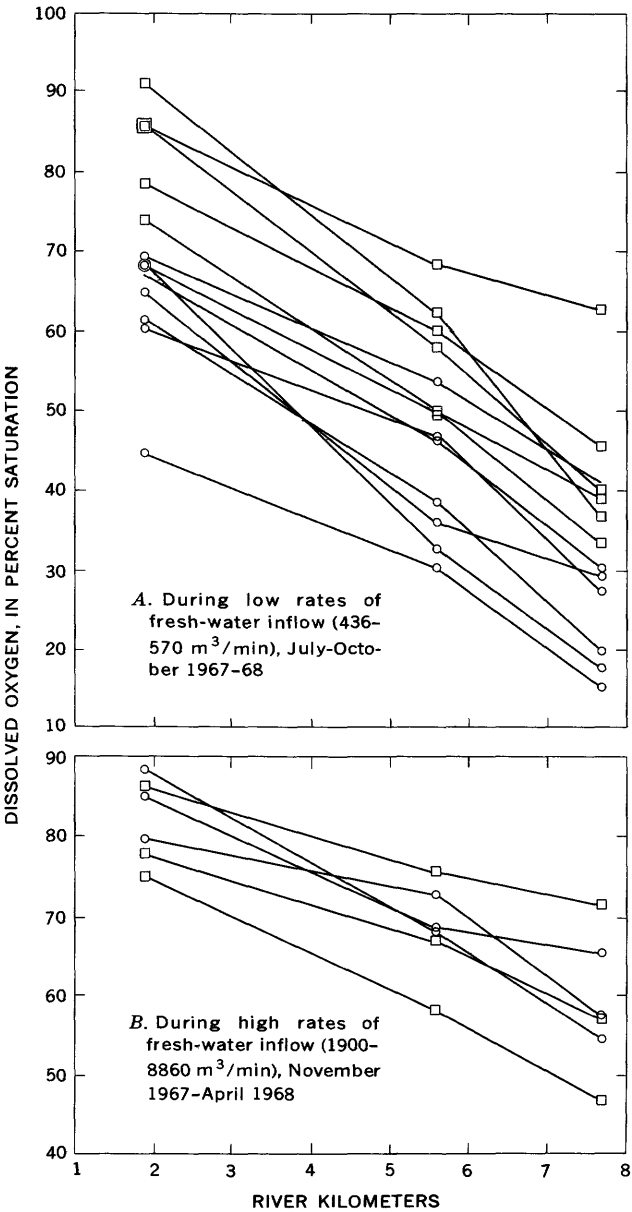


FIGURE 8.—Dissolved-oxygen gradients in the salt wedge during periods of low and high rates of fresh-water inflow. Squares represent samples collected at high tide; circles, low tide.

on the basis of previous knowledge (Welch, 1969). DO gradients for a 5.8-km reach of the estuary (Spokane Street to 14th

Avenue) are shown by the curves of figure 8. Although winter DO-decline curves slope less (fig. 8*B*) than summer curves (fig. 8*A*), the differences in slope are smaller than expected.

The possible use of the DO data to extend the knowledge of the hydrodynamics of the estuary became apparent when the DO-decline curves for consecutive sampling periods one flood or one ebb apart were found to be similar. The similarity permitted an estimation of the distance a tide change of a given range causes the salt wedge to move upstream or downstream. All the measurements used for this purpose were made in the daytime; the first set on the first daylight turn of the tide, and the second set on the next succeeding turn of the tide. Repeated measuring throughout the year yielded data for nearly 24 pairs of salt-wedge conditions, each pair representing a consecutive relation of one high-water and one low-water wedge condition. Tide range for each pair was calculated as follows:

1. "Midpoint time" was calculated for each measurement run from which wedge data were plotted. The midpoint time was half the time difference between arrival at the first profiling station (km 1.9) and departure from the last (km 10.4 or 12.6).

2. From the two midpoint times for each pair, a "sampled tide range" was determined by interpolation on the predicted tide curve for Elliott Bay. Measurement runs varied in duration. During the runs precise knowledge of the actual stage of the tide was not available, but if delays extended the run too far beyond slack water, the increased flow velocity of the estuary gave warning, and the run was abandoned.

3. The wedge-pair curves were sorted according to the sampled tide range and were divided into six groups, each group containing six curve pairs (chosen without regard to season of the year or rate of stream inflow).

4. Within each group the curves were sorted and composited on two graphs—one for high and one for low tide—and mean DO values from each sampling site were calculated for each graph. The line joining these mean DO values is called the mean gradient. Figures 9*A* and *B* show the position of the mean gradient for the group that represents the smallest tide ranges.

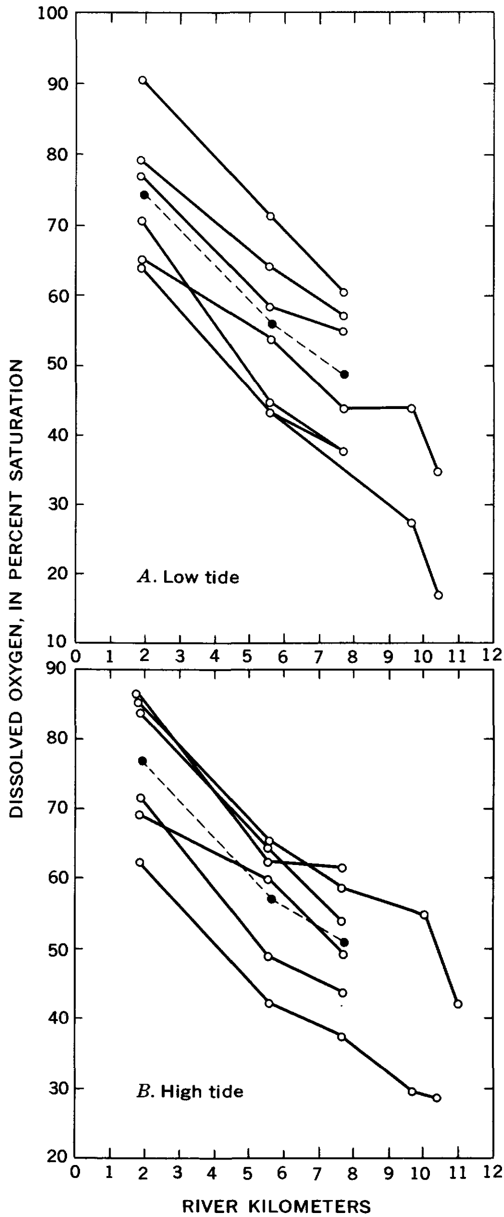


FIGURE 9.—Dissolved-oxygen gradients in the salt wedge for small tidal ranges (0.2–0.8 m) at low tide (*A*) and high tide (*B*). Dashed line represents mean gradient for the corresponding set of gradient curves.

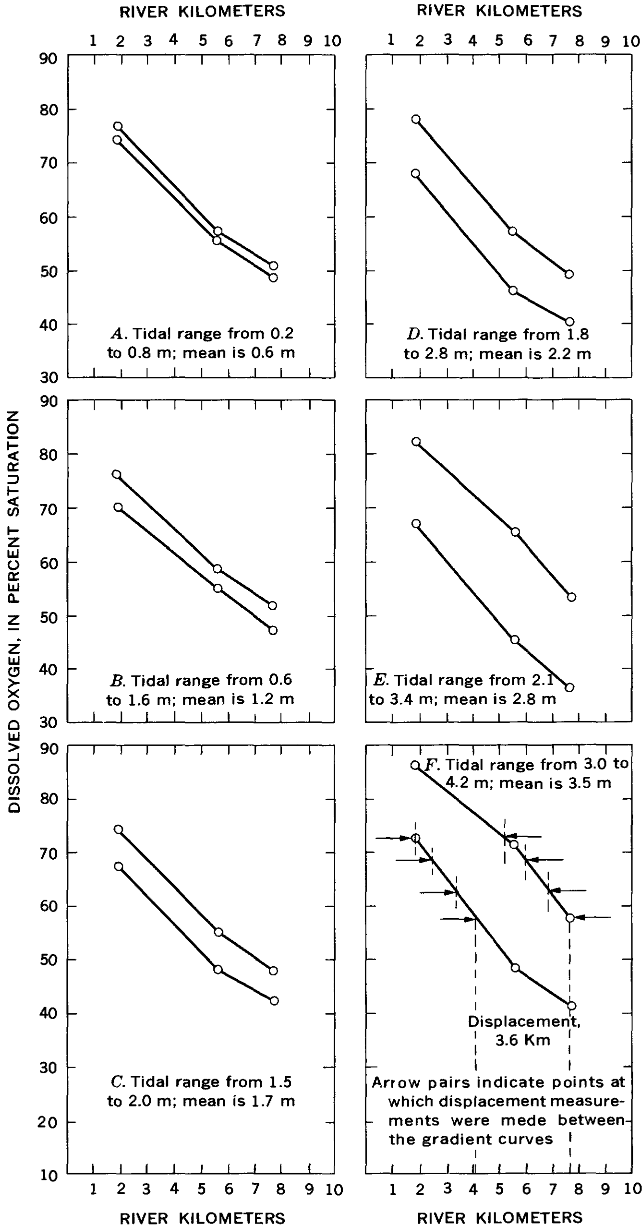


FIGURE 10.—Mean dissolved-oxygen gradients in the salt wedge at high and at low water for selected tidal ranges.

5. The mean-gradient data so developed were plotted in pairs for each of the six tidal ranges. Figure 10 *A–F* shows

these plots of mean DO decline—one for high and one for low tide—for each of the tide-range groups.

6. The horizontal displacements between each curve pair were measured at four points, as shown by the arrow pairs in figure 10*F*. The horizontal distance between the mean-gradient curves for each graph of figure 10 should then give a rough indication of salt-wedge excursion distances for the corresponding tidal ranges; for example, for tidal ranges between 3.0 meters and 4.2 meters, an excursion of about 3.6 km might be expected (fig. 10*F*). A plotting of all the displacements indicated by figure 10 against their mean tidal range yielded the graph in figure 11; from this graph an estimate of salt-wedge excursion for any tidal range can be determined.

Strictly speaking, the path of any water particle through a tidal excursion should be such that the volume of water between the water particle and a hypothetical upstream point of zero tide is a constant (Thames Survey Committee and Water Pollution Research Laboratory, 1964, p. 6–7). The effect of this type of water movement in a tapering estuary would be a divergence in the upstream direction between the line pairs of gradients depicted in figures 9 and 10. Apparently the natural taper of the estuary has been adjusted by man to such a small value that, in a first approximation, such a divergence can be neglected. Accordingly, only one excursion value, the mean of four measurements, was taken from each of the plots of figure 10.

CONCLUSIONS

A close relationship between tidal excursion (longitudinal water movement) and tidal range (rise and fall of water level) is only to be expected in a nonestuarine embayment. Estuaries with their irregular fresh-water inputs are known to be less predictable in their tidal behavior. The data on which this analysis of hydrodynamics of the Duwamish River estuary is based were gathered over a wide range of fresh-water inflow rates, and the writers, who made these observations, have had ample first-hand experience with the changes which these inflow variations can produce in the estuary as a whole. One discovery is that one of the estuary's components, the salt wedge, seems to have more regularity to its behavior than had been suspected.

It might be assumed that the excursion-range relationship was also an excursion-stage relationship. This assumption implies

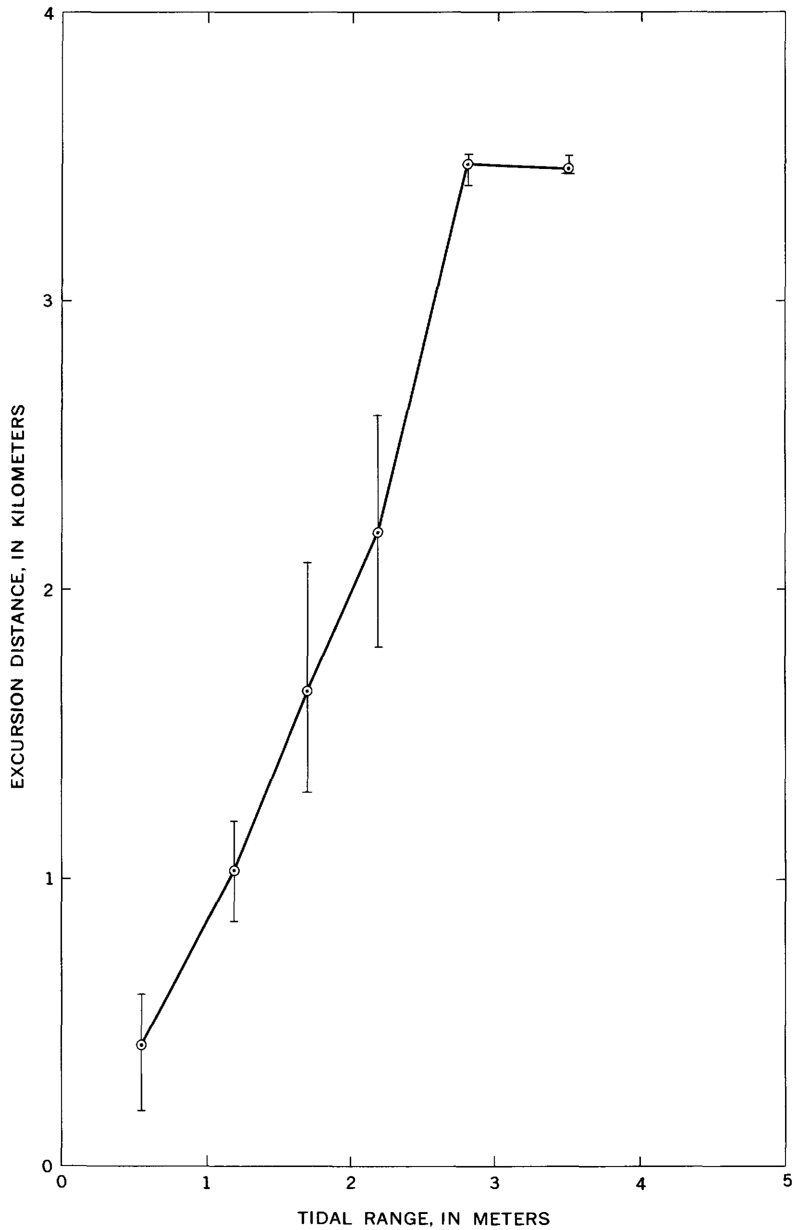


FIGURE 11.—Variation of salt-wedge excursion distance with tidal range. Each point is the mean of four measurements; vertical bars show excursion-distance range for a given tidal range.

that the wedge moves as far on one foot of tidal rise (or fall) as the average change in excursion with a one-foot difference in tidal range. If this were true for all values of fresh-water inflow, the task of formulating the hydrodynamics of the Duwamish would be vastly simplified. However, it is far more likely that variations in fresh-water inflow induce corresponding temporary changes in the wedge's behavior. The formal description of the estuary will require that these changes be quantified by means of further hydrodynamic studies.

The indicated relationships between tidal ranges and salt-wedge excursions have almost certainly been rendered simpler as a result of man's modification of the channel and of the fresh-water flow of the Duwamish River. Similarly, these and other relationships and processes within the estuary could be changed by further channel modifications. For example, an extension of the present navigation channel farther upstream would also lengthen the salt wedge. Conceivably, an increased wedge length could result in an increase in wedge-water erosion rate and entrainment of salt water by the upper-layer water, and the increased entrainment might produce some benefit by increasing the dilution of any pollutants in the upper layer. On the other hand, a lengthened salt wedge would mean increased traveltime of the wedge water to the upstream end and would thereby give oxygen-consuming processes more time to act. In this manner, the apparently unrelated action of dredging would cause a local degradation of water quality that would decrease the ability of the estuary to assimilate wastes and support fish life.

Thus the results of upsetting the delicate balance by arbitrarily altering the estuary can be beneficial or detrimental. Before prediction of all the imbalances and their ultimate consequences is possible, however, hydrodynamic analysis of the estuary must progress considerably beyond the present state of knowledge.

REFERENCES

Collias, E. E., and Barnes, C. A., 1964, Physical and chemical data for Puget Sound and approaches. September 1956–December 1957: Univ. Washington [Seattle] Dept. Oceanog. Tech. Rept. 110, p. 1–167.

Herlinvaux, R. H., and Tully, J. P., 1961, Some oceanographic features of Juan de Fuca Strait: Jour. Fisheries Research Board Canada, v. 18, no. 4, p. 1027–1071.

Pritchard, D. W., 1967, What is an estuary? *in* G. H. Lauff, ed., Estuaries: Am. Assoc. Adv. Sci. Pub. 83, p. 3–5.

Stoner, J. D., 1967, Prediction of salt-water intrusion in the Duwamish River estuary, King County, Washington, *in* Geological Survey research, 1967: U. S. Geol. Survey Prof. Paper 575–D, p. D253–D255.

Thames Survey Committee and Water Pollution Research Laboratory, 1964, Effects of polluting discharges on the Thames Estuary: London, Dept. Sci. and Indus. Research, Water Pollution Research Tech. Paper 11, 609 p.

U. S. Coast and Geodetic Survey, 1952, Tidal current charts, Puget Sound, Northern part [2d ed.]: Washington, D. C., U. S. Govt. Printing Office.

———1967a, Tide tables, high and low water predictions, 1968, west coast, North and South America Washington, D. C., U. S. Govt. Printing Office, 224 p.

———1967b, Tidal current tables, Pacific Coast of North America and Asia, 1968: Washington, D. C., U. S. Govt. Printing Office, 254 p.

Waldichuk, M., 1957, Physical oceanography of the Strait of Georgia, British Columbia: Jour. Fisheries Research Board Canada, v. 14, no. 3, p. 321–486.

Welch, E. G., 1969, Factors initiating phytoplankton blooms and resulting effects on dissolved oxygen in Duwamish River estuary Seattle, Washington: U. S. Geol. Survey Water-Supply Paper 1873–A, 62 p.

U.S. GOVERNMENT PRINTING OFFICE. 1972 O—469-468