A Numerical Model of Material Transport In Salt-Wedge Estuaries

GEOLOGICAL SURVEY PROFESSIONAL PAPER 917

Prepared in cooperation with the Municipality of Metropolitan Seattle

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Part I. Description of the Model

By H. B. FISCHER

Part II. Model Computation of Salinity and Salt-Wedge Dissolved Oxygen in the Duwamish River Estuary, King County, Washington

By J. D. STONER, W. L. HAUSHILD, *and* J. B. McCONNELL

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CONVERSION FACTORS

In recognition of the worldwide use of the metric system of measurements, the following factors are provided for conversion of English values used in this report of metric values:

Multiply	*By*	*To Get*
Feet (ft)	0.3048	metre (m)
Miles (mi)	1.609	kilometres (km)
Cubic feet (ft^3)	0.02832	cubic metres (m^3)
Cubic feet per second (ft^3/s)	1.699	cubic metres per minute (m^3/min)
Feet per second (ft/s)	0.3048	metres per second (m/s)

PART I. DESCRIPTION OF THE MODEL

By H. B. Fischer

ABSTRACT

Water in a salt-wedge estuary ideally is characterized by an oscillating well-mixed wedge of undiluted seawater topped by a series of successively more dilute overlying layers. In the wedge the flow is back and forth, with a net landward component to replace water entrained upward into the overlying layer; in the overlying layers the flow also oscillates, but with a net seaward component because of the input of fresh river water and entrained wedge water. The flow is modeled by a computer program, and the flow is used as an input to the constituent-transport model. The computer program then is used to determine the advection and dispersion of dissolved constituents and plankton, and their concentrations throughout the system in response to given inputs. The report describes required input data and method of operation of the computer program.

INTRODUCTION

In some estuaries, predominantly those in which the inflow of fresh water is relatively large and the rate of mixing by tidal action is relatively small, salinity intrusion takes the form of a wedge of nearly undiluted seawater. The mouth of the Mississippi River, described by Stommel and Farmer (1952), and the Ishikari River in Japan, described by Fukushima, Yakuwa, and Takahashi (1969) are typical examples. The Duwamish River estuary at Seattle, Wash., contains a wedge of Puget Sound water even when the river discharge is relatively small. The Duwamish River estuary, for which the program described in this paper was specifically derived, is described by Santos and Stoner (1972) and in Part II of this paper. Part I describes the program itself, as an aid for possible application in studies of other salt-wedge estuaries.

The purpose of the program is to model the transport and mixing of chemical and biological constituents in a salt-wedge estuary as a means of predicting the ecological consequences of man-induced changes in the estuarine system. A common ecological problem in salt-wedge estuaries is a detrimentally low level of dissolved oxygen (DO) at the toe of the wedge, caused by oxygen demand in the wedge and the lack of a mechanism for oxygen replenishment. This program therefore focuses on predicting concentrations of biochemical oxygen demand (BOD) and DO in the salt wedge. The transport of other biological constituents, such as plankton, also is modeled, in part to compute its effect on DO.

The hydrodynamics of a stationary salt wedge are described by Stommel and Farmer (1952) and Keulegan (1966). The distribution of flow in a stationary wedge is shown in figure 1; the flow is inward from the ocean along the channel bottom, and outward to the ocean both in the upper part of the saltwater wedge and in the overlying layer of mixed fresh and salt water. A net inward flow of saltwater in the wedge makes up for the salt water entrained from the wedge into the overlying layer. A stationary wedge is formed where a river flows into a tideless sea; if the sea is tidal the wedge will oscillate back and forth in the estuary, moving landward during the rising (flood) phase of the tide and seaward during the falling (ebb) phase. No complete solution for the hydrodynamics of an oscillating wedge has been found. The flow within the wedge will be turbulent because of the shear stress at the bottom, and entrainment into the overlying layer may be greater than for the stationary wedge. The time-averaged flow distribution may be assumed to be similar to that in the stationary wedge, although it will not be identical; the instantaneous flow distribution may deviate substantially from its time average during parts of the tidal cycle. In modeling constituent transport in a salt-wedge estuary, some assumptions must be made about the flow distribution and its effect. Discussed in the report are (1) the assumed flow distribution and the method of modeling dispersion, and (2) the transport of biological and chemical constituents.

THE FLOW MODEL

The flow model represents an attempt to describe the flow in the salt wedge and the overlying layer in a way sufficiently simple that (1) computer modeling of constituent transport is possible and (2) the model approximately represents observed distributions of flow and salinity. It should be stressed that no attempt has been made to solve the hydrodynamic equations of motion.

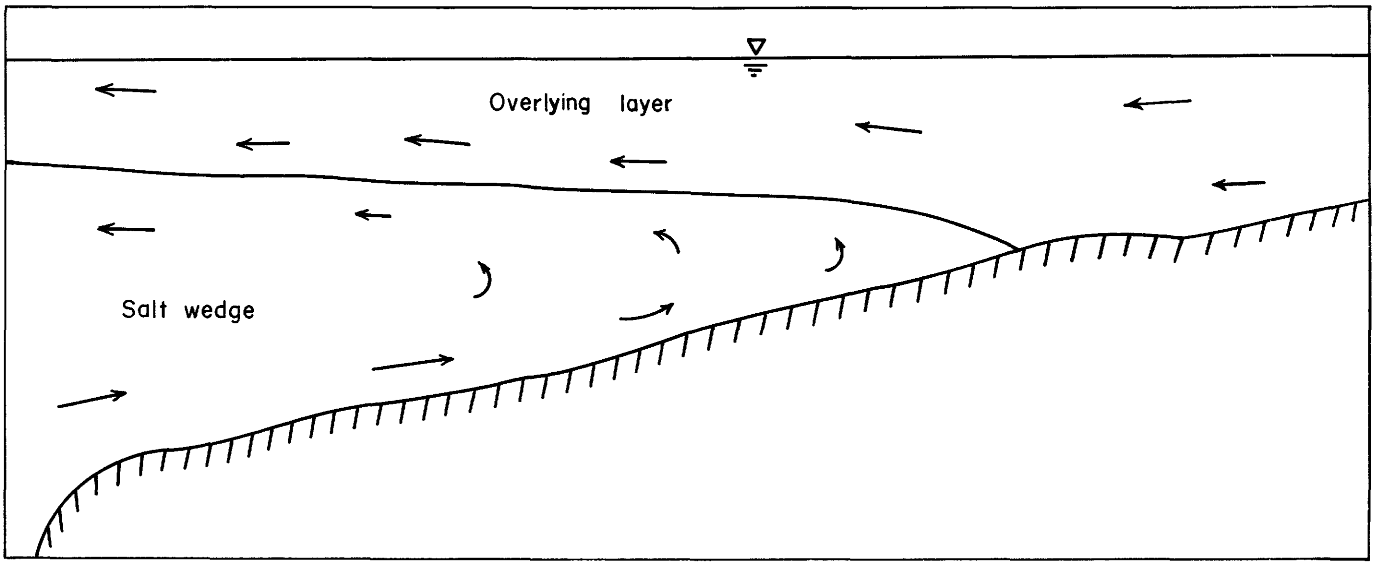

FIGURE 1.—Distribution of flow in a stationary salt wedge.

Rather, a shape is assumed for the wedge, as shown in figure 2, and flow in the wedge is computed so that water volume is conserved. Field measurements are used to determine the thickness of the wedge at the estuary mouth, the slope of the interface of the wedge and overlying layer, and the location of the wedge toe.

Figure 3 shows a typical vertical profile and a typical longitudinal distribution of salinity, as observed in the Duwamish River estuary. The nearly constant salinity in the wedge suggests that it is a well-mixed zone of turbulent flow. The overlying layer, which carries the freshwater from the river out to the ocean, is strongly stratified because the salinity, and therefore the density, decreases almost linearly throughout the layer. Therefore, turbulence and vertical mixing may be assumed to be strongly suppressed in the overlying layer. These observations form the basis of the flow model. The wedge is modeled as a sectionally homogeneous tidal flow, using a technique developed by the writer in a study of Bolinas Lagoon, Calif. (Fischer, 1972). The overlying layer is assumed to float back and forth on top of the wedge. The restricted nature of vertical mixing in the overlying layer is modeled by dividing the layer into sublayers and assuming that entrainment between sub-

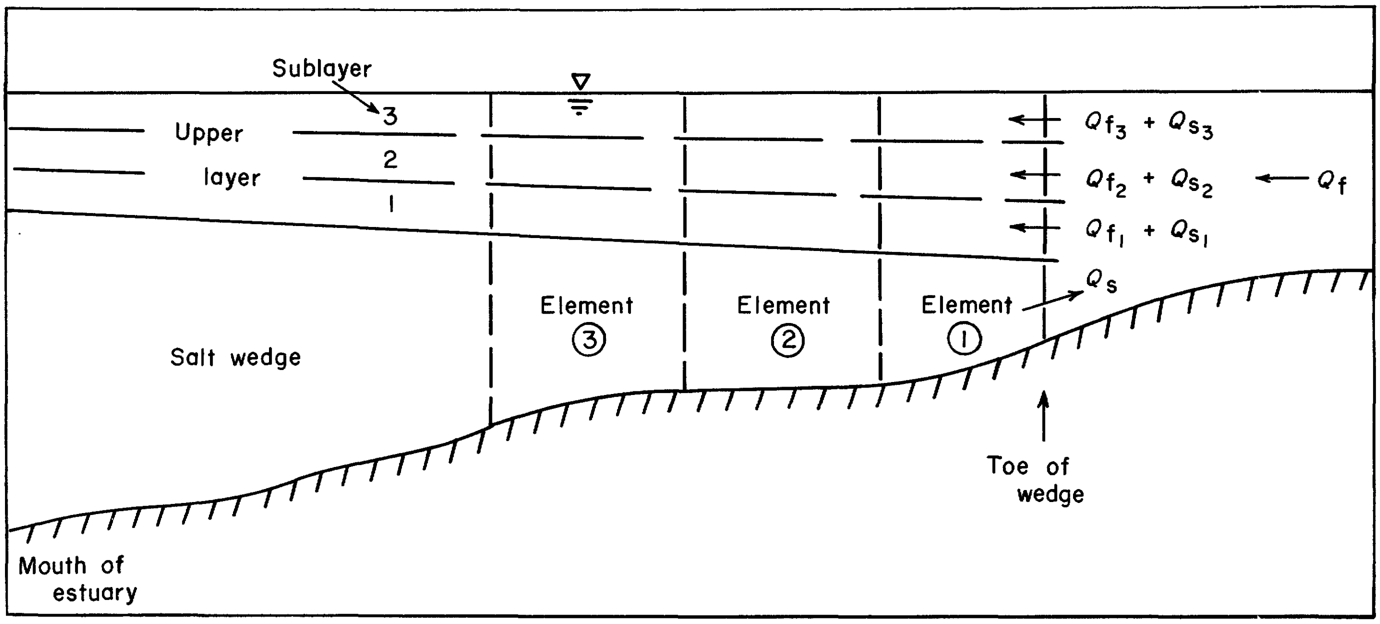

FIGURE 2.—Idealized longitudinal section through a salt-wedge estuary, showing divisions used for modeling.

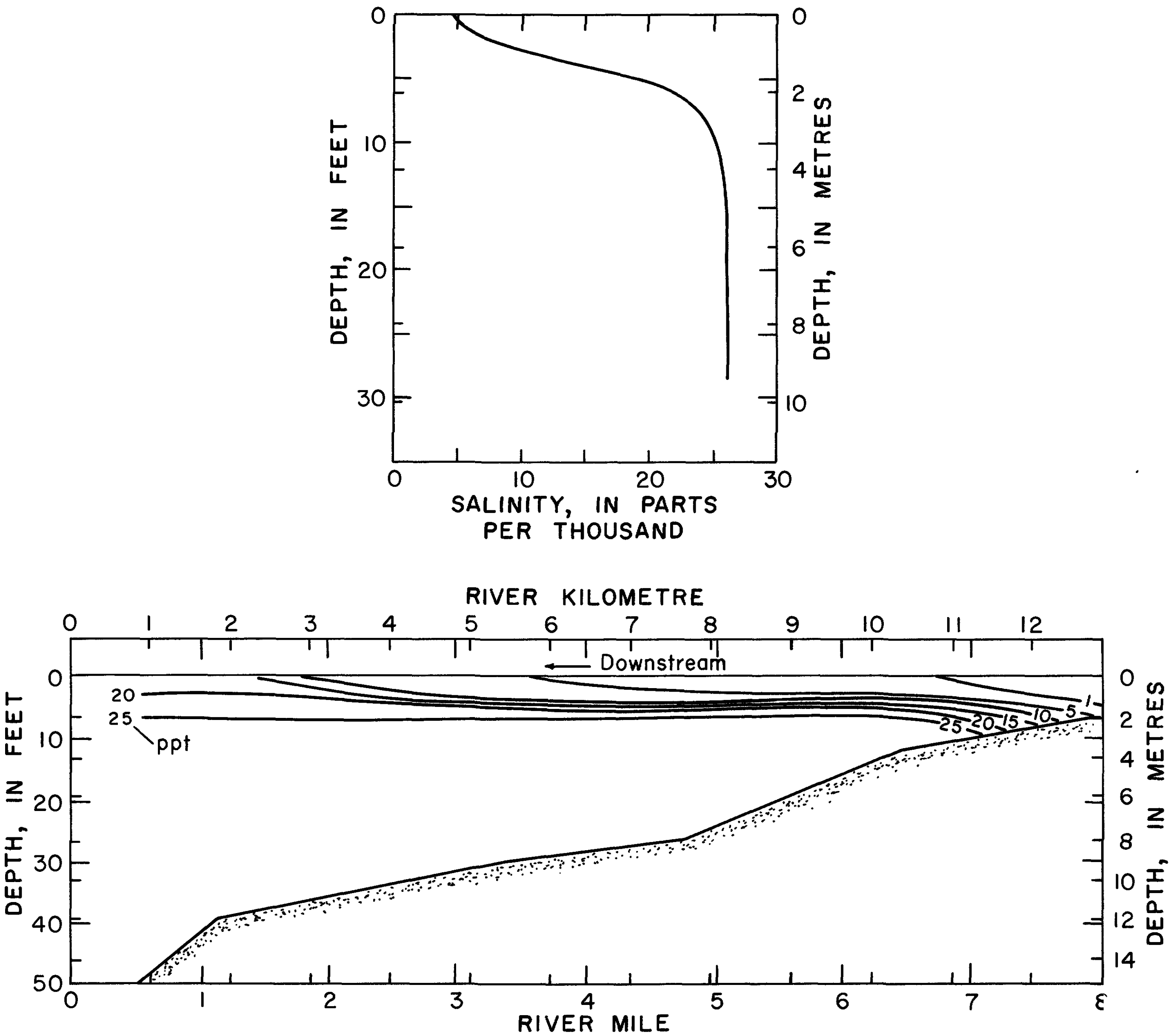

FIGURE 3.—Typical observed profile (upper graph) and longitudinal distribution (lower graph) of salinity in the Duwamish River estuary. Lower graph is from Dawson and Tilley (1972, fig. 5).

layers and from the wedge into the lowest sublayer occurs at empirically determined rates.

FLOW IN THE WEDGE

The wedge is treated as a turbulent open-channel flow, except that water is removed by entrainment through the upper surface and through the vertical face of the toe. The wedge is divided into elements in the same way as was the water in the channels in Bolinas Lagoon (Fischer, 1972). A typical element is shown in figure 4. An element is defined as a homogeneous volume of water occupying the entire channel cross section and extending along the channel axis a distance determined by dividing the element volume by the channel cross-sectional area. An element is assumed to maintain its coherence as it moves back and forth along the channel axis so that in the absence of entrainment or longitudinal mixing the element would always contain the same water; the effect of entrainment is to continuously remove water through the upper surface of each element, thereby reducing its volume. Mixing is allowed only with adjacent elements. Thus, the concentration of any constituent carried by the water is modified only by mixing and by appropriate biochemical reactions.

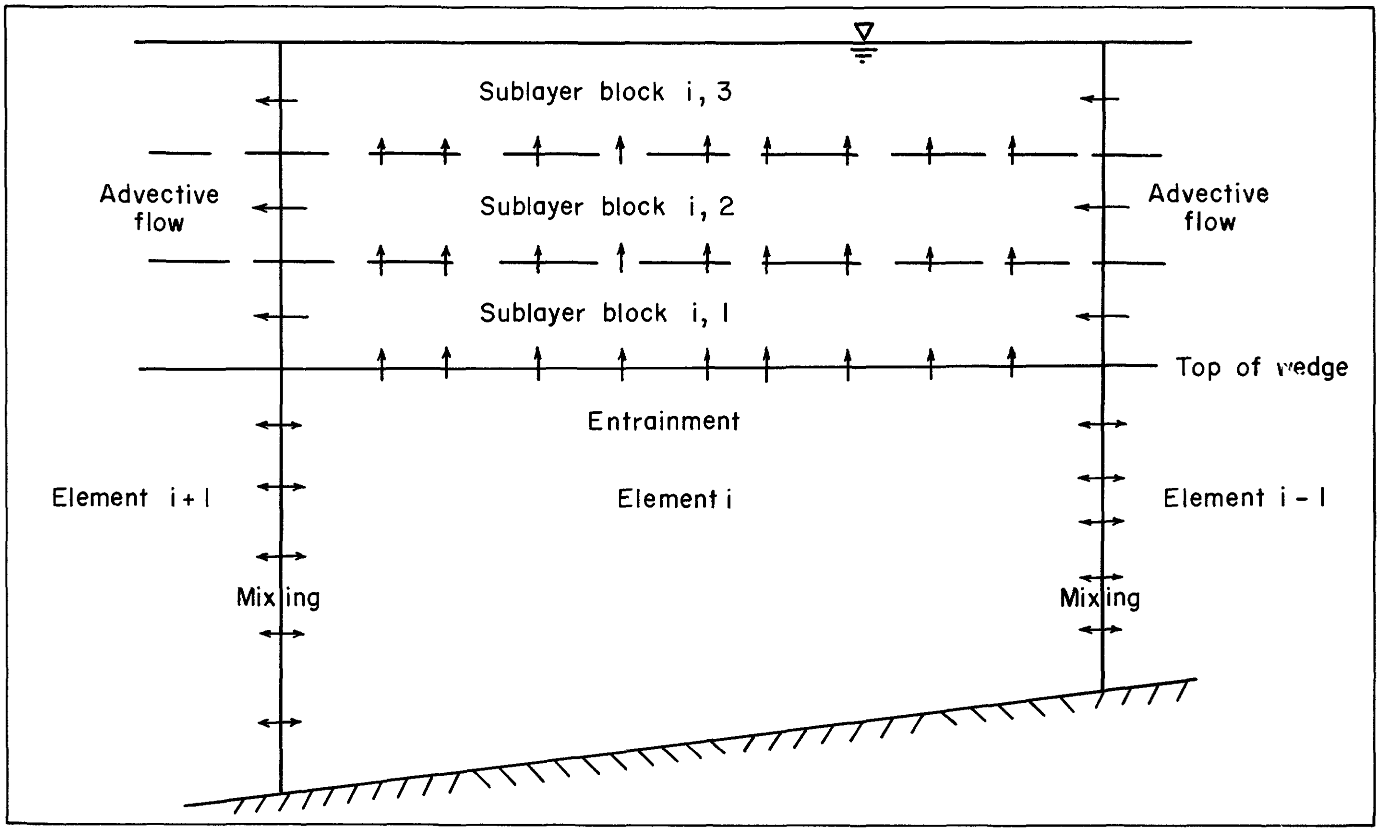

FIGURE 4.—Typical element, showing transport processes included in the model; settling velocities of suspended particles also are included in the model.

To find the location of a given element the program starts with element 1, which is at the toe of the wedge, and computes its length by dividing its volume by the cross-sectional area of the wedge; then the location of the upstream end and the length of element 2 are computed, and so on, to the mouth of the estuary. Wedge cross-sectional areas are computed from the geometry of the given estuary and wedge, as discussed in the section entitled "Model Operation." During tidal inflow the outermost element moves upstream from the estuary mouth, and a new element is formed from water that enters the estuary during each time step. (A 15-minute time step has been found convenient.) During tidal outflow, water leaving the estuary mouth is assumed to be fully mixed with the sea water and is removed from the computation, and the number of elements or the volume of the outermost element is reduced.

Transfer between the wedge and the various upper layers is modeled by assuming entrainment velocities upward across the bounding surfaces. The entrainment velocities must be found empirically; theoretical studies and laboratory measurements such as those of Turner (1968) and Kato and Phillips (1969) do not provide an adequate basis for estimating the rate of turbulent entrainment across a density interface in a real estuary. On the other hand, the technique developed by Stoner (1972) may be used to compute entrainment velocities from detailed salinity and longitudinal-velocity measurements at an estuary cross section. These computed entrainment velocities are supplied to the program as observed data and can be adjusted if necessary to improve the program's modeling of salinity. In the model the volume of each wedge element is reduced after each time step by an amount calculated as

$$\Delta V = U_{e1} W L \Delta t, \tag{1}$$

where U_{e1} is the entrainment velocity between the wedge and sublayer 1, W is the channel width at the top of the wedge, L is the length of the element, and Δt is the duration of the time step.

Because of entrainment, the volume of each wedge element continuously decreases. To avoid having a large number of small elements, an element reduction subroutine is included. Whenever an element becomes shorter than an arbitrary length of 200 feet (60 m), the element is combined in volume with the shorter of the adjacent elements to form one new element; all the identifying numbers of the elements seaward of the combination are then reduced by one. The same element reduction, using the shortest two elements, is made when the number of elements exceeds the program storage capability of 50 elements. A further constraint is for a special case that can occur only in element 1, the farthest upstream. Because the model provides for flow from this element out of the upstream end as well as upward into the upper layer, the flow out during a time step may exceed the volume contained in the first element. If the model determines that the volume of the first element will be less than the volume expected to flow out of it during a time step, the first element is combined with the adjacent downstream element.

The way in which the flow in the wedge is modeled may be summarized from the point of view of a water particle, as follows: A water particle that enters the wedge on a floodtide becomes part of a wedge element and is carried upstream. On the ebbtide the particle moves back downstream, in most cases leaving the estuary not to return. A particle that enters the estuary at the beginning of the floodtide, however, may be in an element that remains in the wedge after the following ebb. It then begins a backward and forward progression, on each flood moving slightly farther landward than it returns seaward on each ebb. Occasionally longitudinal dispersion may cause it to move from one element to the adjacent one, but on the average the particle will maintain a net landward drift. Finally, a time comes when the particle is entrained from the wedge into the first sublayer, and possibly farther into the higher sublayers. When this happens the net drift becomes seaward, and the particle is carried back to sea.

FLOW IN THE OVERLYING LAYER

The freshwater discharge of the river mixes with the saltwater entrained from the wedge to flow as a mixed layer above the wedge. Because this layer is strongly stratified, it is modeled in the flow model as a series of sublayers, each with its own fluid velocity. The total freshwater discharge is allocated between sublayers to obtain the best possible agreement between observed and predicted salinity distributions. The sublayers begin directly over the toe of the wedge. Because the toe of the wedge is taken to be a vertical face (fig. 2), and because in reality the estuary upstream from the toe of the wedge is characterized by considerable vertical saltwater transport, each sublayer is given an initial flow of saltwater as well as freshwater. The total volume of saltwater put into the layers is taken from element *1* of the wedge, further reducing the volume of that element during each time step. Thus, the total discharge in sublayer j at the seaward end of element i, assuming no accumulation of water in sublayer blocks, is given as

$$Q_{l_{i,j}}=Q_{f_j}+Q_{s_j}+(U_{e_j}-U_{e_{j+1}})\sum_{k=1}^{i} W_k L_k \ , \qquad (2)$$

where Q_{f_j} is the freshwater discharge into the upstream end of the layer, Q_{sj} is the saltwater discharge into the upstream end of the layer, U_{ej} is the entrainment velocity through the bottom of the sublayer, U_{ej+1} is the entrainment velocity out of the top of the sublayer (zero for the uppermost sublayer), and W_k and L_k are the top width and length of element k. Note that the term on the right side of the equation, which accounts for entrainment between sublayers, assumes that the channel width at each sublayer boundary is the same. This corresponds to assuming that the estuary has vertical sides above the top of the wedge; the error introduced will depend on the geometry of the estuary.

COMPUTATION OF SALINITIES

The salinity of the wedge is assumed to be that of the ocean, or whatever body of water is at the estuary mouth. This corresponds to assuming that entrainment is a one-way process from the wedge to the upper layer, as verified by the observed salinity distributions shown in figure 3. The salinity of the water entering the upstream end of each overlying sublayer is that resulting from complete mixing of the saltwater and freshwater inputs, given as

$$S_j=Q_{s_j}S_w/(Q_{s_j}+Q_{f_j}) \ , \qquad (3)$$

in which S_w is the wedge salinity. Complete mixing is assumed within each block of a sublayer. For any block the salinity at the end of a time step is given as

$$S'_{i,j}=S_{i,j}+\frac{\Delta t}{V_{l_i}}\Big\{Q_{l_{i-1,j}}S_{i-1,j}-Q_{l_{i,j}}S_{i,j} + W_iL_i\,(U_{e_j}S_{i,j-1}-U_{e_{j+1}}S_{i,j})\Big\} \ , \qquad (4)$$

where $S_{i,j}$ is the salinity in the block at the beginning of the time step, Δt is the length of the time step, and V_{l_i} is the volume of each sublayer block above wedge element i. This equation expresses the conservation of salt; it states that the salt in a block at the end of the time step is equal to that at the beginning of the step, plus that brought in by the flow through the upstream end of the block, minus that carried out by flow through the downstream end, plus that entrained from the next lower sublayer, minus that entrained into the next upper sublayer. The salinity computation for each time step begins at the landward end of the wedge and progresses seaward. Salinities are determined essentially by using an explicit backward-difference–finite-difference solution of the advective-transport equation. Dispersion due to flow within the sublayers is not explicitly modeled; however, the numerical scheme does generate a substantial amount of numerical dispersion of the sort discussed by Bella and Grenny (1970).

THE MATERIAL-TRANSPORT MODEL

The model includes provisions for study of the motion, decay, and reactions of suspended and dissolved biological and chemical constituents. The transport and mixing of these constituents is assumed to follow that of salinity, which has already been discussed, but additional programming is included for constituents which have a settling velocity, and for chemical and biological reactions between constituents. In particular, the model is equipped to simulate the motion of saltwater plankton which enter the wedge from the sea, and which are entrained into the flowing layers before possibly settling back into the wedge. The model also is equipped to study the effect of oxygen demand by plankton or other sources of BOD on DO levels in the wedge. Dissolved oxygen in the upper layers has not been included in this model. The upper layers seldom have a low-DO problem; however, the DO deficit in the wedge often represents a severe environmental problem because there is no source of oxygen for the wedge, and oxygen consumed in the wedge by any source of BOD can only be replaced by mixing with aerated water from the ocean.

Plankton are assumed to enter the wedge with each inflow of ocean water, and the plankton concentration in each newly formed wedge element is given as that of the ocean. Within the wedge the plankton concentration at the end of each time step, C'_i, is given as

$$C'_i=(1-\mathrm{k_d})C_i+\frac{\Delta t}{V_i}\left\{(C_{i,1}-C_i)\,W_iL_iU_s\right\}+\mathrm{E}(C_{i+1}+C_{i-1}-2C_i), \quad (5)$$

in which C_i is the concentration of plankton in wedge element i, at the beginning of the time step, $C_{i,1}$ is the concentration in the first sublayer above element i, $\mathrm{k_d}$ is a dimensionless decay coefficient for plankton in the wedge, V_i is the volume of wedge element i, U_s is the sinking speed of the plankton, and E is an exchange coefficient between wedge elements due to longitudinal dispersion. On the right side of this equation the first term represents a first-order decay, the second term represents addition to the wedge by settling from above and reduction by settling to the bed, and the third term represents longitudinal dispersion due to the velocity gradient in the wedge. The coefficient E is obtained in the same way as described by Fischer (1972).

Within the upper layers, the change in plankton concentration is given by an equation similar to that for salinity, but with additional terms expressing settling and growth, as follows:

$$C'_{i,j}=(1+a_jk_g)\,C_{i,j}+\frac{\Delta t}{V_l}\left\{Q_{l_{i-1,j}}C_{i-1,j}-Q_{l_{i,j}}C_{i,j}+W_iL_i\,(U_{e_j}C_{i,j-1}-U_{e_{j+1}}C_{i,j})\right\}+\frac{U_s\Delta t}{h_i}(C_{i,j+1}-C_{i,j}), \quad (6)$$

where a_j is a factor to account for light attenuation in layer j, k_g is a growth coefficient, $C_{i,j}$ is concentration in the jth sublayer above element i, and h_i is the thickness of each sublayer. (Note that the sublayers have equal thicknesses.)

Other constituents can be modeled in the same way as plankton, using appropriate growth, decay, and settling coefficients. For instance, DO is modeled by assuming a sink equal to the BOD in each wedge element. Although the program written for the present model includes only plankton and DO, extension to other constituents and other sources would be straightforward.

MODEL OPERATION

This section summarizes the inputs required by the model, its method of verification, and the results obtainable. A simplified flow diagram is shown in figure 5. The procedure is as follows:

1. The program is given a physical description of the estuary, in the form of tables of width versus depth at a number of longitudinal stations, the tidal variation at the mouth, and the freshwater discharge. This information is usually available from published records. The program includes an interpolation subroutine to compute the channel cross-sectional area versus depth at any location.
2. The thickness of the upper layer at the mouth, the slope of the interface between the upper layer and the wedge, and the number of sublayers are specified. According to Stommel and Farmer (1952), the thickness of the upper layer at the mouth can be computed by setting the interfacial Froude number equal to unity. In practice, however, measurements of the location of the interface are desirable.
3. The location of the toe of the wedge is specified as a function of time throughout the tidal cycle. Field measurements of the location throughout the cycle are preferable, although in their absence an estimate can be made based on the known location of the toe at one time and an estimate of the tidal excursion.
4. The total freshwater discharge is divided among the sublayers. An equal division can be used as an initial estimate.
5. Estimates are given of entrainment velocities

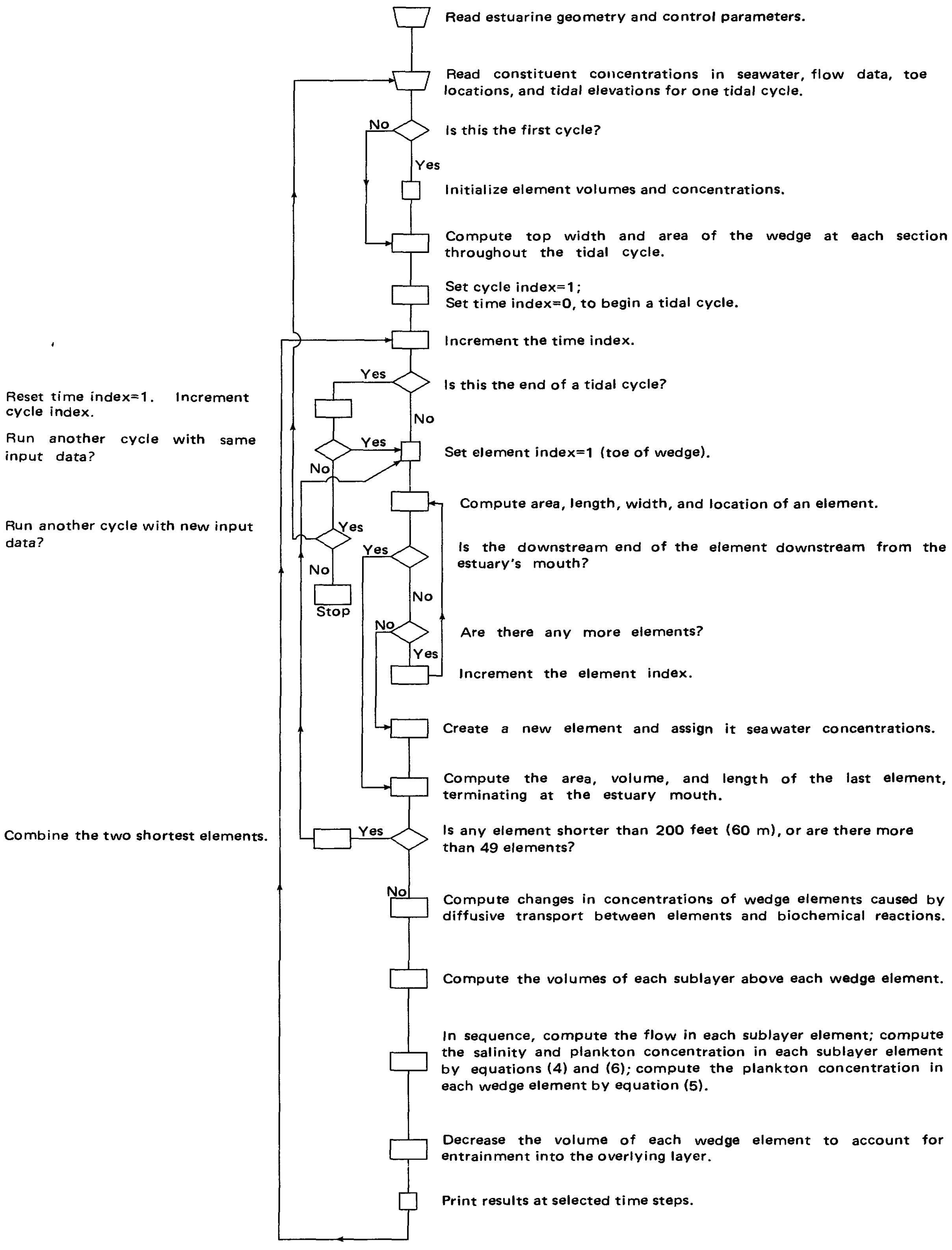

FIGURE 5.—Simplified flow diagram of computer program.

between the wedge and the lowest sublayer, and across each interface between sublayers.

6. An estimate is given of the amount of saltwater transferred from the toe of the wedge into the beginning of each sublayer. A first estimate of these quantities must be a guess, to be improved in the verification stage.
7. The program is operated with the data described in steps 1 through 6, and a salinity distribution is generated. The model salinity distribution is compared to a distribution observed in the prototype, and adjustments are made to the estimates called for in steps 4 through 6 to achieve as close a verification as possible. If possible, prototype salinity distributions should be observed for a range of tidal and freshwater-discharge conditions, so that the values called for in steps 4 through 6 can be expressed as functions of tidal range and freshwater discharge.

Assuming that an adequate verification has been obtained, step 7 completes the description and verification of the flow model. The material-transport model requires specification of biological parameters; for instance, to model the growth of plankton the program must be given the following parameters:

1. Settling velocity.
2. Growth rate under ideal light conditions.
3. Reduction in growth rate with reduced solar radiation.
4. Attenuation coefficient for reduction of solar intensity with depth beneath the water surface.
5. Decay rate in the wedge.

Because none of these parameters are accurately known for any species of plankton, and because many species may be present, it is apparent that one cannot expect a high order of accuracy in the prediction of biological constituents.

The verified model can be used to trace the movement and dispersion of any constituent introduced into the estuary. For example, if BOD is being introduced into the wedge from a constant source its distribution and decay can be traced, and its effect on DO can be predicted. The distribution, growth, and decay of plankton also can be traced—provided the biological parameters can be estimated with sufficient accuracy—and it may be possible to predict the growth and decay of plankton blooms. A second major use of the program is prediction of the effect of changing the estuarine geometry, such as extending a dredged channel or deepening an existing one. This type of prediction requires that some of the parameters, such as the entrainment velocities, do not change significantly when the geometry is changed, and it also requires extrapolation of the wedge geometry to fit the changed estuary geometry. Within these limits, however, the program can be useful in providing an informed estimate of the effect of changes in geometry. For example, if the length of a dredged channel is increased, so that the length of the wedge is increased, the residence time for water in the wedge will increase and the program can be used to predict the further decrease of DO concentrations.

SUMMARY AND CONCLUSIONS

This paper has described a numerical program which has been used to model the transport of salt and other constituents in one salt-wedge estuary, the Duwamish River estuary at Seattle, Wash. The results of the model application are given in Part II of this report. The program can be used to predict the distributions of such constituents as BOD, DO, and plankton, and to predict the effect of changes in the estuarine geometry on these distributions. It is hoped that the program will prove useful in studies of other salt-wedge estuaries.

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Model Computation of Salinity and Salt-Wedge Dissolved Oxygen in the Duwamish River Estuary, King County, Washington

By J. D. STONER, W. L. HAUSHILD, *and* J. B. McCONNELL

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PART II. MODEL COMPUTATION OF SALINITY AND SALT-WEDGE DISSOLVED OXYGEN IN THE DUWAMISH RIVER ESTUARY, KING COUNTY, WASHINGTON

By J. D. Stoner, W. L. Haushild, and J. B. McConnell

ABSTRACT

Saltwater from Elliott Bay on Puget Sound forms a wedge in the lower part of the Duwamish River estuary. The numerical model described by Fischer in Part I of this report was used in computing salinity distributions in the estuary, and oxygen-use rates and dissolved-oxygen distributions in the salt wedge. Computed spatial distributions of salinity agreed well with observed distributions during about 30 slack tides in July and August 1968. Analyses of the sensitivity of computed salinity to changes in model input parameters indicate that salinity changed most in response to changes in the wedge salinity and the location of the wedge toe.

The rate of use and the concentration of dissolved oxygen (DO) in the salt wedge were computed by the model for June–August 1968 and for the June–September periods of 1967 and 1969–71. Before 1970, the estuary received discharges of treated, partly treated, and raw industrial and municipal wastes; after 1970, the only major source of waste was the effluent from the Renton Treatment Plant, a secondary treatment plant. Attributable to these changes in waste disposal to the estuary were (1) observed wedge DO concentrations generally 2 mg/l greater in 1970–71 than in 1967–69, and (2) oxygen-use rates in the wedge 60 percent greater during 1967–69 than during 1970–71. Analyses of covariance indicate that computed wedge DO concentrations were not different (95-percent confidence level) from observed concentrations, and the standard error of estimate of the computed concentrations ranged from 10 percent (1971) to 22 percent (1967) of the observed mean concentrations. Sensitivity analyses indicate that wedge DO concentration changed proportionally with oxygen-use rate and also was sensitive to changes in the wedge toe location and in the velocity of the water entrained from the wedge.

The model was used to predict the changes that would have occurred in the oxygen-use rate and DO concentrations in the wedge during June–September 1971 if discharge of Renton Treatment Plant effluent had been increased from a 1971 average of 37 ft^3/s (63 m^3/min) to the planned maximum of 223 ft^3/s (379 m^3/min). The predictions suggest that (1) the oxygen-use rate would have been increased by 92 percent, (2) a relatively low DO concentration (4 mg/l) would have been decreased by 45 percent, and (3) a relatively high concentration (9 mg/l) would have been decreased by 8 percent.

INTRODUCTION

The Duwamish River estuary, which is the lower part of the Green-Duwamish River and the important industrial waterway in Seattle, Wash. (fig. 1), is undergoing a change in the patterns of its waste-water inputs. The estuary has been receiving industrial and municipal wastes since the early 1900's, but the effects of such disposal were not considered serious until the 1940's. Later increases in wastes resulting from population and industrial expansion degraded the quality of the estuarine water to the extent that endangerment of the fisheries resources and aquatic life in the estuary was of concern to local, State, and Federal agencies and private groups.

In 1958 the people in the greater Seattle area voted to form the Municipality of Metropolitan Seattle, generally referred to as Metro. Metro is a federation of a number of towns and cities which united to deal with the growing problems of waste-water disposal in the area. Metro's comprehensive plan for water-pollution control resulted in construction of an extensive network of sewer trunklines and several sewage-treatment plants, including the Renton Treatment Plant (RTP) near the head of the Duwamish River estuary.

In the 9 years before August 1970, discharges of raw or partly treated sewage into the Duwamish River estuary and into Puget Sound along the Seattle waterfront (including Elliott Bay) progressively were being intercepted and pumped to primary treatment plants (not shown in fig. 1) which discharge effluent into Puget Sound. In June 1965, discharge of effluent from RTP began and increased progressively thereafter. In a report prepared by the Metropolitan Engineers (1971), Metro states that "the last [major] raw-sewage discharge to the Duwamish River and Elliott Bay was intercepted in August 1970." Although several sources outside Metro's jurisdiction may have continued to discharge minor quantities of sewage into the estuary, the principal waste discharge into the estuary after August 1970 has been the effluent from RTP.

The RTP discharges its effluent into the lower part of the Green River about 1 mile (1.6 km) upstream from its confluence with the Black River. Downstream from the confluence (fig. 1), the Green River becomes the Duwamish River. Sewage received mostly from areas east of Lake Washington but also from areas south and east of RTP is given secondary treatment (activated-

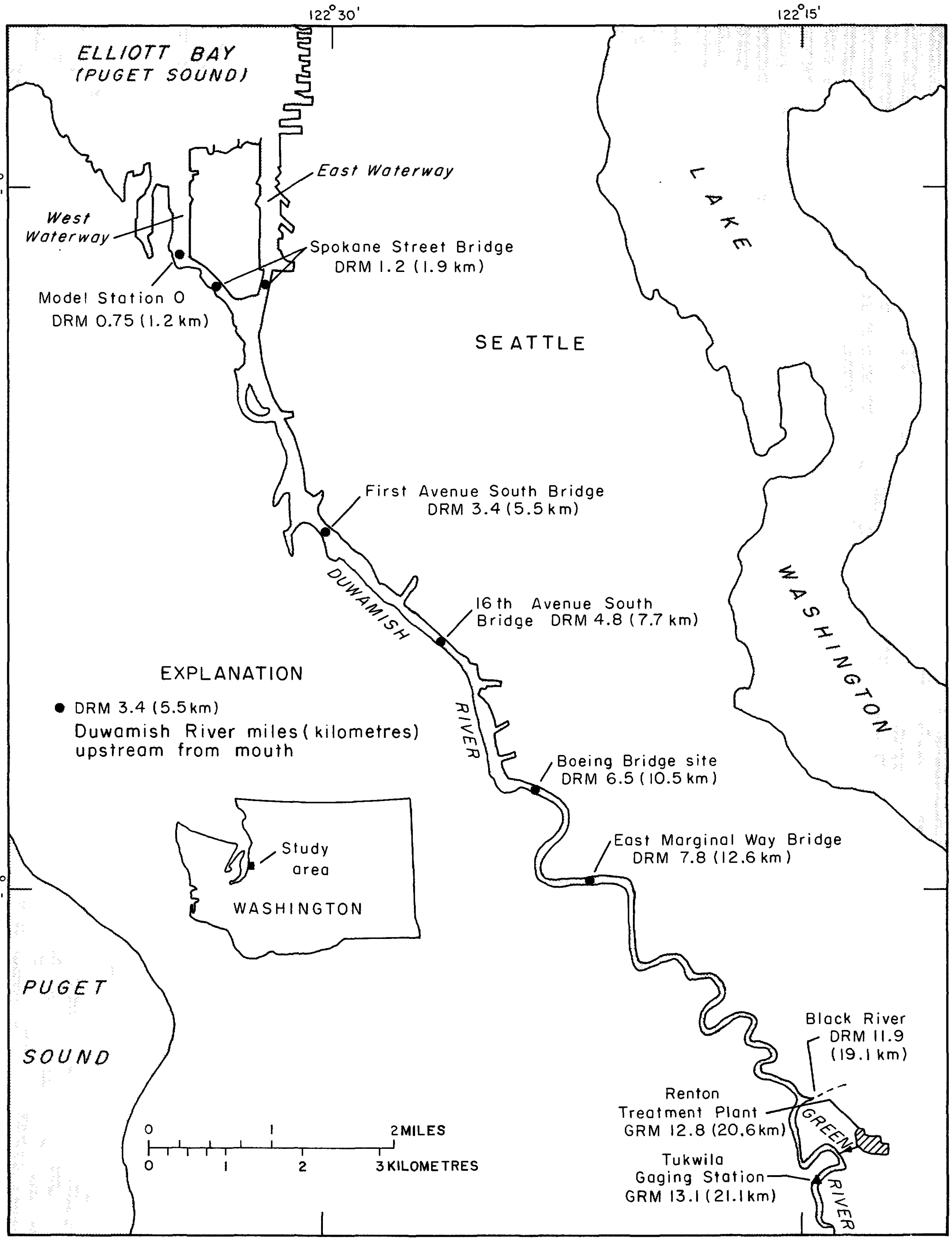

FIGURE 1.—Elliott Bay, Duwamish River estuary, and downstream reach of Green River.

sludge method) at RTP. Included in the plant effluent are the nutrients, dissolved oxygen-demanding material, and suspended solids not removed during treatment of the sewage. Grit, sludge, and scum removed during treatment are not discharged into the Green-Duwamish River. Grit is trucked to a landfill, and sludge and scum are pumped to the primary-treatment plant at West Point (not shown in fig. 1). By 1972, the design maximum of 37 ft³/s (63 m³/min) of discharge from the first-stage facilities at RTP had been reached and additional facilities were being constructed to double the sewage-treatment capacity. The RTP has been designed to ultimately discharge 223 ft³/s (379 m³/min) of effluent.

In 1963, Metro and the U.S. Geological Survey together began a study to evaluate the effects of changes in waste disposal on water quality of the salt-wedge Duwamish River estuary. In the estuary, the tides and freshwater inflow cause water circulation and concentrations of dissolved and suspended material to continually change in space and time. The dual inflow of water—saltwater from Elliott Bay and freshwater from the Green-Duwamish River—further complicates the transport of water and dissolved and suspended constituents in the estuary. Consequently, Metro and the Geological Survey decided in 1971 to proceed with the development of a numerical model for use in estimating water circulation and constituent transport in the estuary.

The model described in Part I of this report was developed by Fischer for application to salt-wedge estuaries. The purpose of Part II is to present some of the results derived from adapting and applying Fischer's general model to the Duwamish River estuary. Part II includes a description of the Duwamish River estuary and information and data peculiar to the model of the estuary that supplements the description of the general model given in Part I. The modeling reported here is restricted to salinity distributions within the downstream reach of the estuary and to the rate of use and distribution of DO (dissolved oxygen) in the estuary's salt wedge. From 1967 to 1971, only the June-September periods of relatively low DO in the salt wedge were modeled. These years include (1) those during which waste entering the estuary was the discharge of treated effluent from RTP and the discharges of raw or partly treated sewage from industrial and municipal outfalls and (2) those in which waste was primarily the RTP effluent. Therefore, comparisons of results for these years indicate the relation of oxygen-use rate and DO concentration in the salt wedge to the type and quantity of waste received by the estuary. Also evaluated are the sensitivities of salinity in the estuary and DO concentration in the salt wedge to changes in the controlling parameters of the model. The model was used to predict the oxygen-use rates and DO concentrations in the salt wedge for a future time, when RTP will be discharging an ultimate-design quantity of effluent. Finally, other probable and possible uses of the model are discussed.

ACKNOWLEDGMENTS

The authors are grateful for the continuing support and encouragement of Glen D. Farris, superintendent of the Water Quality and Industrial Waste Division of the Municipality of Metropolitan Seattle.

In applying the model to the Duwamish River estuary, the authors benefited considerably from the suggestions, criticisms, and guidance provided by H. B. Fischer of the Department of Civil Engineering of the University of California at Berkeley.

DUWAMISH RIVER ESTUARY

The Duwamish River, which is an extension of the Green River downstream from its confluence with the Black River, generally flows northwestward and discharges through its East and West Waterways into Elliott Bay of Puget Sound (fig. 1). Most of the water flows in the West Waterway, because sediment deposits constrict the channel of the East Waterway near and under the Spokane Street Bridge. The West Waterway is an extension of a waterway in the Duwamish River; ships and barges use these waterways upstream to about the First Avenue South Bridge at DRM 3.4 (Duwamish River mile 3.4; km 5.5)[1] and barges go upstream to about DRM 6.3 (km 10.1).

Regardless of tide stage, saltwater from Elliott Bay does not intrude up the Duwamish River to the East Marginal Way Bridge (DRM 7.8; km 12.6) when river discharge is more than 1,000 ft³/s (1,700 m³/min), but it intrudes at least that far upstream during most flood-tides when the river discharge is less than 625 ft³/s (1,060 m³/min) (Stoner, 1967). Salt has been observed in the river water at DRM 10.2 (km 16.4) during some periods of low discharges and high high tides. The farthest upstream intrusion of saltwater is not known, but saltwater probably only rarely intrudes as far as the Tukwila gaging station at GRM 13.1 (Green River mile 13.1, km 21.1). For various river flows and tides, the upstream limit of tide effect on stage and flow of the Green-Duwamish River also is unknown; however, high tides usually affect stage and flow at the Tukwila gaging station at all discharges less than about 7,000 ft³/s

[1]River miles in this report agree with those reported in previous publications agreement was obtained, with a few exceptions, by adding 0.9 mile (1.4 km) to the river miles reported by the Pacific Northwest River Basins Commission (1969).

(12,000 m^3/min). The farthest upstream point at which the flow may reverse directions also is unknown; reverse flow has been observed so seldom at the Tukwila gaging station that its occurrence there is presumably rare.

Observed spatial distributions of salinity indicate that saltwater from Elliott Bay intrudes as a wedge into the lower Duwamish River estuary for all river flows and tides (Dawson and Tilley, 1972; Santos and Stoner, 1972). The part of the estuary included in the model is that downstream from the wedge toe, which is defined as the farthest upstream cross section where salinity of the wedge water is 25 ppt (parts per thousand). The river reach within which the wedge toe moves upstream and downstream with the tides varies with river discharge; graphs used in the model for determining the wedge toe location are given in the section describing the Duwamish River estuary model. A mixture of salt and fresh water from upstream of the wedge toe flows into the layer overlying the wedge. The overlying layer also receives the saltwater entrained from the wedge at the interface. Water in the overlying layer moves upstream and downstream with the tides but has a net downstream movement toward Elliott Bay. The wedge water entrained into the overlying layer or advected upstream of the wedge toe is replaced by inflowing saltwater from Elliott Bay. Therefore, although water in the wedge also moves upstream and downstream with the tides, wedge water has a net upstream movement away from Elliott Bay.

TIDES

The tides that originate in the Pacific Ocean affect the flow and level of water in the estuary and usually cause two high tides (high high and low high) and two low tides (high low and low low) in a day. Heights of successive high or low tides normally are unequal; the largest inequality is in heights of the low tides, although the heights of two high tides differ considerably on some days. At times, the heights of the two high tides of a day differ by more than 4 ft (1.2 m) and the heights of the two low tides differ by more than 8 ft (2.4 m). Data from the National Oceanic and Atmospheric Administration (1973, table 2) indicate that the ranges and level of the tide heights at DRM 3.4 (km 5.5) are as follows: (1) the difference in height between mean high tide and mean low tide (mean range) is 7.5 ft (2.3 m); (2) the difference in height between mean higher high tide and mean lower low tide (diurnal range) is 11.1 ft (3.4 m); and (3) the elevation midway between mean low tide and mean high tide (mean tide, or half tide, level) is 6.5 ft (2.0 m). Recorded tide heights have ranged from minus 4.6 to plus 14.7 ft (−1.4 to 4.5 m). In this report, the datum from which all elevations are measured is the mean lower low tide, which is 6.6 ft (2.0 m) below mean sea level.

RIVERFLOW

Since September 30, 1961, the discharge of the Green River has been determined at the Tukwila gaging station (fig. 1), above which the drainage area is about 440 mi^2 (1,140 km^2). Downstream from the Tukwila gage, the Green-Duwamish River receives some seepage of ground water, local runoff from precipitation and (or) snowmelt, and the effluent from the RTP. Mean monthly discharges for 1961–71 (fig. 2) indicate that discharge at the Tukwila gage usually is greatest during January–February, decreases in March, increases somewhat during April–May, decreases to a minimum in August, and then increases during September–December.

The maximum and minimum monthly discharges shown in figure 2 indicate that flow within a specific season varies considerably from year to year, which is further illustrated by the variation in mean daily discharge at the Tukwila gage for each June–September

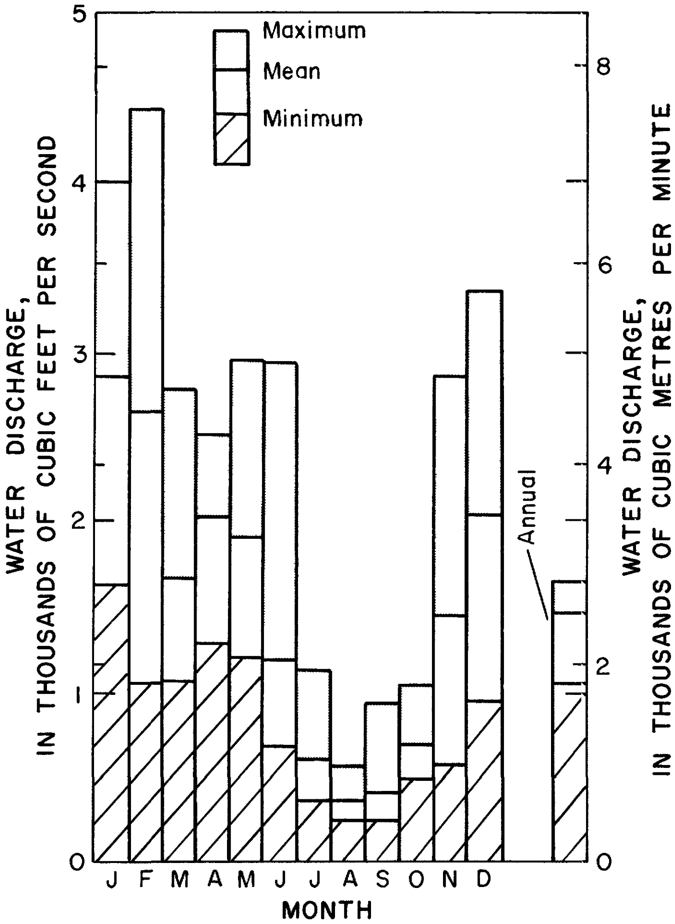

FIGURE 2.—Means and extremes in monthly and annual discharges of Green River at Tukwila during 1961–71 water years.

period during 1967–71 (fig. 3). Although the mean daily discharges during each period generally follow the usual variation pattern for this time of the year, the magnitude and timing of changes in discharge differ from year to year.

DUWAMISH RIVER ESTUARY MODEL

Because Part I of this report contains a description of the numerical program used for modeling the Duwamish River estuary, and the theory and operation of the model, these will not be discussed in detail here. This section describes the estuary geometry and the various inputs used in applying the general model to the Duwamish River estuary.

ESTUARY GEOMETRY

The geometry of the estuary is described by 11 cross sections which were determined from maps made in 1971 by the U.S. Army Corps of Engineers of the dredged part of the Duwamish River estuary, and from U.S. Geological Survey measurements of cross sections upstream from the dredged part. The plan and elevation views of the estuary (fig. 4) show a general perspective of the geometry used in the modeling. Tables of width versus depth of each cross section are used in the model to generate, for any tide stage, areas at any cross section within the estuary.

WEDGE TOE LOCATION

Observations of temporal and spatial distributions of salinity in the upstream part of the estuary and concurrent tide and flow data indicate that the location of the wedge toe is a function of the tide stage and the freshwater inflow. The interface between the wedge and the upper layer was distinct and wedge salinity remained relatively constant downstream from the farthest upstream cross section at which salinity was 25 ppt (fig. 4). Therefore, the location of this cross section was used as the wedge toe location. Upstream of the wedge toe, the interface between the wedge and the upper layer tends to diffuse, and salinity decreases erratically in the upstream direction. As will be described later in the report, a saltwater flow out of the wedge and a saltwater flow back into the upper layer at the wedge toe has been incorporated into the model.

A family of curves that define wedge toe locations for a wide range of tide stage at DRM 3.4 (km 5.5) and for various freshwater inflows was developed from observed data (fig. 5). The model computes wedge toe locations either by using the equations for these curves or interpolating for freshwater inflows between those given for the curves.

WEDGE ELEMENTS

At the beginning of any period modeled, the wedge was divided into a number of elements of equal volume. The elements were assigned an initial volume such that the wedge did not contain too few or too many elements; an initial volume that caused division of the wedge into 30 to 40 elements was desirable, with 50 elements being the maximum. For the Duwamish River estuary, each wedge element was assigned an initial volume of 10 million ft^3 (280,000 m^3); thereafter, the number and volumes of elements were determined by the numerical program described in Part I of this report.

ENTRAINMENT

Because of strong stratification, the upper layer was divided into three sublayers, with sublayer 1 adjacent to the wedge and sublayer 3 extending to the water surface (fig. 4). Salt-wedge water is therefore entrained into sublayer 1 and water in sublayers 1 and 2 is entrained into the respective overlying sublayers.

Stoner (1972) estimated that the entrainment velocity between the wedge and sublayer 1 varied from 3×10^{-5} to 10×10^{-5} ft/s (9×10^{-4} to 30×10^{-4} cm/s). (The entrainment velocity was computed by dividing the volume of water crossing the upper surface of the wedge per unit of time by the area of the surface.) Stoner attributed the variations in the entrainment velocity to the variations in freshwater inflow and tidal-prism thickness. Tidal-prism thickness, which is a measure of the tidal exchange, is the difference between the sum of the elevations of the two high tides and the sum of the elevations of the two low tides during a tidal cycle. The equation used in the model to compute the entrainment velocity between the wedge and sublayer 1 is

$$U_{e_1} = -5.2\times10^{-7}+2.6\times10^{-6}(T_\mathrm{P})+3.6\times10^{-8}(Q_\mathrm{f}),$$

where U_{e_1} is the entrainment velocity between the wedge and sublayer 1 in feet per second, T_P is the tidal-prism thickness in feet, and Q_f is the freshwater inflow in cubic feet per second.

In the Duwamish River estuary, the relatively large (and usual) difference in flow velocity between the wedge and the upper layer (fig. 6) probably is the dominant factor affecting entrainment between the wedge and sublayer 1 even though the fluid density tends to suppress entrainment the most at their interface (fig. 6). Entrainment velocities between sublayers were not expected to be as great as U_{e_1} and were expressed as proportions of U_{e_1}.

UPPER-LAYER THICKNESS

Observed spatial and temporal distributions of salinity and concurrent flow and tide data indicate that the average tidal-cycle thickness of the upper layer at the mouth of the Duwamish River estuary is related to tidal-prism thickness and freshwater inflow. The rela-

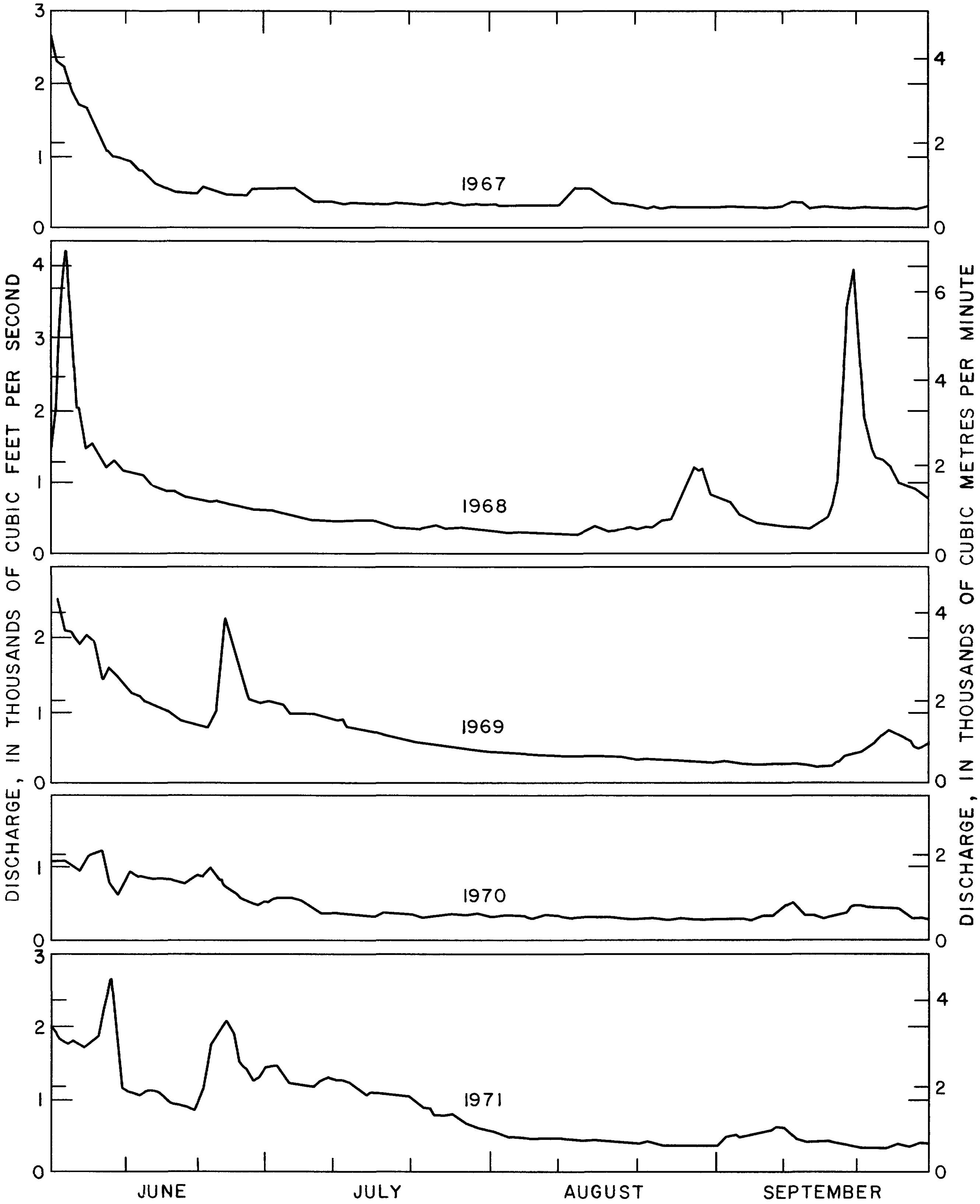

FIGURE 3.—Mean daily discharges of Green River at Tukwila during the June–September periods of 1967–71.

tionship between these variables is expressed by the regression equation

Upper-layer thickness = 2.5 + 0.30 (T_P) + 0.003 (Q_f) .

In the model, the estuary has a level water surface and the interface between the salt wedge and the upper layer slopes downward from mouth to toe at a rate of 0.06 foot per 1,000 feet (0.06 m per 1,000 m) (Dawson and Tilley, 1972). The sublayers are equally thick in the model.

INFLOW AND OUTFLOW

In the model, saltwater from Elliott Bay is advected into and out of the estuary by adding or subtracting elements at the mouth. The mixture of fresh and salt water flowing into the upper layer at the wedge toe results from a mixing of the freshwater of the Green-Duwamish River and RTP with the saltwater advected upstream of the wedge toe. Saltwater inflow to the upper layer is modeled as equal to the outflow from the salt wedge at its toe. Freshwater inflow is computed as the sum of the daily mean discharge of the Green River at the Tukwila gaging station and the mean daily outflow from the RTP. During some low-flow periods the outflow from the RTP was as much as 10 percent of the total freshwater inflow. The relic Black River and the drainage area downstream of RTP usually contribute only negligible quantities of water to the Green-Duwamish River during summer and early fall.

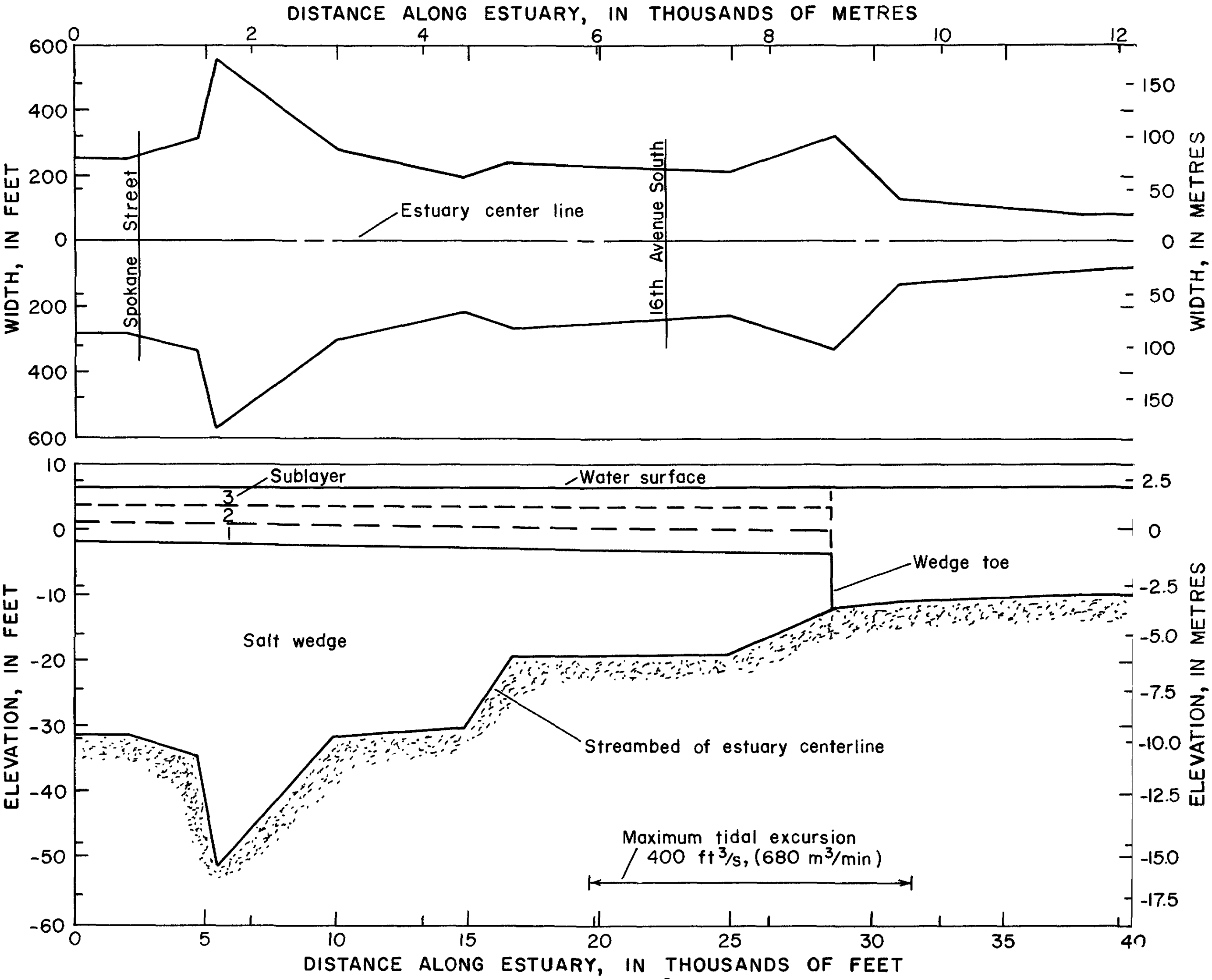

FIGURE 4.—Idealized longitudinal geometry of Duwamish River estuary during a mean tide of 6.5 ft (2.0 m) and a Green River discharge of 400 ft³/s (680 m³/min).

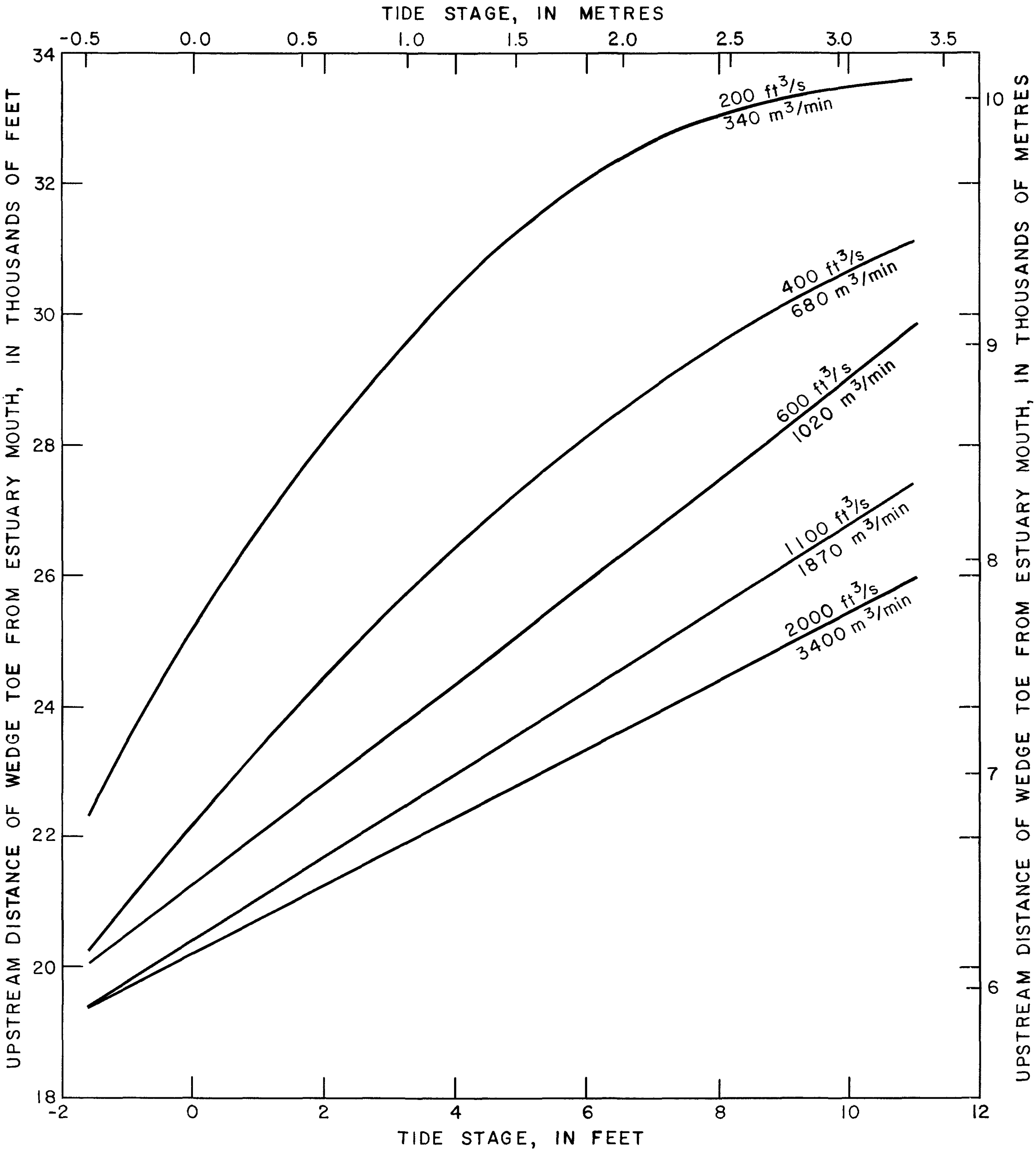

FIGURE 5.—Variation of wedge toe location with tide stage and freshwater inflow of the Duwamish River estuary.

TIDE STAGES

Hourly values of tide stage are input to the model; they were computed by using the method and tables of data published by the Environmental Science Services Administration (1968–71). The reference station used for computing tide stages was Seattle, Wash.

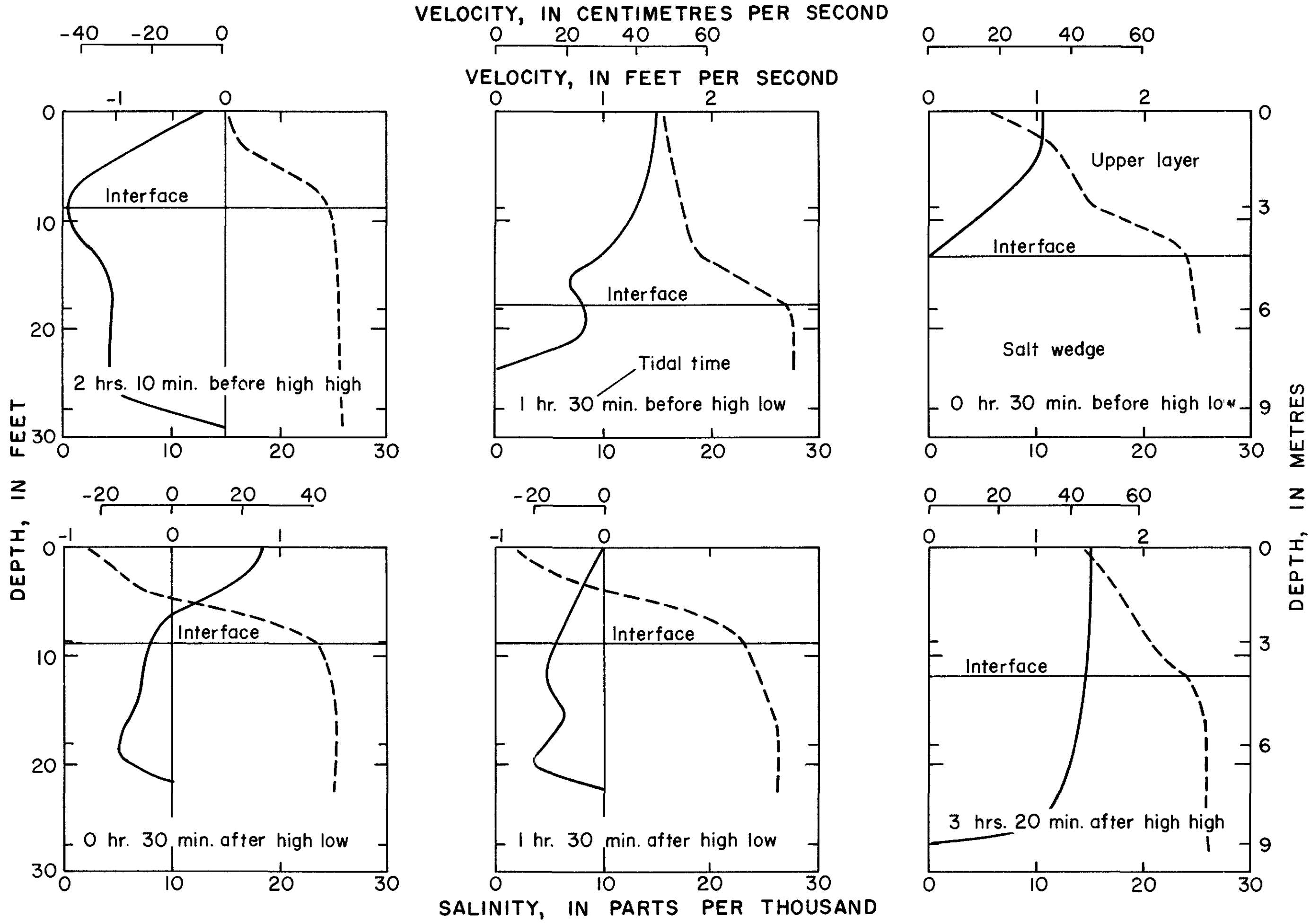

FIGURE 6.—Velocity (solid line) and salinity (dashed line) profiles at 16th Avenue South Bridge for various tidal times during September 6–7, 1967. Negative velocity indicates upstream flow.

SALINITY

OBSERVED DATA

Salinity is relatively easy to measure in the estuary, and many data for determining its distribution in time and space are available. Because salinity in the estuary results from mixing essentially zero-salinity freshwater from the river with essentially constant-salinity water from the wedge, its value at any time at any point indicates the percentage of water originating from both sources. Consequently, verification of salinity distribution in the estuary is a check of circulation and movement of fresh and salt water within the estuary.

The data used for model verification of salinity distribution in the estuary were 31 salinity profiles (salinity distributions in midstream verticals) at First Avenue South Bridge and 30 salinity profiles at 16th Avenue South Bridge during July and August 1968. The observed data were equally distributed between high slack and low slack tides. During the salinity observations, the tidal-prism thickness ranged from 9.9 to 20.0 ft (3.0 to 6.1 m) and freshwater inflow ranged from 273 to 1,220 ft^3/s (464 to 2,070 m^3/min); inflow at the times for the majority of the profiles was between 350 and 500 ft^3/s (590 to 850 m^3/min). These ranges represent those anticipated in the Duwamish River estuary during the periods of low flow in summer and early fall.

MODELING SALINITY

Verification of salinity distribution consisted of determining values of four parameters in the model so that computed distributions agreed with observed distributions. The model parameters were sublayer entrainment velocities, sublayer freshwater inflows, sublayer saltwater inflows, and saltwater outflow. Values of these parameters in modeling salinity were varied within the following limits: (1) Computed salinities were to agree within 10 percent with observed salinities, and (2) even though they could not be measured or empirically estimated from observed data, the parameter values should fall within ranges that were roughly estimated from gross approximations of, and some assumptions about, the physical processes occurring in the Duwamish River estuary.

Several assumptions and approximations are considered in modeling salinity. Freshwater flow into the upper layer at the wedge toe might be expected to be distributed approximately equally among the three sublayers; if not, less water would be expected to flow into the lower sublayers. Saltwater flow into the upper layer at the wedge toe might be expected to be distributed such that less saltwater would flow into the higher sublayers. Entrainment velocities between sublayers were constrained such that less water was entrained out of than was entrained into a sublayer. Saltwater flow out of the wedge at its toe, Q_s, is approximately 200 ft³/s (340 m³/min), which is about the midvalue of a range (140 to 270 ft³/s, 240 to 460 m³/min) computed from data given by Stoner (1972).

The results of using many combinations of the four variable parameters in the model indicated that computed salinities agreed well with observed salinities for a Q_s of 200 ft³/s (340 m³/min) and the following values for the other parameters:

Item	Sublayer		
	1	2	3
Sublayer entrainment velocity, in percent of U_e	75	60	0
Sublayer freshwater inflow, in percent of Q_f	25	37.5	37.5
Sublayer saltwater inflow, in percent of Q_s	75	15	10

The model computes the salinities of water in the sublayers at the end of every 15 minutes. The salinities computed for the sublayers at either First Avenue South Bridge, or 16th Avenue South Bridge, were compared with observed salinities at these locations. The differences between the means of computed and observed salinities were evaluated for statistical significance by using the t test in the method of pairing observations (Dixon and Massey, 1957, p. 124–127). The results given in the following table indicate that only the means in sublayer 1 at First Avenue South Bridge were significantly different from one another at the 99-percent confidence level.

Location	Number of observations	Values of t in sublayer			
		1	2	3	1,2,3
16th Avenue South Bridge	30	2.51	−0.16	0.61	----
First Avenue South Bridge	31	4.46	−.84	2.53	----
Both stations	183	----	----	----	2.56

By using the equation, $y = bx$, a regression of computed salinities against observed salinities indicated that (1) computed salinity is 0.92 of observed salinity, (2) the standard error of estimate is 3.1 ppt, and (3) the correlation coefficient is 0.98. The t test and the regression analysis indicate that the differences between computed and observed salinities are within the 10-percent-limit criteria for model estimates of salinity in the Duwamish River estuary.

DISSOLVED OXYGEN

INPUT AND OUTPUT DO

Because upper-layer water does not move downward into the underlying salt wedge in the Duwamish River estuary, DO concentration in the wedge is unaffected by the content of DO and dissolved BOD (biochemical oxygen demand) in the upper layer. Photosynthesis produces only negligible quantities of oxygen in the wedge water, which is usually below the photic zone that ordinarily extends about 13 ft (4 m) below the water surface (Welch, 1969). As postulated by Welch, the phytoplankton that sink from the upper layer contribute to the suspended-particulate and benthic oxygen-demanding material of the wedge. Therefore, the concentration of DO can only decrease while wedge water moves from Elliott Bay to the wedge toe.

In modeling wedge DO, concentrations in Elliott Bay water entering the wedge at the model mouth were assumed to be the same as those measured by the bottom water-quality monitor in the West Waterway at Spokane Street Brridge. The elevation of this monitor's intake is such that upper-layer water is sampled during as much as 2–3 hours of some low low tides. Wedge DO concentrations during those period were estimated from adjacent-in-time concentrations and from the temporal-variation pattern in wedge DO concentration at this site; the pattern was determined from concentrations observed frequently during several tidal cycles. Modeling of wedge DO concentration was considered verified when hourly computed concentrations at 16th Avenue South Bridge agreed with hourly observed concentrations there; comparisons were made only for the periods when wedge water was being sampled by the lower monitor at this site.

Daily extremes in observed DO concentrations of wedge water at Spokane Street Bridge are shown for each June–September of 1967–69 in figure 7 and for each June–September of 1970–71 in figure 8. Comparisons of the data for the two periods indicate the following major differences: (1) Daily minimum DO concentrations during August-September periods were higher in 1970–71 (about 5–7.5 mg/l) than in 1967–69 (about 3–5.5 mg/l), and (2) ranges in daily DO concentrations (difference between maximum and minimum) were higher during 1967–69 than during 1970–71—the ranges for 1969 and 1970 given in figure 8 exemplify this difference.

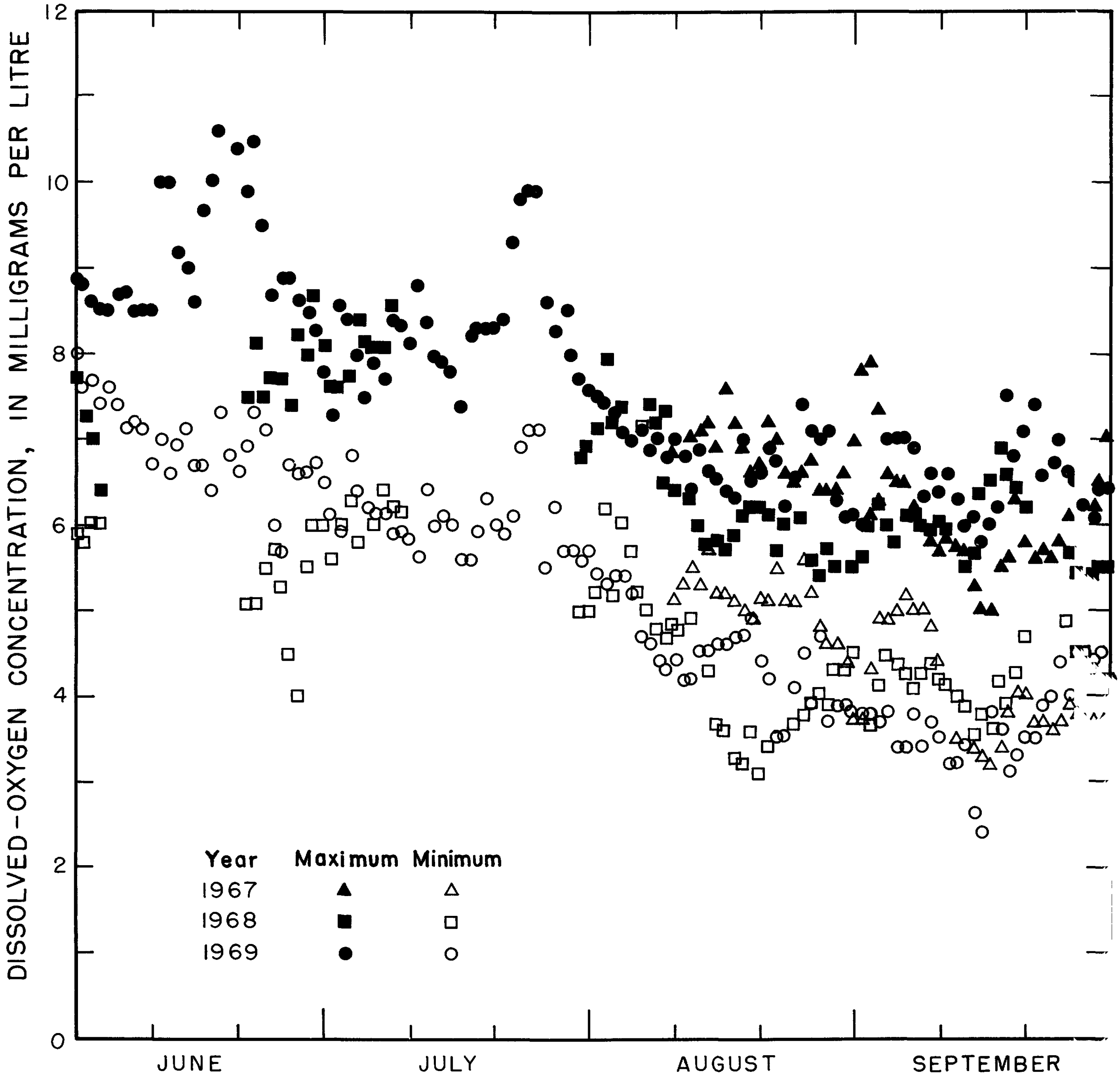

FIGURE 7.—Daily extremes in hourly observed DO concentration in salt wedge at Spokane Street Bridge during the June–September periods of 1967–69.

The differences in observed DO concentration at Spokane Street Bridge between the two periods probably were caused by lesser consumption of oxygen in the downstream part of the wedge and by higher DO concentrations in Elliott Bay water that flowed into the wedge during 1970–71. The relative importance of these two causative factors may be evaluated from an analysis of the changes in extremes in daily DO concentrations between 1967–69 and 1970–71. Daily minimums in wedge DO concentrations occur at the bridge during low low tides in water that has spent a relatively long time in the wedge. The increase of about 2 mg/l in daily minimum DO concentrations between 1967–69 and 1970–71 suggests that oxygen consumption in the wedge decreased between the two periods.

Daily maximums in wedge DO concentrations generally occur at the bridge during high high tides in water that probably has recently arrived from Elliott Bay and may have spent a relatively short time, or no time, in the wedge. The differences in daily maximum DO con-

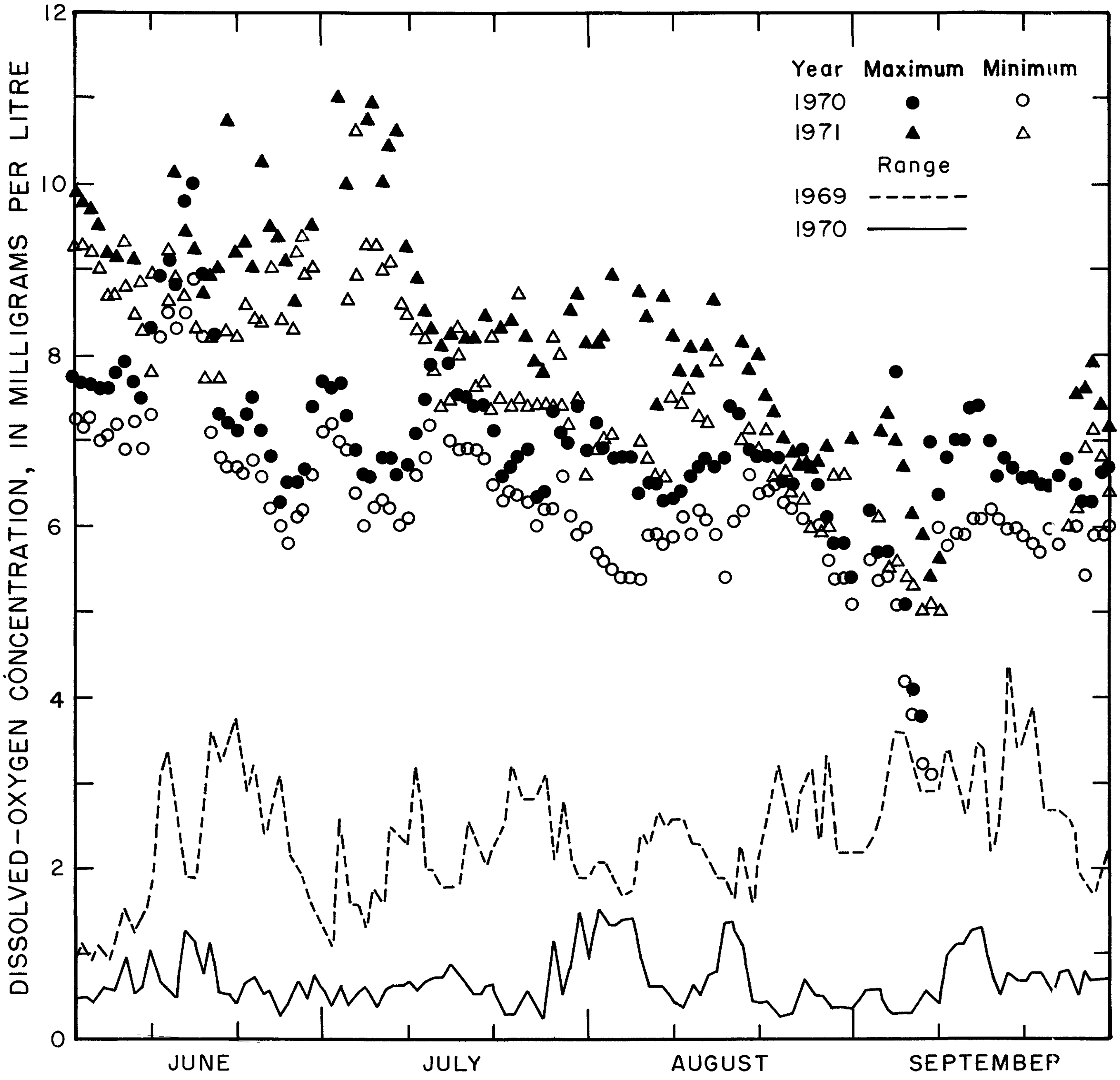

FIGURE 8.—Daily extremes and ranges in hourly observed DO concentration in salt wedge at Spokane Street Bridge during the June–September periods of 1969–71.

centrations between 1967–69 (fig. 7) and 1970–71 (fig. 8) are not easily distinguishable. However, frequency distributions of the daily maximum DO concentrations during August and September of the two periods (fig. 9) show a greater occurrence frequency of higher values of daily maximum DO concentrations in 1970–71 than in 1967–69; this suggests that DO concentrations in the Elliott Bay water arriving at Spokane Street Bridge did increase slightly between the two periods.

C. V. Gibbs and Glen Farris (written commun., 1973) of Metro found that annual minimum DO concentrations in water at a depth of 3.3 ft (1 m) in Elliott Bay have increased from 4.5 to 6.5 mg/l during the period 1968–71. This increase in DO concentration is considerably greater than that suggested by data reported here for the Elliott Bay water arriving at Spokane Street Bridge (fig. 9). The origin in the bay of water arriving at this bridge is unknown and determination of its origin is

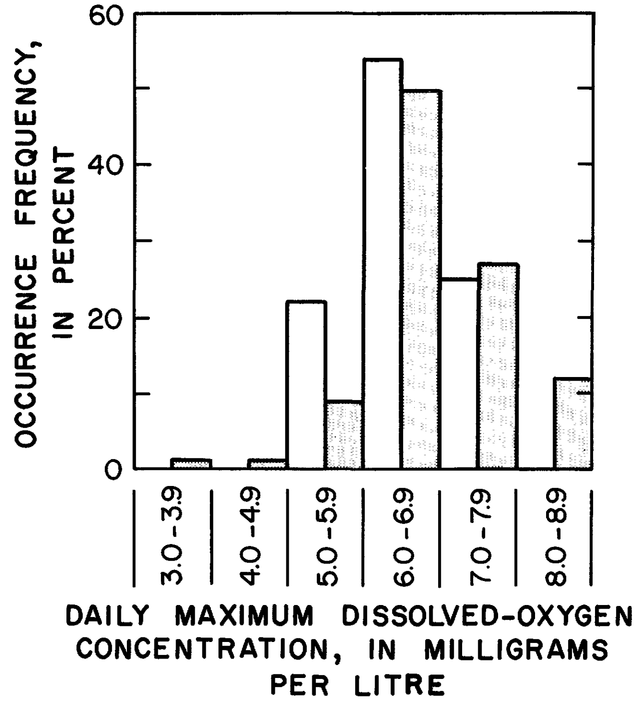

FIGURE 9.—Frequency distributions of daily maximums of hourly observed DO concentration in salt wedge at Spokane Street Bridge during the August-September periods of 1967–69 (unshaded bars) and 1970–71 (shaded bars).

beyond the scope of this study. However, newly arrived water in the wedge at Spokane Street Bridge may originate from relatively deep waters within the bay, and between 1967–69 and 1970–71, DO concentrations in this deep bay water may not have increased as much as in water near the bay surface. Thus, between 1967–69 and 1970–71, a decrease in oxygen consumption in the wedge probably was the major contributor (relative to an increase in DO concentration in the inflowing Elliott Bay water) to the increase in observed DO concentration of wedge water at Spokane Street Bridge.

As at the Spokane Street Bridge, daily maximum and minimum DO concentrations in wedge water at 16th Avenue South Bridge usually occur during high high tides and low low tides, respectively. Concentrations of DO in the wedge water at 16th Avenue South Bridge were much lower in 1967–69 (fig. 10) than they were in 1970–71 (fig. 11). Frequency distributions of the daily extremes in wedge DO concentrations during August and September of the two periods (fig. 12) show that daily minimums ranged from less than 1 to 5 mg/l in 1967–69 and from 3 to 7 mg/l in 1970–71, and that daily maximums ranged from 2 to 6 mg/l in 1967–69 and from 4 to 8 mg/l in 1970–71. These increases in the extremes of wedge DO concentration at this station confirm the inferred decrease in consumption of DO in the wedge between the two periods.

MODELING DO

The rate of use and distribution of DO in the wedge were modeled for the parts of each June–September period during 1967–71 when data were available. DO concentrations for the period of a particular year were computed in the model which was supplied with the observed DO concentrations at Spokane Street and an arbitrarily selected constant oxygen-use rate. The agreement between computed and observed DO concentrations then was evaluated from a regression (using the equation $y = bx$) of hourly computed DO concentrations at 16th Avenue South Bridge against hourly observed DO concentrations there. From this evaluation, an oxygen-use rate that would reduce the error in the computed DO concentration was selected and used in the model to again compute DO concentrations. The foregoing sequence of operations was repeated until the best agreement between computed and observed DO concentrations was obtained.

The relation between computed and observed DO concentrations at the 16th Avenue South Bridge for June 13–September 30, 1971 is shown in figure 13. Results of modeling the June–September periods of 1967–71 are summarized in table 1. The oxygen-use rate varied each year during 1967–69 whereas the rate was the same in 1970 and 1971. More confidence may be placed in the oxygen-use rates for 1969–71 than for 1967–68, because a greater number of observed data were available for computing the rates in 1969–71 (table 1). The data in figure 13 and similar data for 1970 (not shown) show that occurrences of computed DO concentrations higher or lower than observed concentrations generally were distributed randomly during the June–September periods. This randomness indicates that an oxygen-use rate that did not vary with time could be used in modeling DO in the wedge during 1970–71.

As expected, oxygen was consumed at a faster rate in the wedge in 1967–69 than in 1970–71; the average model oxygen-use rate in the wedge was 60 percent higher during 1967–69 (table 1). The effluent discharges from the RTP evidently contributed less oxygen-demanding materials to the wedge during 1970–71 than did the combined discharges from outfalls along the estuary and from RTP during 1967–69, even though the RTP discharge was greater during 1970–71. Effluent from RTP contains mostly dissolved and colloidal BOD that cannot enter the wedge and therefore is transported in the estuary's upper layer, whereas effluent from the outfalls along the estuary downstream from RTP may have been discharged directly into the wedge at times and also may have contained BOD in the form of solids that could settle into the wedge. Notable in the data of table 1 is the progressive increase, from about 3

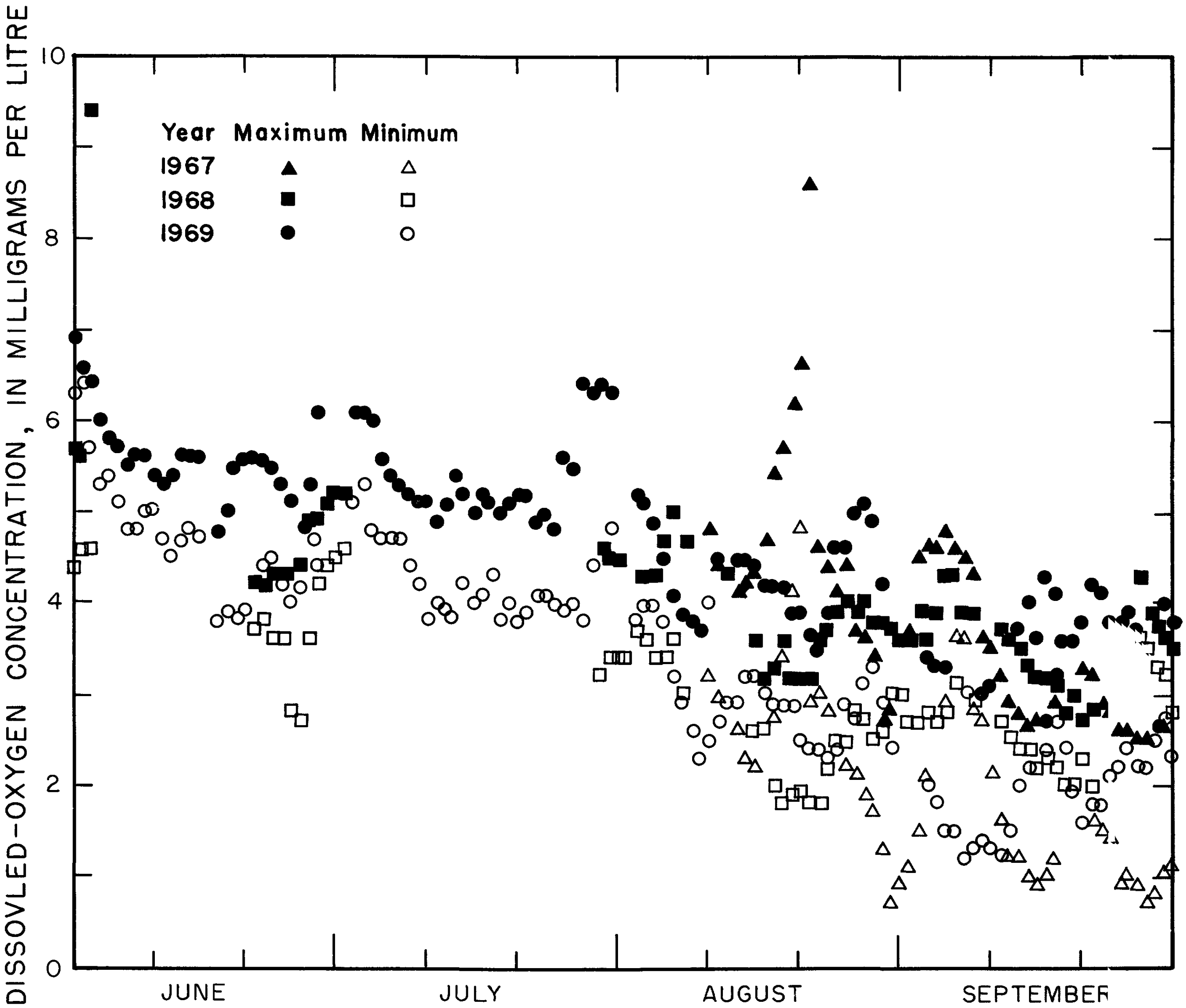

FIGURE 10.—Daily extremes of hourly observed DO concentration in salt wedge at 16th Avenue South Bridge during the June–September periods of 1967–69.

mg/l in 1967 to about 6 mg/l in 1971, in mean wedge DO concentration for the June–September periods.

PREDICTING DO

Several restrictions and assumptions were made in predicting the effects of a future increase in discharge of RTP effluent on wedge DO concentrations. Only the planned ultimate RTP discharge of 223 ft³/s (379 m³/min) was used in the predictions. Because the efficiency of the RTP probably will not change with discharge, effluent quality (constituent concentrations) at the ultimate discharge was presumed to be the same as that for the average discharge of 37 ft³/s (63 m³/min) in 1971. As discussed earlier, DO concentrations in the Elliott Bay water arriving at Spokane Street Bridge were inferred to be relatively unaffected by the major changes that occurred in the waste discharged to the lower Green-Duwamish River and Elliott Bay during 1967–71. Therefore, DO concentrations of bay water entering the estuary probably would be unaffected by a change in RTP effluent discharge and were assumed to be the same as they were in 1971. Finally, the prediction was made by using in the model the river discharges and tide stages for June–September 1971 and an estimated rate of oxygen use in the wedge.

As in 1971, the oxygen-use rate in the wedge when the RTP discharges an ultimate quantity of effluent may be expected to be constant in time and with longitudinal distance. The change in oxygen-use rate between the two discharges then may be approximated by evaluat-

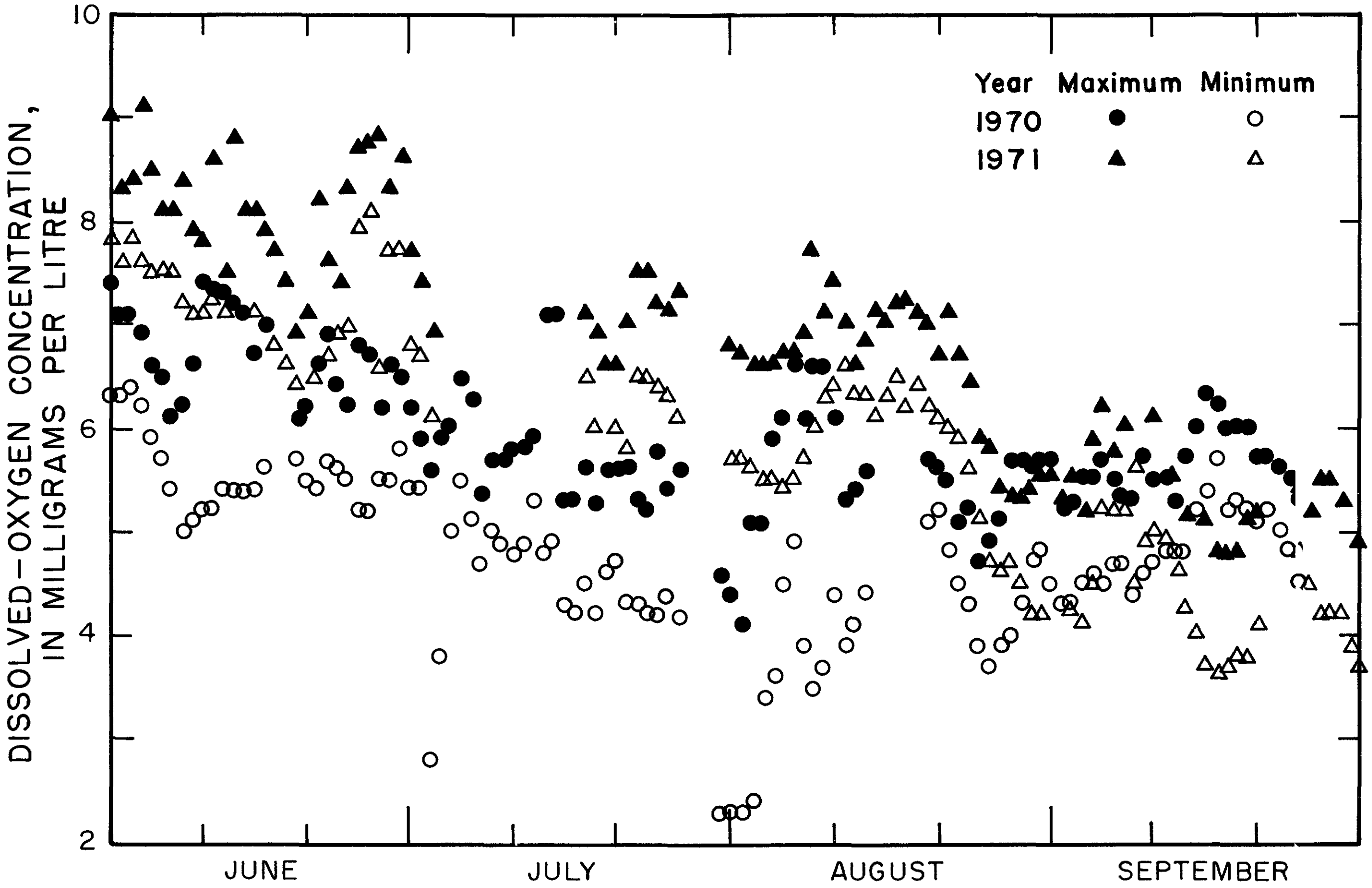

FIGURE 11.—Daily extremes of hourly observed DO concentration in salt wedge at 16th Avenue South Bridge during June–September periods of 1970–71.

ing the possible changes in a wedge column 10.7 ft² (1 m²) in cross section that has a height equal to the average wedge thickness. For the mean tide of 6.5 ft (2.0 m), the average wedge thickness is esimated to be 24.3 ft (7.4 m) during low-flow periods.

The first step in estimating the change in oxygen-use rate was to evaluate conditions in the wedge column for a RTP discharge of 37 ft³/s (63 m³/min) in June–September 1971. The modeling of DO concentrations during this period indicated that the oxygen-use rate in the wedge was 0.016 mg/l/hr. The latest available data for BOD are those from analyses of 20 samples of wedge water collected at five stations during low flows of 295–693 ft³/s (500–1,080 m³/min) during August 1969–March 1970; the data indicate that 5-day BOD ranged from 0.5 to 2.8 mg/l and averaged 1.4 mg/l. Assuming that oxygen in a sample was used at a uniform rate during the first 5 days, the average 5-day BOD for the 20 samples converts to 0.012 mg/l/hr. Using this value as an estimate of the average BOD of wedge water in June–September 1971, various uses of oxygen in the wedge column are computed as follows:

Suspended-dissolved use: $7.4\times1\times1\times1{,}000\times0.012 = 88.8$ mg/hr

Total use: $7.4\times1\times1\times1{,}000\times0.016 = 118.4$ mg/hr

Benthic use: $118.4-88.8 = 29.6$ mg/hr

where suspended-dissolved use is the oxygen consumed by particulate and dissolved oxidizable material in the water, and benthic use is the oxygen consumed by oxidizable material in and on the streambed. During July–October 1973, measurements made at 20 locations in the estuary indicated that oxygen consumption in wedge water—trapped in a bell-jar apparatus placed on the streambed—ranged from 0 to 131 mg/hr/m² and averaged 46.0 mg/hr/m² (R. I. Matsuda of Metro, written commun., 1974). The average measured benthic oxygen consumption is about 1.5 times that computed for the wedge column; however, the computed benthic oxygen consumption in the column is an estimate of the average consumption by the benthic materials in the entire wedge during June–September 1971.

The suspended solids in RTP effluent that reach the

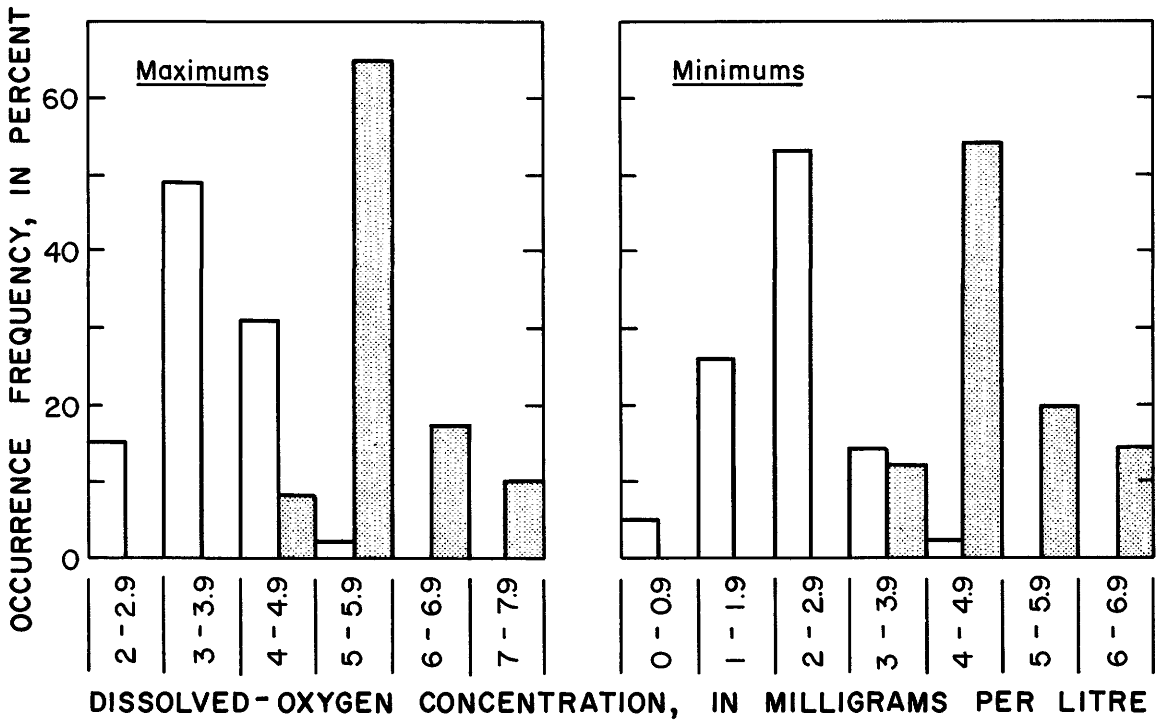

FIGURE 12.—Frequency distributions of daily extremes of hourly observed DO concentration in salt wedge at 16th Avenue South Bridge during the August–September periods of 1967&69 (unshaded bars) and 1970–71 (shaded bars).

upper layer and sink from it into the wedge are a likely source of oxygen demand in the wedge because either they are oxidizable material or they may have oxidizable material affixed to them. For this reason, a change in oxygen-use rate in the wedge, between the average 1971 discharge and a future ultimate discharge of RTP effluent, was related to an estimated change in concentrations of suspended solids in the freshwater inflow between these discharges.

The derivative form of an equation that defines the mixing of suspended solids in RTP effluent with those in the river is

$$\frac{dC_m}{dQ_e} = \frac{(C_e - C_r)Q_r}{(Q_r + Q_e)^2},$$

where Q_r and Q_e are discharges of the river and RTP, in cubic feet per second, respectively, C_r and C_e are concentrations of suspended solids in the river water and RTP effluent in milligrams per litre, respectively, and C_m is the concentration of suspended solids in the freshwater inflow (the mixture of river water and plant effluent), in milligrams per litre. This mixing equation shows that the higher that C_e is relative to C_r, the more C_m changes for a given change in Q_e. Therefore, C_r was assigned the value of 1 mg/l. A C_r value of zero would maximize the change in C_m; however, the river at Tukwila would be expected to contain at least 1 mg/l of suspended oxidizable particulates. Because plant efficiency presumably will not change with quantity of sewage treated, C_e will be the same in the future as the average 8.4 mg/l for June–September 1971. By using daily discharges of the Green River at Tukwila for Q_r, and the known or assigned values of C_e and C_r, the change in C_m was determined for a change in Q_e from 37 to 223 ft³/s (63 to 379 m³/min) for every day from June 1 to September 30, 1971.

Suspended solids in the water overlying the wedge would move faster toward Elliott Bay at the higher discharge of RTP effluent. The computed daily changes in C_m were adjusted for differences in flushing times by using the flushing times for the Duwamish River estuary from mile 21.0 (km 33.8) to the mouth (Santos and Stoner, 1972) as approximations of the flushing times from the toe to the mouth of the wedge. Little error probably is introduced by using these approximations, because ratios of the flushing times were used in adjusting the daily changes in C_m.

The results indicate that the average concentration of suspended solids in mixtures of 1971 river discharges with 223 ft³/s (379 m³/min) of RTP effluent would be 1.92 times greater than with 37 ft³/s (63 m³/min) of RTP effluent. The oxygen-use rate in the wedge water then would increase from 0.016 to 0.031 mg/l/hr, provided that oxygen consumption by both suspended-dissolved and benthic oxidizable material increased in proportion to the estimated increase in suspended solids in the overlying layer. An increase in quantity of suspended

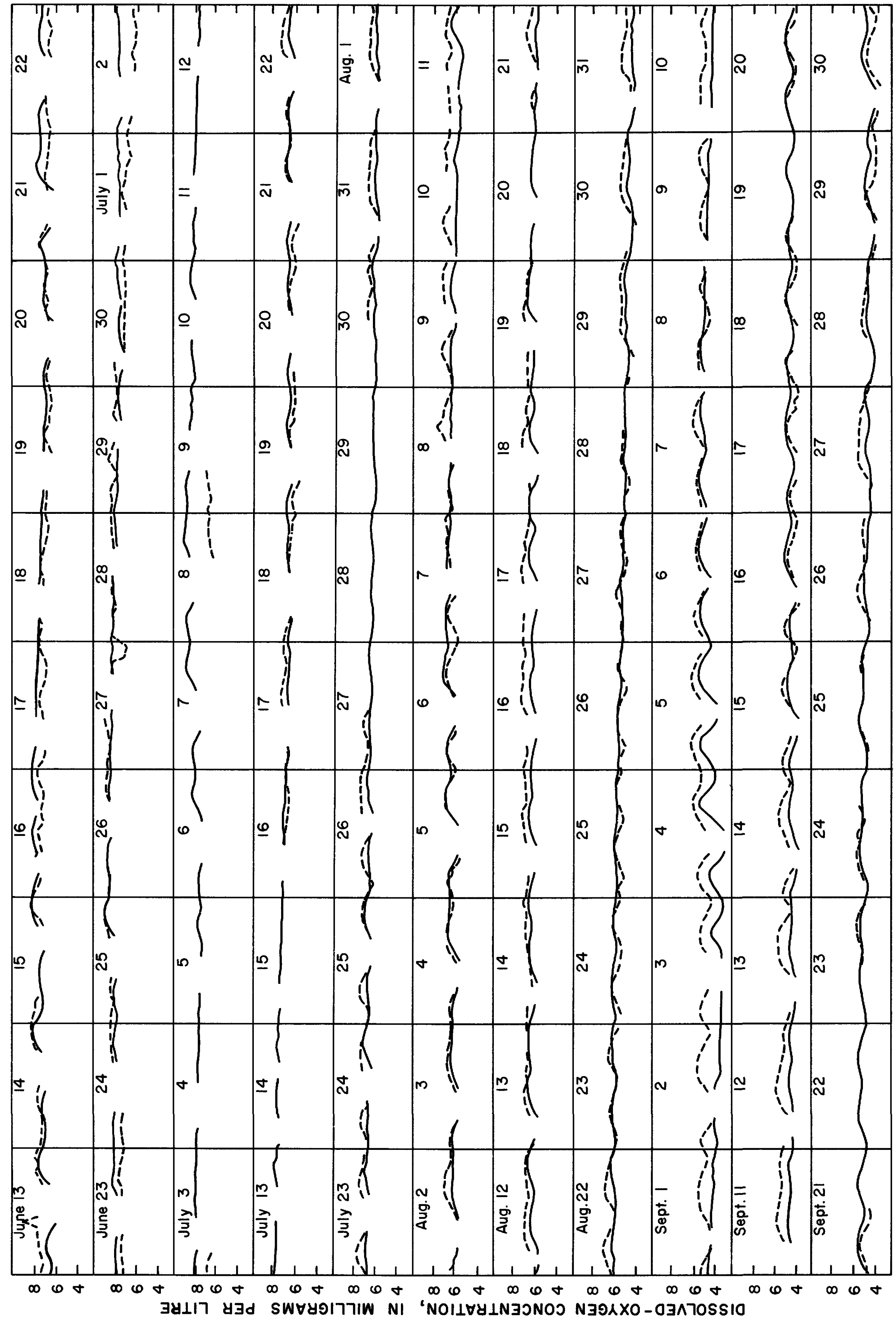

FIGURE 13.—Computed (solid line) and observed (dashed line) DO concentrations in salt wedge at 16th Avenue South Bridge, June 13–September 30, 1971.

TABLE 1.—*Model oxygen-use rates in wedge, mean wedge DO concentrations, and statistics of regressing computed versus observed DO concentrations in salt wedge at 16th Avenue South Bridge during June–September periods of 1967–71*

Year	Oxygen-use rate (mg/l/hr)	Sample size (hourly DO concentrations)	DO concentration (mg/l) Computed Mean	Computed Standard deviation	Observed Mean	Observed Standard deviation	Regression coefficient[1]	Standard error of estimate mg/l	Standard error of estimate Percent of mean	Correlation coefficient
1967	0.028	980	3.14	0.76	3.03	1.17	0.922	0.67	22	0.976
1968	.023	800	3.69	.99	3.73	.81	.991	.45	12	.993
1969	.026	2,200	4.10	1.43	4.04	1.06	1.024	.70	17	.987
1970	.016	1,970	5.32	.73	5.36	.77	.978	.82	15	.988
1971	.016	1,730	6.09	1.23	6.00	1.08	.987	.57	10	.996

[1]Regression coefficient is the value of "b" in the equation: computed DO concentration = b×(observed DO concentration).

solids in the wedge may not change benthic oxygen use, because there might be no change either in the area of bed covered with particulate oxidizable material or in the oxygen demand exerted by the bed area covered by particulate oxidizable material. Assuming no change in benthic oxygen use between RTP discharges of 37 and 223 ft^3/s (63 and 379 m^3/min) computations of the oxygen use and a corresponding oxygen-use rate in the representative column of wedge water are as follows:

Suspended-dissolved use: $7.4\times1\times1\times1{,}000\times0.012\times1.92 = 170.5$ mg/hr

Benthic use: $29.6\times1.000 = 29.6$ mg/hr

Total use: $170.5+29.6 = 200.1$ mg/hr

$$\text{Oxygen-use rate} = \frac{200.1}{7.4\times1\times1\times1{,}000} = 0.27 \text{ mg/l/hr}$$

DO concentrations in the wedge during June–September 1971 were modeled using the oxygen-use rates of 0.027 and 0.031 and a RTP effluent discharge of 223 ft^3/s (379 m^3/min). The differences between predicted wedge DO concentration, assuming present and ultimate RTP discharges, were determined from regression analyses. Figure 14 shows, for a proportionate increase (curve A) and no increase (curve B) in benthic oxygen use, the predicted reductions in wedge DO concentration at 16th Avenue South Bridge due to increased effluent, in relation to observed wedge DO concentration there. The model projections, based on the above data and assumptions, indicate that DO concentrations in the wedge water may be reduced by 45 percent given a relatively low DO concentration (4 mg/l), and by 8 percent given a relatively high DO concentration (9 mg/l), when the RTP eventually is operating at full design capacity.

DISCUSSION

For the June–September periods of 1969–71, the observed and computed DO concentrations have shown that concentrations increased and oxygen consumption decreased in the wedge between 1967–69 and 1970–71. Wedge DO concentrations during June–September periods of 1970–71 still frequently were less than the Washington State standard of 5 mg/l for estuarine waters such as the Duwamish River estuary (Washington Water Pollution Control Commission, 1967). Nevertheless, DO concentrations were less often below 5 mg/l and minimum concentrations were much higher in 1970–71 than in 1967–69. The model was used to predict wedge DO concentrations during a future time, when RTP is discharging a maximum quantity of effluent. These DO concentrations may be 1–2 mg/l less than they were during periods of low DO concentrations (4–5 mg/l) in June–September 1971. The predictions assume that (1) the suspended solids that sink into the wedge from the upper layer are a principal source of oxidizable material there, (2) the concentration of suspended oxidizable particulates in Green River water will be 1 mg/l, and (3) DO concentration in the Elliott Bay water entering the wedge will be relatively unaffected by the increase in RTP effluent discharge. If the quality of the Green River and (or) Elliott Bay degrade in the future, the contribution of the increased discharge of RTP effluent to degra-

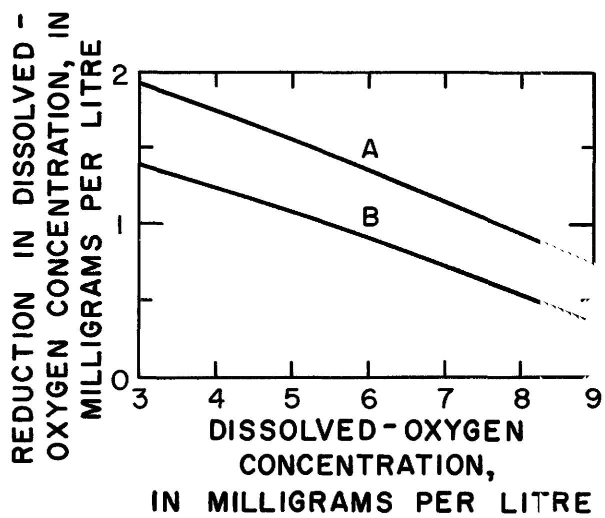

FIGURE 14.—Predicted reduction in DO concentration in wedge (from wedge DO concentration at 16th Avenue South Bridge with 37 ft^3/s (63 m^3/min) effluent discharge from Renton Treatment Plant, June–September 1971), assuming the ultimate RTP discharge of 223 ft^3/s (379 m^3/min), and a proportionate increase (curve A) or no increase (curve B) in benthic oxygen demand.

dation of wedge DO concentration would be comparatively less.

The probable effect on wedge DO concentrations of not discharging RTP effluent to the estuary in June–September 1971 also may be of interest. Again using the assumptions, restrictions, and procedures that were used in predicting the effect of an increase in RTP effluent, an oxygen-use rate of 0.0092 mg/l/hr in the wedge during June–September 1971 is estimated for a zero discharge of RTP effluent. When this rate and a zero RTP effluent discharge was used in modeling 1971, the average computed DO concentration in the wedge for June–September was 0.6 mg/l higher than that computed for a RTP effluent discharge of 37 ft^3/s (63 m^3/ min).

The reliability of predicting the effects of future changes in the variables of the Duwamish River estuary cannot be proved until the changes occur. Presently, the confidence level for the predicted changes in wedge DO concentration is low. Because a technique for predicting oxygen-use rates is necessary, a recommended use of the model is to compute oxygen-use rate in the wedge annually, biennially, or after longer periods. Such modeling would provide information about changes in oxygen use in the wedge relative to changes in RTP discharge; this information could be used in improving the prediction of the effect of increases in RTP discharge on wedge DO concentrations.

Present (1973) plans include (1) completion of modeling of the upper layer of the estuary, and modeling of phytoplankton in the estuary, and (2) combining the model with a model of the adjoining upper estuary and tidal river. The model could be used for estimating transport and distribution of constituents other than wedge DO and estuary salinity. Haushild and Stoner (1973) used the model to predict effects of a proposed change in estuary geometry on residence time and DO concentrations of the wedge water. The model could be used to evaluate methods for improving DO concentrations in the salt wedge. For example H. B. Fischer (author of Part I of this report) suggested that salt water could be pumped from the wedge into the upper layer at a location in the upstream part of the wedge to decrease residence time of water in the wedge. This probably would result in less of the DO in the wedge water being consumed during its travel from the mouth to the toe. The effect on the upper layer DO concentrations, from the introduction of more wedge water of relatively low DO concentrations, would have to be evaluated.

SENSITIVITY ANALYSES

To evaluate the response (sensitivity) of estuary salinity and wedge DO concentration to changes in model parameters, one parameter value at a time was varied while the other parameter values were held constant. In the sensitivity analyses, single-value parameters were equally increased or decreased once each, whereas distribution parameters were changed for the purpose of producing one negative and one positive change in the salinity of each sublayer. The results reported here are based on one-step changes in model parameters; the degree and (or) direction of response in DO and salinity may not be the same for further changes in the parameters. Sensitivity of variables to model parameters will be more completely analyzed in the model that includes the upper layer. For each change in a parameter, the mean increase or decrease of salinity and DO concentration during a period of approximately 2 months and the changes in salinity and DO concentration during a tidal cycle were determined for the estuary only at 16th Avenue South Bridge. The variation of tide stage during the tidal cycle is shown in figure 15. The parameter values determined during the verification of estuary salinity and wedge DO concentration are called base data, and salinity and DO concentrations computed by using the base data are called base values. The salinity and DO concentrations computed using different data were compared with base values.

In the model, salinities of sublayers change in proportion to changes in wedge salinity, as shown by the data in table 2. Among the seven other model parameters analyzed, the data in table 2 indicate that sublayer salinity at 16th Avenue South Bridge is most responsive to wedge toe location and is least responsive to wedge and sublayer entrainment velocities and to outflow of wedge water at the toe.

Salinities in the three sublayers generally vary during a tidal cycle (fig. 16) in accordance with the tide stage (fig. 15). A change in the distribution of saltwater inflow among the sublayers at the wedge toe causes more of a change in sublayer salinity during the period of low low tide than during the remainder of the tidal cycle (fig. 16); this was true also for a change in the outflow of saltwater at the wedge toe. This inequality of change in sublayer salinity was expected, because 16th Avenue South Bridge at low tides is near the wedge toe where sublayer salinity is specified in the model by the saltwater outflow from the wedge and by the distribution of an equal saltwater inflow among the sublayers. The sensitivity analyses for the other parameters indicated that (1) sublayer salinity at the bridge changed less during the period of low low tide than during the other parts of the tidal cycle for a change in sublayer entrainment velocities, because most of the entrainment occurs downstream at low low tides; and (2) throughout the tidal cycle, sublayer salinity changed proportionately with the other five parameters.

The mean changes in wedge DO concentration for changes in each of the controlling parameters in the

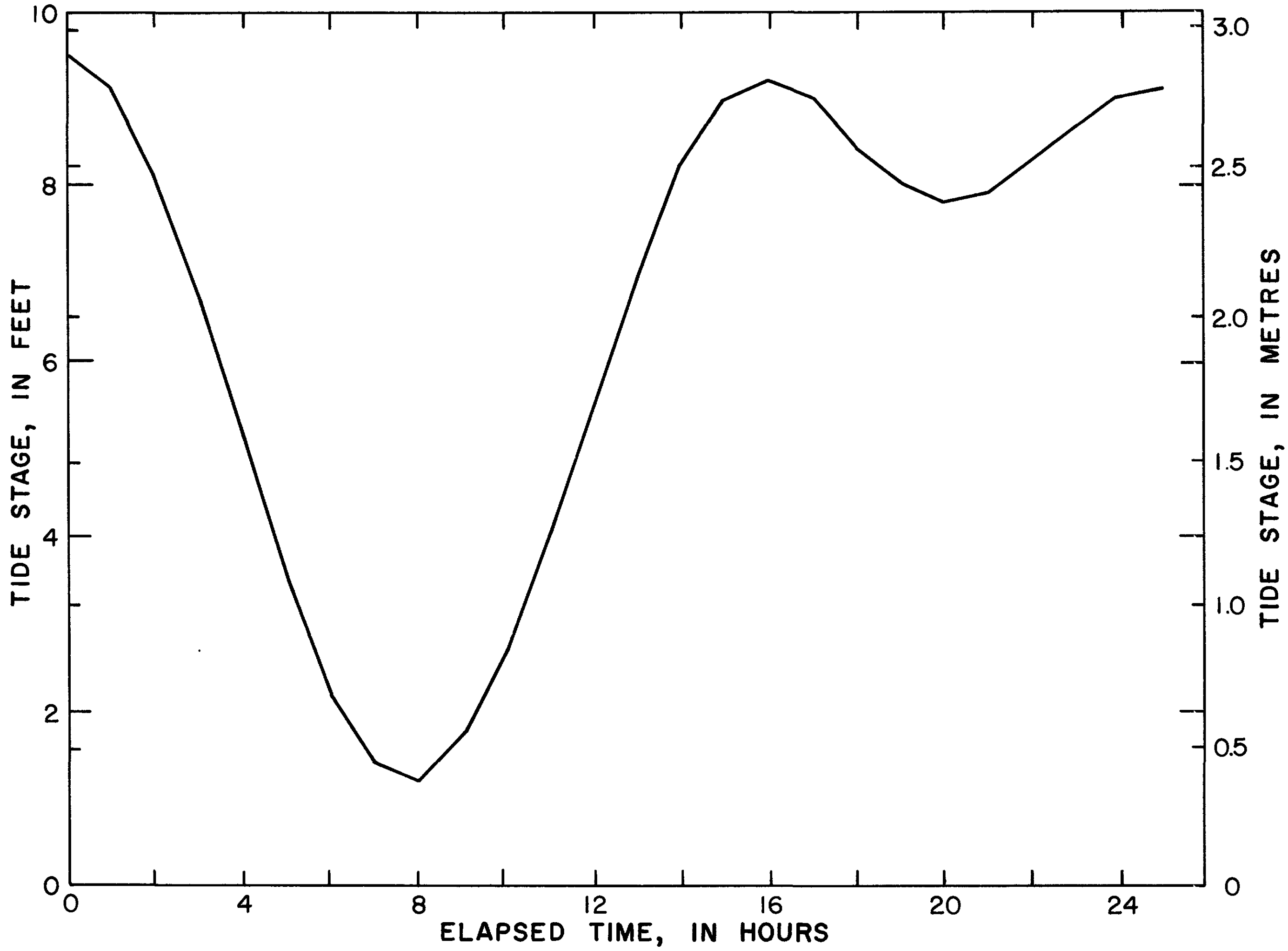

FIGURE 15.—Variation of tide stage during the tidal cycle used in the sensitivity analyses.

TABLE 2.—*Mean changes in sublayer salinities at 16th Avenue South Bridge during a 2-month period, relative to base values of sublayer salinities, for selected changes in the controlling parameters used in the Duwamish River estuary model*

[Positive and negative values indicate increases and decreases, respectively, in sublayer salinity]

Parameter	Change in the parameter	Change in model salinity (ppt) Sublayer 1	2	3
Wedge toe location	+1,000 ft (4 percent of average location)	0.60	0.86	0.36
	−1,000 ft (4 percent of average location)	−.68	−.94	−.36
Saltwater outflow	+10 percent	.24	.36	.29
	−10 percent	−.22	−.32	−.28
Entrainment velocity	+10 percent	.31	.51	.24
	−10 percent	−.30	−.48	−.22
Upper-layer thickness	+2 ft (22 percent of average thickness)	.18	.51	.33
	−2 ft (22 percent of average thickness)	−.11	−.26	−.15
Wedge salinity	+2 ppt (8 percent)	1.45	.74	.33
	−2 ppt (8 percent)	−1.45	−.74	−.33
Sublayer freshwater inflow	Distributed as 20, 40, and 40 percent	1.15	.08	−.17
	Distributed as 30, 35, and 35 percent	−1.04	−.04	−.20
Sublayer saltwater inflow	Distributed as 60, 25, and 15 percent	−.31	.44	.86
	Distributed as 80, 10, and 10 percent	.10	−.24	−.14
Sublayer entrainment velocity	Distributed as 80, 65, and 0 percent	.05	.26	.15
	Distributed as 70, 55, and 0 percent	−.04	−.28	−.15

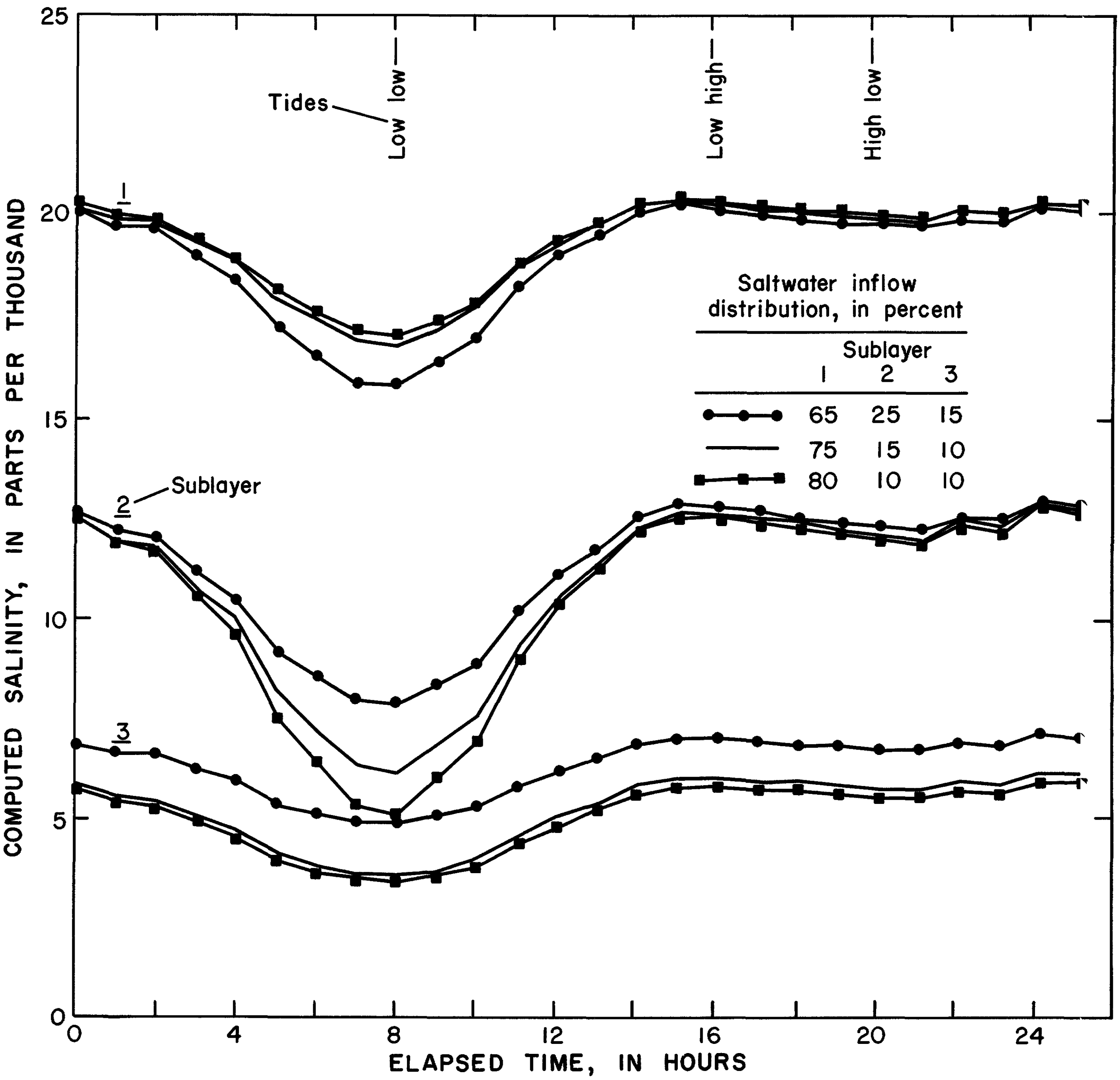

FIGURE 16.—Computed sublayer salinity during a tidal cycle at 16th Avenue South Bridge for various distributions of saltwater inflow among the sublayers at wedge toe, Duwamish River estuary.

model are given in table 3. The data suggest that, on the basis of equal percentage change, wedge DO concentration probably is more sensitive to changes in wedge toe location and entrainment velocity at the top of the wedge than it is to changes in saltwater outflow at the wedge toe and upper-layer thickness.

The variation of computed DO concentration in the wedge during the tidal cycle (fig. 17) agrees with the semidiurnal pattern of variation usually observed (fig. 13). For the changes in upper-layer thickness, wedge DO concentrations departed farthest from base concentrations during the low low tide (fig. 17); this also was true for the other three model parameters used in the sensitivity analyses.

SUMMARY AND CONCLUSIONS

The numerical model described in Part I of this report has been found to yield a good agreement between com-

TABLE 3.—*Mean changes in DO concentration in the saltwater wedge at 16th Avenue South Bridge during a 2-month period, relative to base values of DO concentration in the wedge, for selected changes in the controlling parameters used in the Duwamish River estuary model*

[Positive and negative values indicate increases and decreases, respectively, in wedge DO concentration]

Parameter	Change in the parameter	Change in wedge DO concentration (mg/l)
Wedge toe location	+1,000 ft (4 percent of average location)	0.084
	−1,000 ft (4 percent of average location)	−.098
Saltwater outflow	+10 percent	.081
	−10 percent	−.084
Entrainment velocity	+10 percent	.142
	−10 percent	−.124
Upper-layer thickness	+2 ft (22 percent of average thickness)	.159
	−2 ft (22 percent of average thickness)	−.151

puted and observed salinity distributions in the Duwamish River estuary and the DO concentration in the salt wedge of the estuary. The model input data, determined or estimated from observed data, included estuary geometry, location of upstream end of salt wedge (wedge toe) as a function of freshwater inflow and tide stage, entrainment of water from the wedge as a function of tidal-prism thickness (tidal exchange) and freshwater inflow, upper layer thickness, slope of the wedge-upper layer interface, freshwater inflow, tide stages, DO concentration in Elliott Bay water entering the downstream end of the wedge, and saltwater outflow at the wedge toe. Computed salinities in the estuary and DO concentrations in the wedge near its upstream end were compared with the appropriate observed salinities and concentrations. Because the upper surface of the wedge becomes diffuse and unstable farther upstream, the location of the wedge toe was defined as the farthest upstream cross section where salinity is 25 ppt. The saltwater that flows out at the wedge toe is balanced by an equal flow of saltwater into the upper layer at the wedge toe. Entrainment velocities, proportioning of freshwater and saltwater inflows among the sublayers

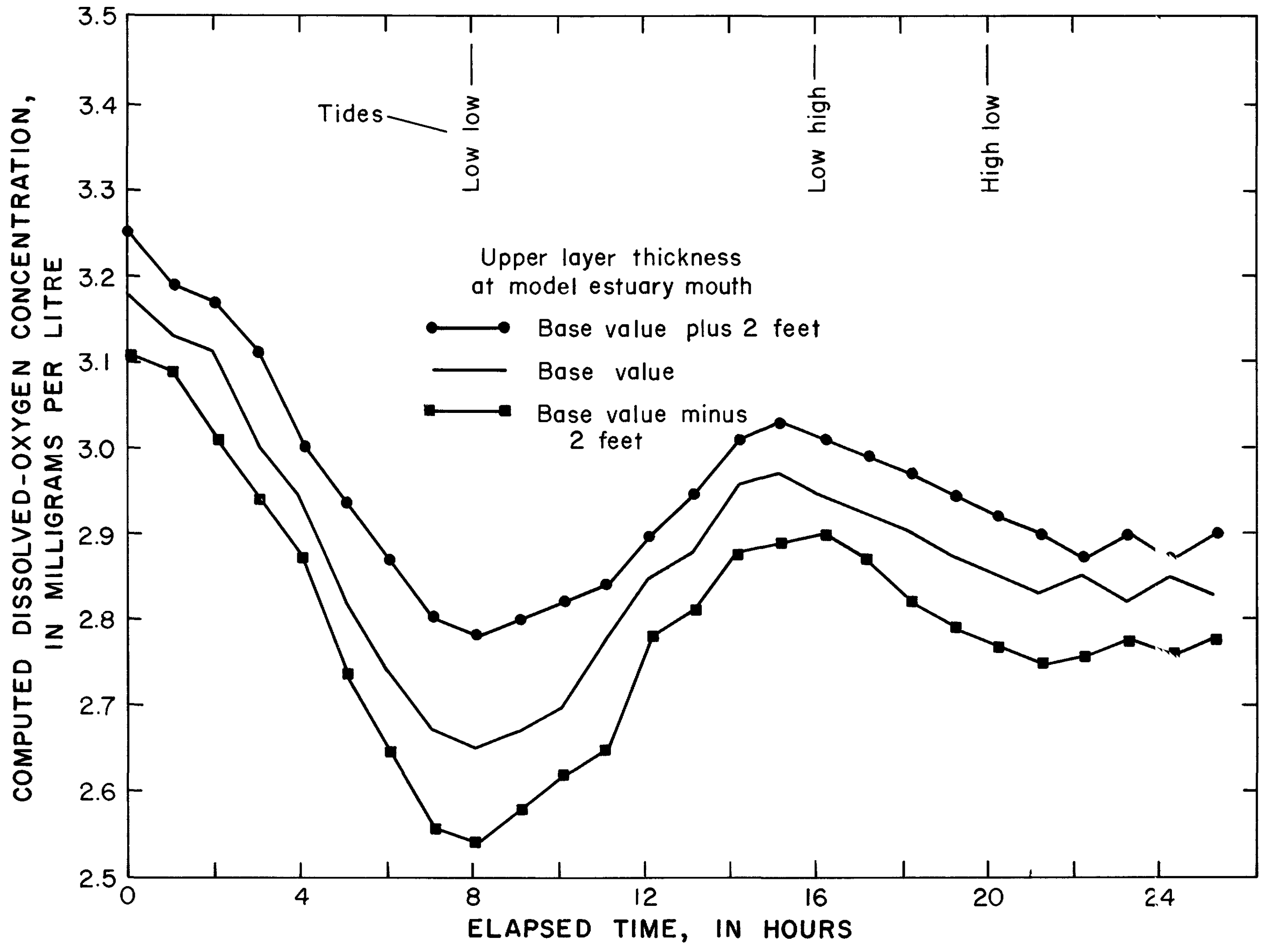

FIGURE 17.—Computed DO concentration in salt wedge during a tidal cycle at 16th Avenue South Bridge.

at the upstream end of the upper layer, and oxygen-use rates in the wedge were the parameters for which values were determined by trial and error. The parameter values necessary for agreement between computed and observed salinities and DO concentrations were within a credible range for the Duwamish River estuary.

DO concentrations in wedge water increased between 1967–69 and 1970–71. Raw and partly treated industrial and municipal wastes as well as effluent from the RTP, a secondary treatment plant, were discharged into the estuary during 1967–69, whereas nearly all the wastes discharged into the estuary during 1970–71 were those given secondary treatment at RTP. In the wedge at a downstream station near the estuary mouth, observed daily minimum concentrations during August-September periods were about 2 mg/l higher in 1970–71 (about 5–7.5 mg/l) than in 1967–69 (about 3–5 mg/l). In the wedge at an upstream station near the wedge toe, observed daily minimum and maximum concentrations during August-September periods increased by 2–3 mg/l and 2 mg/l, respectively, between 1967–69 and 1970–71. The sources of wedge water near the estuary mouth in relation to times of daily extremes in DO concentration suggested that a lower oxygen-use rate in the wedge in 1970–71 than in 1967–69 was the principal contributor, and the slightly higher DO concentration in Elliott Bay water entering the wedge in 1970–71 was a minor contributor to the increase in wedge DO concentrations between the two periods.

Wedge DO concentrations computed by the model agreed well with observed concentrations during the June–September periods of 1967–71. The modeling results indicated that the oxygen-use rate did not vary within any one June–September period, that rates were different (range from 0.023 to 0.028 mg/l/hr) each year in 1967–69, and that rates were constant (0.016 mg/l/hr) in 1970 and 1971. The average oxygen-use rate in the wedge during 1967–69 was 60 percent higher than it was during 1970–71.

The model program was used to predict wedge DO concentrations by assuming that parameters and input data, except freshwater inflow and oxygen-use rate, were the same as they were during June–September 1971. Freshwater inflow was changed to include the ultimate designed discharge of RTP effluent into the estuary (233 ft^3/s or 379 m^3/min) instead of the 1971 discharge (37 ft^3/s or 63 m^3/min). A model oxygen-use rate for the higher discharge was computed by assuming that (1) the rate would increase in proportion to the increase in concentration of suspended solids in the river and, consequently, in the upper layer; (2) the suspended-solids concentration in the river water was 1 mg/l for both 1971 and the time when RTP discharge will be the planned ultimate rate; and (3) the suspended-solids concentration in plant effluent did not change with discharge. An increase from 37 to 223 ft^3/s (63 to 379 m^3/min) in plant-effluent discharge may decrease DO concentrations in the wedge water by 45 percent given a relatively low concentration (4 mg/l) and by 8 percent given a relatively high concentration (9 mg/l). Also, it was estimated that average wedge DO concentrations might have been 0.6 mg/l higher in June–September 1971 if RTP effluent had not been discharged to the estuary.

Sensitivity analyses in which only one positive and one negative change in model parameters was made indicate that sublayer salinity is most responsive to changes in wedge toe location and in salinity of the wedge water and is least responsive to changes in sublayer entrainment velocities and in saltwater flow out of the wedge at its toe. Wedge DO concentration is most responsive to changes in wedge toe location and entrainment between the wedge and the upper layer.

The upper layer is presently (1973) being modeled. Using the model to compute oxygen-use rates in the wedge at the end of future periods is recommended to provide information about response of the rate to changes in RTP discharge and quality of freshwater and saltwater inflows. The model could be used to estimate transport of constituents other than wedge DO and estuary salinity. The model has been used to predict effects of a proposed change in estuary geometry on residence time and DO concentrations of the wedge water. Also, the model could be used to evaluate suggested methods for improving DO concentrations in the salt wedge.

DEFINITION OF TERMS

Entrainment velocity—Velocity at which water moves from the wedge into the overlying layer, in feet per second (centimetres per second).

Freshwater inflow—The total flow of freshwater into the upper layer at the wedge toe, in cubic feet per second (cubic metres per minute).

Initial volume—Initial volume of the wedge elements, in cubic feet (cubic metres).

Saltwater outflow—The total flow of saltwater out of the wedge at its toe, in cubic feet per second (cubic metres per minute); it equals the total flow of saltwater into the upper layer at the wedge toe.

Sublayer entrainment velocity—An entrainment velocity at the top of a specific sublayer, in feet per second (centimetres per second).

Sublayer freshwater inflow—The flow of freshwater into a specific sublayer, in cubic feet per second (cubic metres per minute).

Sublayer saltwater inflow—The flow of saltwater into a specific sublayer, in cubic feet per second (cubic metres per minute).

Upper layer thickness—The total thickness of the upper layer at the model-estuary mouth, in feet (metres).

Wedge salinity—Salinity of the saltwater wedge, in parts per thousand.

Wedge toe location—Location of the model-wedge toe, in feet (metres) upstream from model-estuary mouth.

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