Physical, Chemical, and Biological Aspects of the Duwamish River Estuary King County, Washington 1963–67

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1873-C

Prepared in cooperation with the Municipality of Metropolitan Seattle

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By J. F. SANTOS *and* J. D. STONER

ENVIRONMENTAL QUALITY

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By J. F. SANTOS and J. D. STONER

ABSTRACT

This report describes the significant results to 1967 of a comprehensive study that began in 1963 to evaluate what changes take place in an estuary as the loads of raw and partially treated industrial and municipal wastes are replaced by effluent from a secondary treatment plant. The study area is the Duwamish River estuary, about 18.3 river kilometers long. At mean sea level the estuary has a water-surface area of about 1 square mile and a mean width of 440 feet. At the lowest and highest recorded tides, the volume of the estuary is about 205 and 592 million cubic feet, respectively. The estuary is well stratified (salt-wedge type) at fresh-water inflows greater than 1,000 cfs (cubic feet per second), but when inflow rates are less than 1,000 cfs the lower 5.6 kilometers of the estuary grades into the partly mixed type. The cross-channel salinity distribution is uniform for a given location and depth. Salinity migration is controlled by tides and fresh-water inflow. At fresh-water inflow rates greater than 1,000 cfs, water in the upper 8.4 kilometers of the estuary is always fresh regardless of tide. At inflow rates less than 600 cfs and tide heights greater than 10 feet, some salinity has been detected 16.1 kilometers above the mouth of the estuary. Studies using a fluorescent dye show that virtually no downward mixing into the salt wedge occurs; soluble pollutants introduced at the upper end of the estuary stay in the surface layer (5–15 ft thick). On the basis of dye studies when fresh-water inflow is less than 400 cfs, it is estimated that less than 10 percent of a pollutant will remain in the estuary a minimum of 7 days. Longitudinal dispersion coefficients for the surface layer have been determined to be on the order of 100–400 square feet per second.

Four water-quality stations automatically monitor DO (dissolved oxygen), water temperature, pH, and specific conductance; at one station solar radiation also is measured. DO concentration in the surface layer decreases almost

linearly in a downstream direction. Minimum DO concentration in the surface layer is usually greater than 4 mg/l (milligrams per liter). The smallest DO values are consistently recorded in the bottom layer at the station 7.7 kilometers above the mouth; monthly means of less than 3 mg/l of DO have occurred at this point. Manual sampling shows that the DO sag in the bottom layer oscillates between 7.7 and 10.4 kilometers above the mouth of the estuary. Multiple-regression analysis shows that the surface DO content can be estimated from the fresh-water inflow and water temperature. Tidal exchange and fresh-water inflow indirectly control the bottom DO content. Information available from previous studies failed to indicate a progressive decrease in DO content during the period 1949–56, but data from the present study suggest a slight general decrease in the annual minimum DO concentrations in both the upper and lower layers. Average nitrate concentration in fresh water at station 16.2 has increased progressively since 1964, by amounts greater than those which can be attributed to the Renton Treatment Plant, 4.3 kilometers upstream from station 16.2.

The BOD (biochemical oxygen demand) in both surface and bottom layers is generally less than 4 mg/1 of oxygen, but values greater than 6 mg/1 have been measured during a period of phytoplankton bloom. Phytoplankton blooms can occur during periods of minimum tidal exchange and fresh-water inflows of less than 300 cfs if solar radiation and water temperature are optimum. Nutrients (nitrogen and phosphorus compounds) do not control the occurrence of a bloom, because sufficient quantities of these nutrients are always present. Nutrients in the treated effluent may increase the biomass of the bloom. Trace-element studies have not defined any role that these elements may play in algal growth.

The inflowing fresh water contains principally calcium and bicarbonate and has a dissolved-solids content ranging from 33 to 71 mg/l. During the study period, concentrations of suspended sediment ranged from 20 to 1,000 mg/l, and the maximum sediment load was 31,000 tons per day. Because bottom deposits contain large amounts of coal from upstream sources, it was not possible to quantitatively determine other organic material by carbon analysis.

INTRODUCTION

The Duwamish River estuary, the important industrial waterway in South Seattle, Wash., has been receiving wastes since the early 1900s, but the effects of such waste disposal were not considered serious until the 1940's. Since then an increase in wastes resulting from population and industrial expansion have degraded the quality of the estuarine water to the extent that fisheries-resources agencies and commercial interests have become concerned about the aquatic life in the estuary.

In 1958 the people in the greater Seattle area voted to form the Municipality of Metropolitan Seattle, generally known, and herein referred to, as Metro. Metro is a federation of 16 cities (1967) and rural areas in the Seattle–Lake Washington drainage area that united to deal with the growing problems of waste-water disposal in the area. Metro's comprehensive plan for water-pollution control includes an extensive network of sewer trunklines and several sewage-treatment plants (fig. 1).

Types of wastes presently (1967) entering the estuary includes raw and partially treated sewage, as well as wastes from manufacturing and food-processing plants (Peterson and others, 1955, p. 7). Since June 1965 the Renton Treatment Plant has been discharging its effluent into the Duwamish River, and the increasing amount of treated sewage effluent has been increasing as new sewer trunklines are constructed. As a result, the direct discharge of raw or partially treated wastes to the river is decreasing. Inflow to the Duwamish River of such wastes will probably be mostly eliminated within Metro's boundaries by 1970, when all proposed

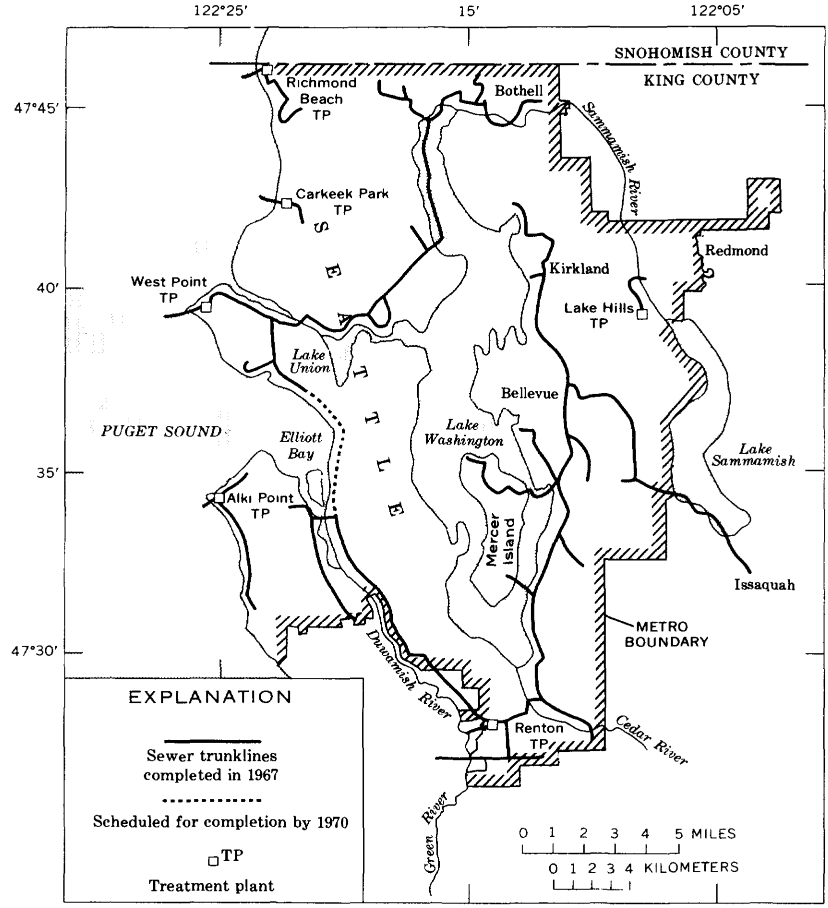

FIGURE 1.—Metro's network of facilities for water-pollution control. After Municipality of Metropolitan Seattle.

sewer trunklines are complete. Then, only several minor sources outside Metro's jurisdiction probably will continue to use the estuary for direct waste disposal, and the principal discharge will be the treated sewage from the Renton Treatment Plant. In 1963 Metro and the U.S. Geological Survey began the present cooperative study of water quality in the lower Duwamish River (fig. 2).

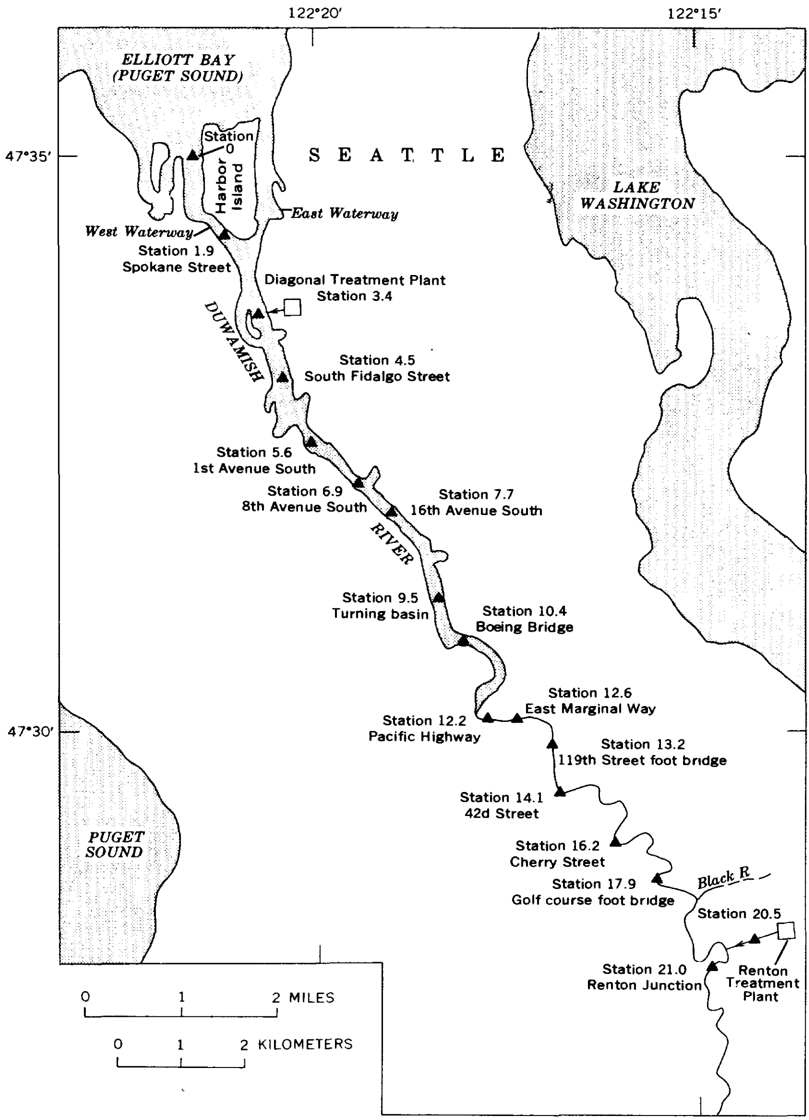

FIGURE 2.—Duwamish River estuary and location of sampling stations, in kilometers upstream from river mouth.

PURPOSE AND SCOPE OF THE INVESTIGATION

The objective of the study is to determine the chemical, physical, and ecological changes that take place in the estuary as raw or partially treated wastes are replaced by treated effluent from the Renton Treatment Plant. The investigation has been divided into several parts which, though related, lend themselves to separate study. The various parts of the investigation are grouped as follows:

1. Hydraulics of the estuary, including determination of the movements of the salt-water and fresh-water bodies; time of travel of the fresh water and residence time of the salt water in the estuary; and mixing and dispersion of the two waters during various conditions of river flow and tide stage.
2. Physical and chemical characteristics of the water, including temperature and density, sediment load DO (dissolved oxygen) content, BOD (biochemical oxygen demand), and reaeration rates.
3. Chemical quality of the fresh and salt waters in the estuary and of the inflowing fresh water upstream from major waste discharge, including determination of variations in concentrations of chloride, nitrate, phosphorus, alkalinity, and selected trace constituents.
4. Certain aspects of the ecology of the estuary, including determinations of the primary production of oxygen by phytoplankton (tiny free-floating plants), number and species in the plankton community, and variations related to physical and chemical conditions.

The results of these individual studies will be used to identify the changes in the estuary resulting from the shift in waste-disposal practices and hopefully also will allow prediction of environmental conditions in the estuary for various rates of effluent discharge from the Renton Treatment Plant.

Studies being conducted concurrently in the Duwamish River estuary by Metro personnel include: (1) Sanitary quality of the water; (2) inventory of migrant and resident fishes using the estuary; (3) enumeration and identification of benthic organisms; and (4) studies of the BOD of bottom deposits.

This report summarizes significant results of the study to date (1967) and discusses work planned for the future to accomplish the long-term objective of the study in the estuary. The report also briefly describes water-quality conditions upstream, beyond the immediate study area, which relate directly to conditions in the estuary. The preliminary results described in this report pertain to (1) the estuary mechanics, or how the estuarine system functions, (2) distribution of DO and BOD in the estuary, (3) factors that influence phytoplankton bloom, and (4) chemical and physical characteristics of the fresh and salty waters.

Six reports on various phases of this study have been published separately: two are on dispersion in the estuary and inflowing fresh water (Williams, 1967; Fischer, 1968), three describe phytoplankton and related water-quality conditions in the estuary (Welch, 1968 and 1969; Welch and Isaac, 1967), and the other deals with prediction of the intrusion of salt water into the estuary (Stoner, 1967).

METHODS AND EQUIPMENT

The ecological and hydraulic environment in the Duwamish River Estuary is especially difficult to study because of the variable character of the estuary. Seasonally the estuary varies from a well-stratified salt-wedge type to a partially stratified, partially mixed type. (See section on "Salt-Wedge Advection" for description of estuary types.) This dynamic environment makes duplication of experiments virtually impossible. Experiments made on samples taken from the estuary produce results that represent one set of transitory conditions and are not necessarily representative of specific or "average" conditions; experiments that include living organisms are especially nonrepresentative. The changes in inflow rate and in water-quality input to the system (waste and sediment load) also add to the difficulty of defining specific causative factors for observed results.

Most of the methods and equipment used to date (1967) in this investigation are well known in the fields of hydrologic and water-quality studies and are not described in detail in this report. Some of the methods and equipment, however, were developed during this investigation. Insofar as the innovations are significant to the results of this investigation and may be applicable to similar studies elsewhere, they are described in detail either in the present report or in other reports resulting from this investigation.

SAMPLING AND FIELD MEASUREMENTS

Water sampling was done from a boat or a bridge. All samples, except those taken for dye studies, were collected in a 4-liter sampler made of polyvinyl chloride. The sampler is equipped with a flexible rubber hose and clamp for dividing the 4 liters into containers for specific determinations of phytoplankton, specific conductance and major chemical constituents, trace elements, DO, and BOD. Samples for DO and BOD always were drawn off first. Samples for dye studies were taken separately in 16-ounce glass bottles. Throughout the report reference will be made to surface or bottom in discussing the elements of the study. "Surface" samples were collected about 3 feet below the water surface, and "bottom" samples 3 feet above the bottom.

Suspended-sediment samples were collected by using a depth-integrating sampler (DH–49) from a fixed facility on the bridge at station 21.00. Samples for bedload were taken using a bed-material sample (BM–54). Field measurements of specific conductance, salinity, and water temperature were obtained by using an electrodeless induction-type salinometer.

SPECIAL EQUIPMENT

Automatic water-quality monitors installed at stations 1.9, 7.7, 12.6, and 21.0 (fig. 2) sample water from 3 feet below the surface and measure specific conductance. DO, temperature, and pH. In addition, at stations 1.9 and 7.7, water is sampled automatically from 3 feet above the bottom and is analyzed for the same parameters except pH. At station 12.6 solar radiation also is measured. Positive-displacement pumps are used to bring the river water to the monitor. All plumbing is made of polyvinyl chloride.

ANALYSIS

Chemical constituents were determined using procedures given in Rainwater and Thatcher (1960). Trace elements were determined spectrographically, employing the procedures of Silvey (1967). Analysis of chlorophyll was made by the method of Richards and Thompson (1952) as modified by Creitz and Richards (1955). DO was determined by using the azide modification of the Winkler method (American Public Health Association, 1965).

Both suspended-sediment and bed-material samples were analyzed using the procedures of the U.S. Geological Survey.

ACKNOWLEDGMENTS

Chemical-quality data for the Green River were collected in cooperation with the Department of Water Resources and the Water Pollution Control Commission of the State of Washington. The Seattle Department of Engineering provided the results of their 1948–49 Duwamish River estuary sanitary survey.

The authors are grateful for the helpful suggestions provided by C. V. Gibbs, Executive Director of Metro, and G. D. Farris, Superintendent, Water Quality and Industrial Wastes of Metro; Prof. E. B. Welch, University of Washington; and R. W. Paulsen, Hydrologist, U.S. Geological Survey.

PREVIOUS INVESTIGATIONS

Formal water-quality investigations of the Green–Duwamish River began in 1948, and during the period 1948–63 several investigations were made. The first formal study was a bacteriological and DO survey made during June–September 1949 by the Washington State Pollution Control Commission (Sylvester and others, 1949).

An investigation also was made by the Engineering Department of the City of Seattle (written commun., 1967) from November 1948 to April 1950. Samples were taken for measurements of DO, BOD, salinity, water temperature, and pH at seven stations in the downstream section of the estuary. The samples were collected at the top and bottom at approximately twice-weekly intervals. The resulting report contains data only, and no interpretations or conclusions were made. The data indicate, however, that there was no serious oxygen depletion in the lower Duwamish River estuary under the rate of fresh-water inflow recorded.

The Washington State Pollution Control Commission conducted another sanitary-quality survey of the Green–Duwamish River during the summer of 1955. The commission reported on bacteriological character, DO, BOD, and toxic compounds (Peterson and others, 1955). The report states that the amount of dissolved oxygen in the river was, in general, satisfactory; however, it also states that the samples were collected during a year of high fresh-water inflow and of low water temperature and that low amounts of dissolved oxygen certainly could exist during low-water years in the estuary.

The present and future effect of pollution in the Green–Duwamish River was the subject of a University of Washington post-graduate thesis by R. W. Okey (written commun., 1957). Okey's evaluation was based on temperature, DO, BOD, and chloride data collected during the summer and fall of 1956. He concluded that unless increases in streamflow can be obtained, no additional discharges of oxygen-demanding wastes of any magnitude can be tolerated at the present level of DO. He also stated that the construction of Howard A. Hanson Dam should have no material effect upon DO levels in the lower estuary.

In 1956 the City of Seattle authorized a survey of sewerage and drainage problems and methods of solving the problem of water pollution. The survey (Brown and Caldwell Engineers, 1958) reported on types, amounts, and composition of wastes being discharged to the Duwamish River, the effect of various waste loads on DO, estimates of flushing time, and needed waste-treatment facilities. The report resulting from the survey was the basis for Metro's comprehensive sewerage plan.

The most recent report (Isaac and others, 1964) was published by Metro; it comprehensively covers water-quality conditions during the low-flow period of 1963 and provides some comparisons with the 1962 low-flow period.

HYDROGRAPHY

THE DUWAMISH RIVER BASIN

The Green–Duwamish River study area is 11.9 miles (19.1 kilometers) long. At mean sea level the water-surface area is about 1 square mile and has a mean width of 440 feet. All river distances used in this report are reckoned from the mouth, kilometer 0, which was arbitrarily established at a line drawn across the mouth of the West Waterway (fig. 2).

Prior to 1906 the drainage basin of the Duwamish River exceeded 1,600 square miles and included the Cedar, Green, Black, and White River basins. In 1906 the White River was permanently diverted to the Puyallup River to the south. In 1916 the Black River (fig. 2), which received the flow from the Cedar River (fig. 1) and Lake Washington, had its flow reduced when the level of Lake Washington (fig. 1) was lowered 9 feet after completion of a ship canal to Puget Sound and it ceased to be a major tributary to the Duwamish River. These changes reduced the Duwamish River to its present drainage area of 483 square miles (fig. 3).

The Green River drains more than 90 percent of the Duwamish River basin (Richardson, 1962). Fresh-water discharge from the remainder of the basin is negligible in comparison.

The Green River heads on the west slope of the Cascade Range and flows north and east about 60 miles (96.5 km) to its confluence with the Black River below which it becomes known as the Duwamish River (fig. 2). The upper reaches of the Green River and its tributaries flow in steep-sided and heavily forested mountain valleys.

Howard A. Hanson Dam (fig. 3), primarily a flood-control structure, was completed in 1962. This dam has altered the natural stream regimen by tending to reduce peak discharges and increase summer flows. Below the dam, the Green River flows through a 15-mile (24.1 km) gorge where many springs contribute to the discharge. The only sizable tributaries downstream from the gorge are Newaukum and Big Soos Creeks. Downstream from Auburn, inflow is negligible except during periods of heavy local rains.

The City of Tacoma diverts 113 cfs (cubic feet per second) daily from the Green River for municipal and industrial use. The diversion point is 2½ miles (4.0 km) southeast of Palmer.

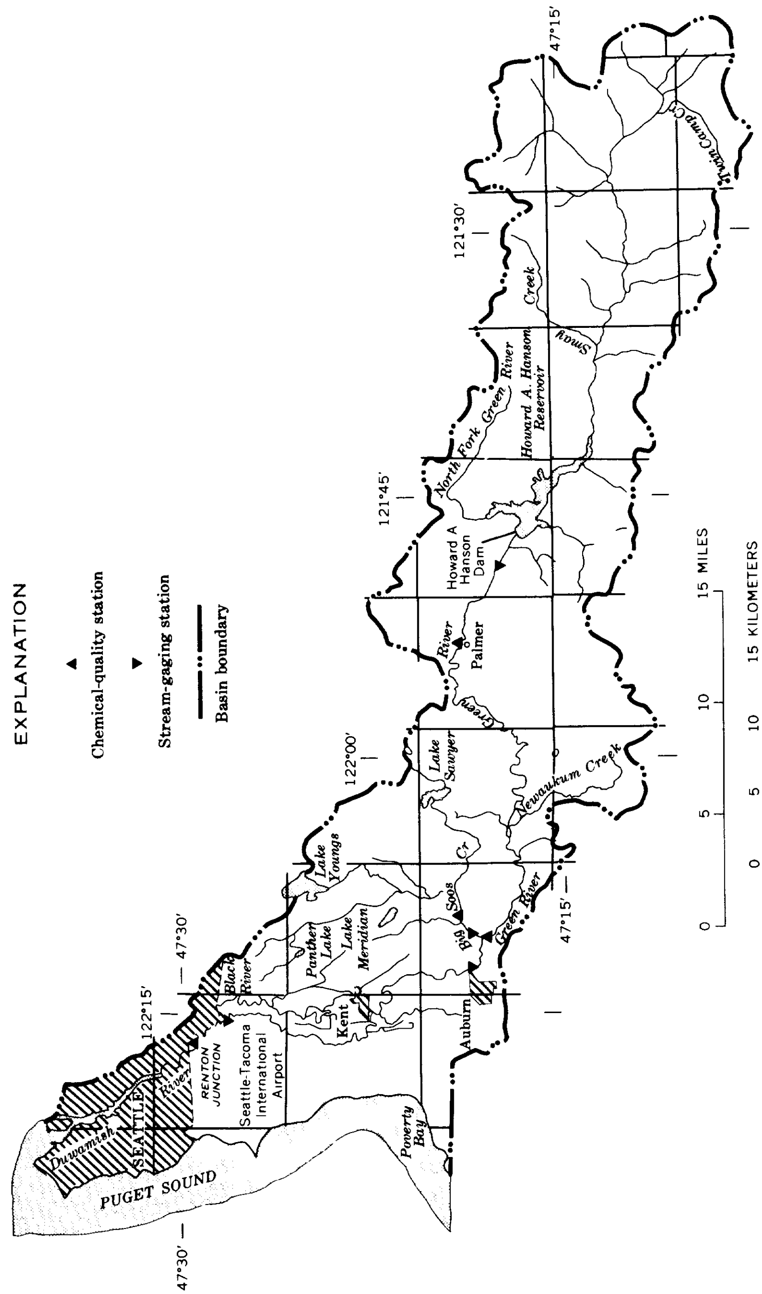

FIGURE 3.—Duwamish River basin.

Streamflow data for the Duwamish–lower Green River are available from two gaging stations, one near Auburn and one at Tukwila (fig. 3). Streamflow records for these stations have been published by the U.S. Geological Survey (1937–60; 1961–66).

For the gaging station near Auburn, a long-term (1937–66) discharge record is available. This long-term record at Auburn has been correlated with a short-term record, 1960–66, for the gaging station at Renton Junction[1] (sta. 21.0) about 20 miles downstream, but the correlation is not applicable for a rising river stage. Thus, the record at Renton Junction cannot be extended back in time on a day-to-day basis, although the correlation has been found to be valid for monthly and yearly means. In addition, the river level at the gaging station at Renton Junction (sta. 21.0) is influenced by the tide at low discharges, and records collected at this station are considered fair—that is, accurate to within 8 percent.

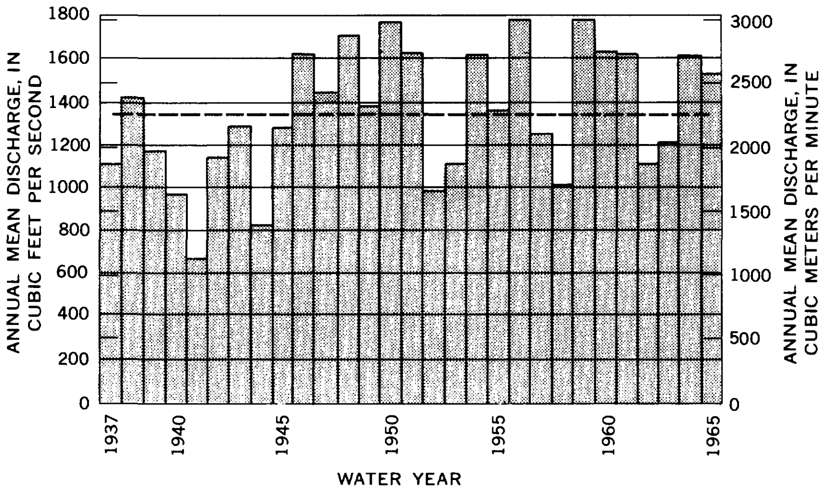

FIGURE 4.—Annual mean discharges of the Green River near Auburn, 1937–65. Heavy dashed line is mean of 1,349 cfs.

Figure 4 shows the annual discharges of the Green River near Auburn. Maximum annual discharge occurred in 1959 and was 132 percent of the 29-year mean; the minimum, in 1941, was 49 percent of the 29-year mean.

Figure 5 shows the monthly mean discharges for 1941 and 1959, respectively the driest and wettest years during the period 1937–65.

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[1] The gaging station is listed as "12–1133.5 Green River at Tukwila Wash." in the streamflow records published by the U.S. Geological Survey (1937–60).

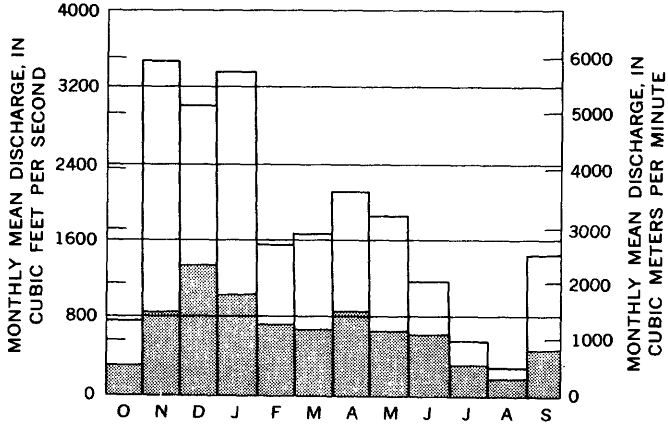


FIGURE 5.—Comparison of monthly mean discharge of the Green River near Auburn for the driest year (1941, shaded bars) and wettest year (1959, shaded plus unshaded bars) during the period 1937–65.

Normally, rains cause high runoff during the late fall and winter months, and snowmelt maintains this high-runoff period into June. During July the runoff decreases rapidly, and the minimum occurs at most places in August. The normal seasonal pattern of flow is shown by the long bars in figure 6. This figure also shows the minimum monthly discharges for the period 1937–65.

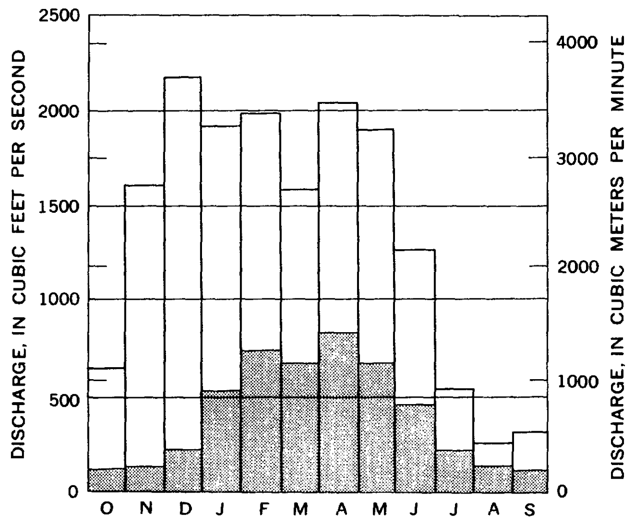


FIGURE 6.—Mean monthly (unshaded plus shaded bars) and minimum monthly (shaded bars) discharges of Green River near Auburn, 1937–65.

Low fresh-water flows are of particular importance to water-quality conditions in the lower estuary. Welch (1969, p. 53) has demonstrated that when fresh-water inflow decreases to about 300 cfs a phytoplankton bloom can occur if the other related factors (principally sunlight, tidal prism thickness, and water temperature) are favorable. This bloom usually is followed by a decrease of DO in bottom water (Welch, 1969, fig. 16) to a value less than many authorities (McKee and Wolf, 1963) consider adequate for the maintenance of fish life. Figure 7 shows the low-flow frequency for the Green River at Auburn; however, because the frequency distribution is based on natural flows prior to flow regulation by Howard A. Hanson Dam, caution should be used in its application.

Howard A. Hanson Dam, with an active storage capacity of 105,160 acre-feet, is primarily a flood-control structure. Water is stored in the dam during periods of floodflow but is released as soon as practicable afterwards to prepare for any subsequent flood. Usuall in late May the dam starts retaining water to augment low summer flows. The low-flow augmentation is designed to maintain 100 cfs in the lower reaches of the Green River.

PRECIPITATION

The rate and character of the fresh-water inflow to the estuary are determined largely by the amount, distribution, and type of precipitation in the Duwamish River basin. The annual precipita-

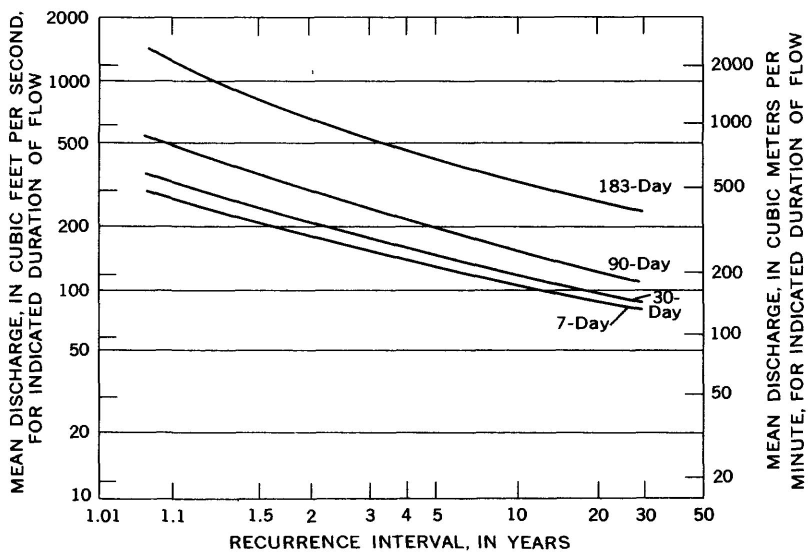


FIGURE 7.—Low-flow frequency of Green River near Auburn, 1946–63, prior to regulation by Howard A. Hanson Dam.

tion varies widely throughout the basin, depending mostly on altitude and proximity to the crest of the Cascade Range. Seattle-Tacoma International Airport (fig. 3) receives an average of 38.9 inches per year, whereas the upper slopes in the eastern part of the basin receive more than 100 inches per year. Data from the Environmental Science Services Administration (U.S. Weather Bureau, 1967) show that most of the precipitation occurs during the cooler months of October through March; in the lowlands it is in the form of rain, but at the higher altitudes it falls mostly as snow. Snow falls occasionally on the lowlands but does not remain long.

Figure 8 shows the average monthly precipitation recorded at the Seattle-Tacoma International Airport for the period 1945–66, and figure 9 compares the 1966 precipitation at the airport station with that at Palmer (fig. 3), which is about 520 feet higher than the airport station and about 20 miles closer to the crest of the Cascades.

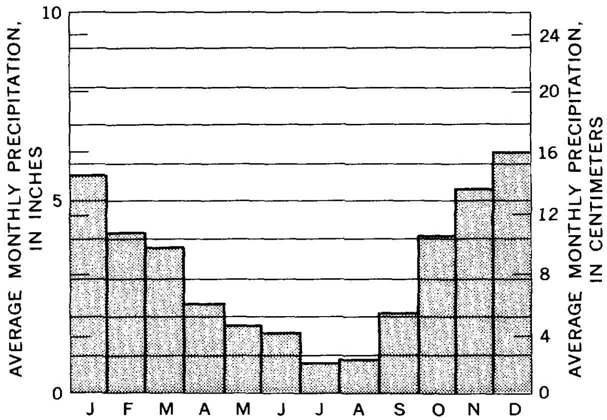


FIGURE 8.—Average monthly precipitation at Seattle-Tacoma International Airport, 1945–66. Data from Environmental Science Services Administration.

TIDES

The U.S. Coast and Geodetic Survey (1963–66) has a tide-recording station in Elliott Bay, data from which have been projected to station 6.9 in the Duwamish River. Stages in the estuary have been measured only when very precise tide data were needed for special studies. The values from station 6.9 for various tidal stages are shown in figure 10. Throughout this investigation the term "tide stage" is referenced to mean lower low water (MLLW), which is

6.6 feet below mean sea level. Mean range of tide in the Duwamish River is 7.5 feet, and mean diurnal range is 11.1 feet. Recorded tides have ranged from minus 4.6 to plus 14.7 feet.

During the investigation, tide stage has been measured at several stations over a tidal cycle (25 hrs), and close agreement between the measured and predicted stages has been found. Figure 11 compares the tide stage measured at station 1.9 with the stage predicted for station 6.9. For all practical purposes the stage predicted for station 6.9 is applicable to the reach between stations 1.9 and 7.7.

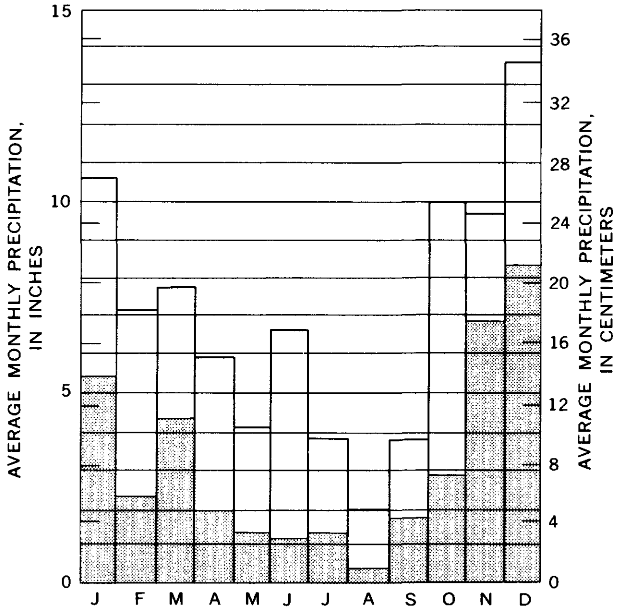


FIGURE 9.—Average monthly precipitation during 1966, for two stations at different altitudes. Shaded bars represent precipitation at Seattle-Tacoma International Airport, altitude 375 feet; shaded plus unshaded bars are precipitation at Palmer, altitude 895 feet. Data from Environmental Science Services Administration.

VOLUME OF THE ESTUARY

The areas of 21 cross sections were determined for computing estuary volume at various tide stages. In the lower 11.3 river km of the estuary, the fathometer soundings on charts of the U.S. Army Corps of Engineers (1965) were used to determine the channel depths of the cross sections and were supplemented by hand soundings where necessary. To determine volumes in the upper 9.7 km, hand soundings were made across cross sectional areas. The 21

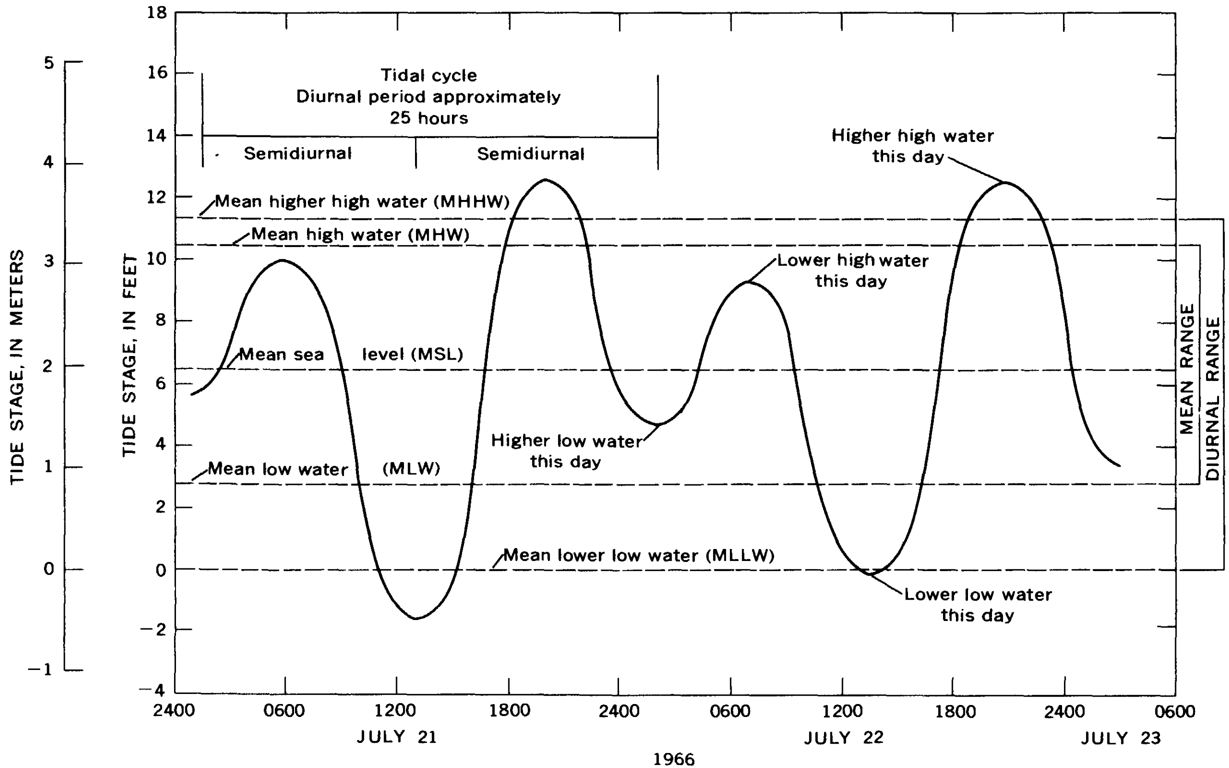


FIGURE 10.—Tide curve for the Duwamish River at station 6.9, illustrating various terms pertaining to tidal fluctuations.

cross sections were chosen so that the volume interval between them was as uniform as possible. The geometry of each particular channel segment provided the basis for determining whether the volume was computed as a rectangular parallelepiped, half a cylinder, or half a frustum of a pyramid. Figure 12 shows the relation of cumulative volume to distance, for mean higher high water and mean lower low water. Volumes were calculated for nine tide levels from the lowest recorded tide to the highest recorded tide, 205 and 592 million cubic feet, respectively. The graph shows that the logarithm of cumulative volume is almost a linear function of distance. These data have been used to test some of the flushing-rate theories reported in the literature. (See section on "Flushing Time.")

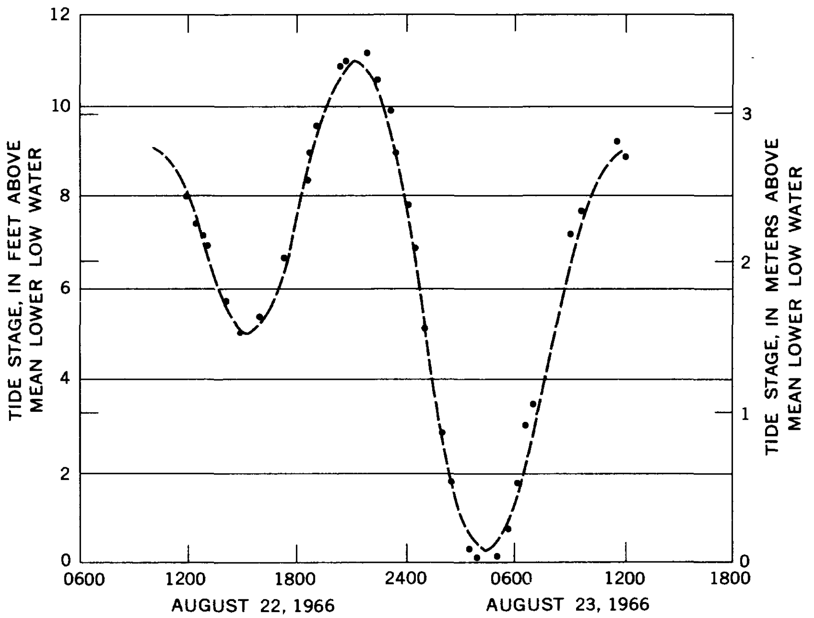


FIGURE 11.—Comparison between tide stage predicted for station 6.9, using data from Elliott Bay (dashed line) and tide stages measured at station 1.9 (dots).

ESTUARY MECHANICS

The effect of the Renton Treatment Plant effluent upon the estuary is dependent primarily upon two things—distribution and residence time of the effluent. The following discussions of salinity distribution, mixing and circulation, flushing, and dye studies are presented to provide a better understanding of the processes involved in the distribution of the treatment plant effluent throughout the estuary.

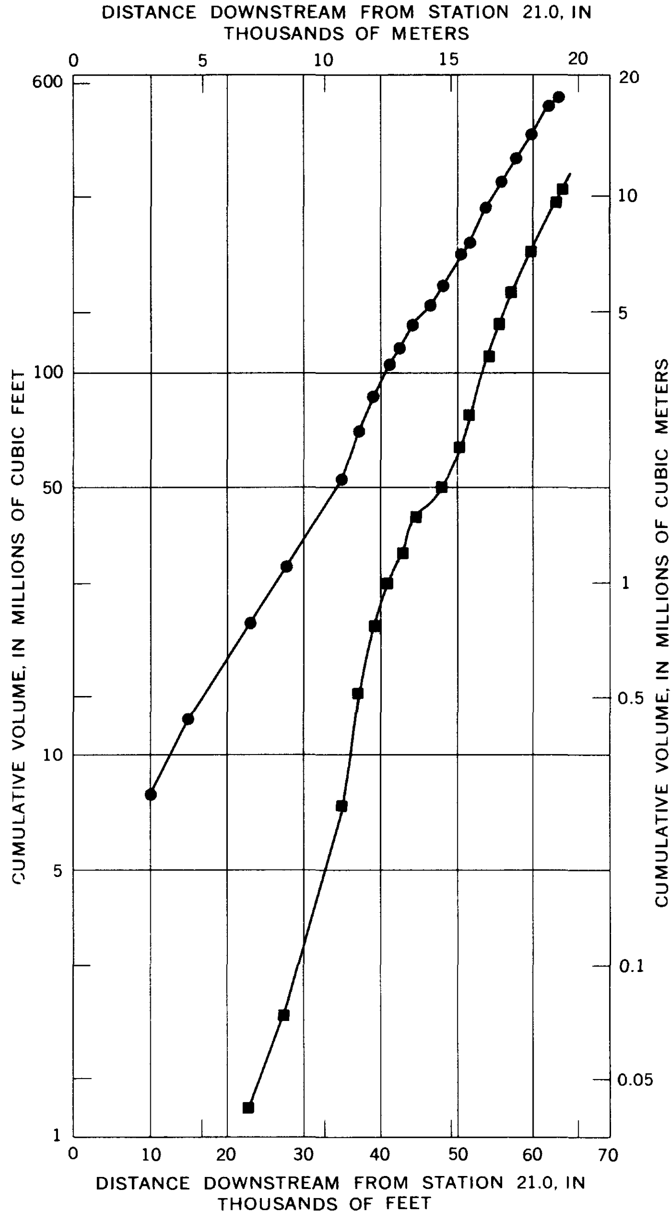


FIGURE 12.—Cumulative-volume curves for mean higher high water (circles) and for mean lower low water (squares).

DISTRIBUTION OF SALINITY

The distribution of salinity throughout the estuary varies vertically, longitudinally, and laterally with time. The vertical and longitudinal variation of the salinity distribution at a given station is dependent upon the combined effects of the fresh-water inflow and the tidal conditions. The maximum and the minimum salinity concentrations are governed primarily by the fresh-water inflow, which varies seasonally. Highest inflow rates generally occur between October and April, and the lowest occur during the period July to September. Salinity concentrations are greatest throughout the estuary during the period of minimum fresh-water inflow.

To define the lateral salinity variation throughout the estuary the distribution of salinity was measured through several different cross sections at two different rates of fresh-water inflow. At a fresh-water inflow of approximately 1,800 cfs, the salinity at a given depth for a specific station was uniform from one side of the channel to the other. At a fresh-water flow of 300 cfs, the salinity in the estuary was laterally uniform also, except where the effluent from the Diagonal Treatment Plant (fig. 2) discharges into the estuary. There, because the effluent is of a lower salinity than the estuary water into which it discharges, it produces a lower salinity pattern at depth along the east bank for a short distance downstream, beyond which the pattern returns to lateral uniformity. The estuary is not wide enough for the lateral-salinity distribution to be significantly affected by the Coriolis force (effect of the earth's rotation). In general, for a given depth and upstream distance, salinity was laterally constant at all rates of fresh-water inflow which occurred during the study.

The vertical salinity distribution, however, is strikingly nonuniform. Vertical salinity profiles taken at various stages of tide and rates of fresh-water inflow show the presence of a saline wedge typical of a stratified estuary (fig. 13). The wedge is distinct in the profiles upstream from river km 5.6 at all measured rates of fresh-water inflow. In the lower estuary, downstream from station 5.6, at flows less than 2,000 cfs, the boundary between the surface layer and the saline wedge becomes less distinct. Salinity stratification becomes well developed at fresh-water inflows greater than 1,500 cfs (fig. 14). As the fresh-water inflow decreases, vertical stratification becomes less sharply defined; at fresh-water flows of less than 1,000 cfs, stratification is no longer clearly defined in the lower section of the estuary (fig. 14). Even at the lower flows, however, the vertical salinity gradient of the estuary is still strong, and the ratio of top-to-bottom salinity rarely exceeds 0.6. For any given river flow, vertical stratification increases in an upstream

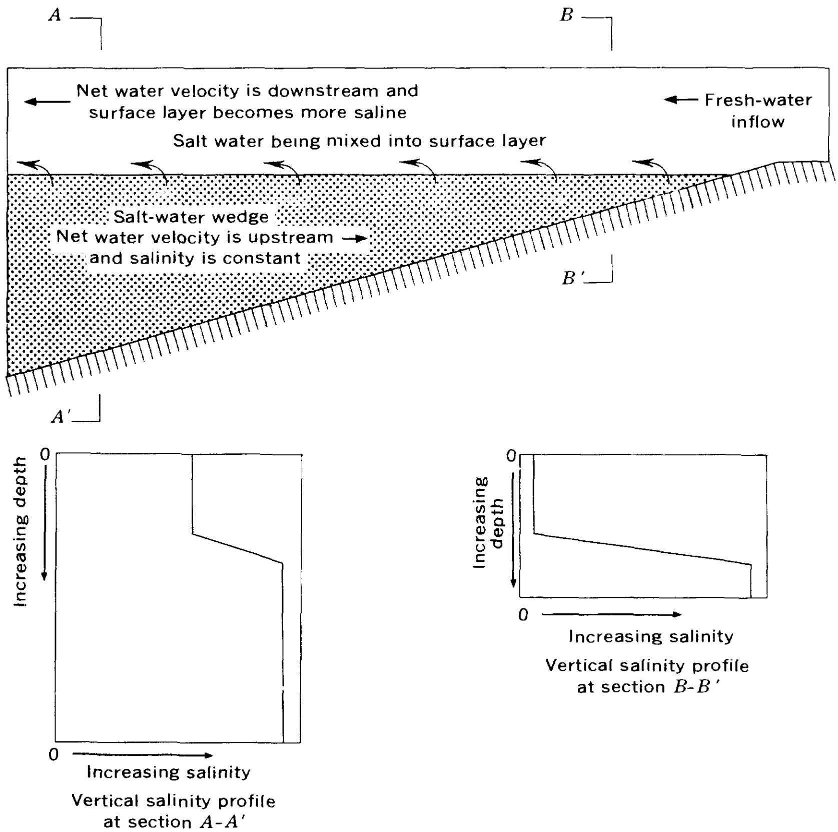


FIGURE 13.—Schematic diagram of an idealized stratified estuary showing net circulation pattern and salinity profiles.

direction to the end of the wedge. The depth of the surface layer, when stratification is evident, varies directly with the fresh-water inflow; this layer ranges from 5 to 15 feet in thickness.

Longitudinal distribution of salinity is dependent upon the tide conditions and the rate of fresh-water inflow. Salinity in the surface layer increases in a downstream direction, whereas salinity in the bottom layer is relatively constant except near the upstream end of the salt-water wedge. The salinity of the surface layer is controlled primarily by the rate of fresh-water inflow (fig. 15). The surface salinity at station 1.9 (Spokane Street Bridge) varies from less than 4 ppt (parts per thousand), at fresh-water inflows of 5,900 cfs or greater, to more than 15 ppt at inflows of 500 cfs or less.

The salinity in the bottom layer, although relatively constant, does decrease slightly in an upstream direction, probably owing mostly to slow diffusion. The upstream end of the wedge terminates

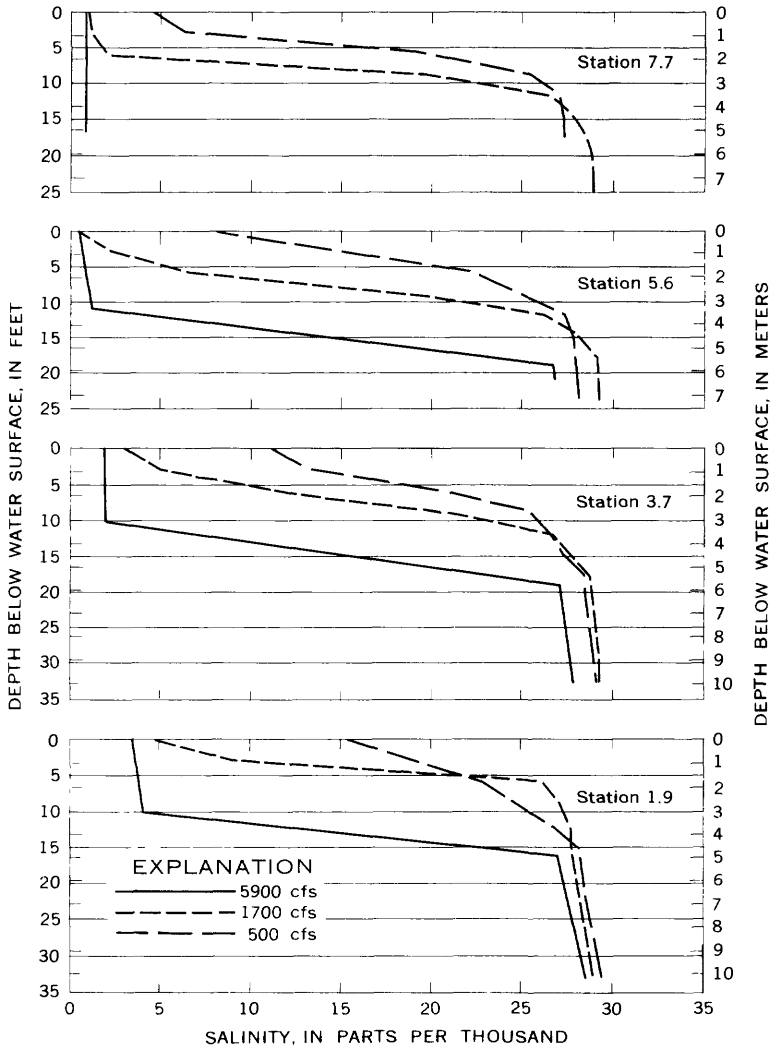


FIGURE 14.—Vertical salinity profiles at selected stations for various rates of fresh-water inflow.

over a relatively short distance. The average salinity throughout the main body of the salt wedge decreases very slightly with increase in the fresh-water inflow. This decrease in salinity is due to the slightly larger proportion of fresh water in the mixture that enters the wedge at its downstream end (fig. 13).

The upstream extent of the wedge is dependent upon fresh-water inflow and tide height, except that inflows greater than 1,000 cfs will prevent intrusion of the wedge farther upstream than station

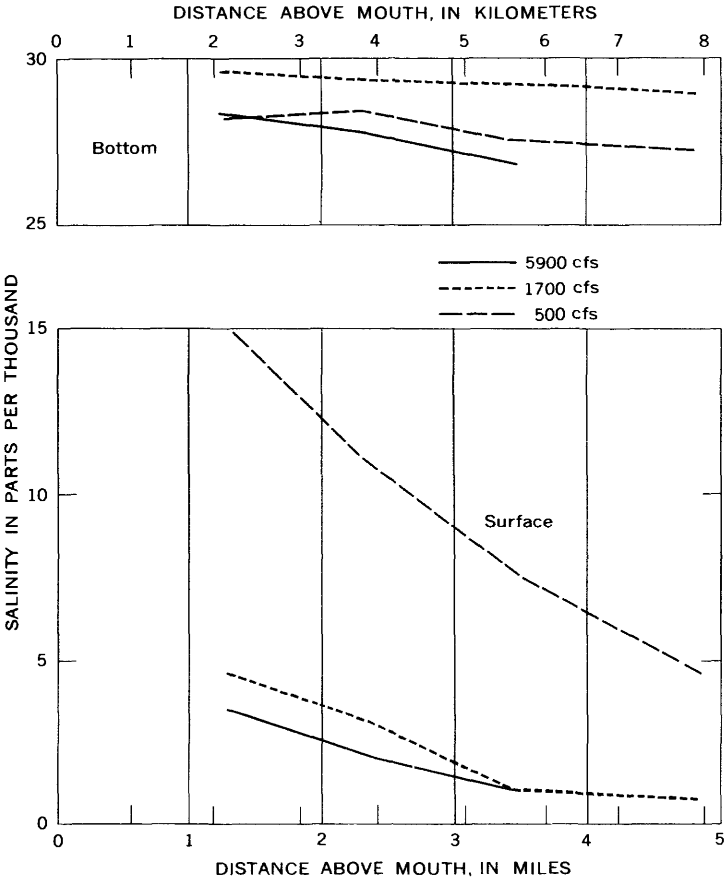


FIGURE 15.—Longitudinal salinity profiles for selected rates of fresh-water inflow.

12.6 (East Marginal Way), regardless of tide height (Stoner, 1967). At low fresh-water inflow (generally less than 600 cfs) and at tide heights greater than 10 feet above mean lower low water, the salt-water wedge has extended upstream approximately 16 km above the mouth. Conversely, the wedge has been pushed downstream as far as 6.4 km above the mouth at low tide and high rates of inflow.

The salinity distribution in the estuary can be described as a two-dimensional system. Any point of salinity data can be described in terms of its longitudinal and vertical position only, inasmuch as salinity differences in the lateral (cross-channel) direction at each point are negligible.

Three cyclic tidal periods in the Duwamish estuary are of importance to the salinity distribution; they are the semidiurnal, diurnal, and biweekly periods. (See fig. 10.) Of these three, the semidiurnal period (from low to high and high to low tide) has the most pronounced effect upon the salinity distribution. The diurnal period is significant because of the inequality of successive high or low tides. The biweekly period is significant because a major range of the tides occurs during this period.

At station 21.0 (Renton Junction), the sampling point farthest upstream, the water is always fresh. The salinity at station 12.6 (East Marginal Way) is highly dependent on rates of fresh-water inflow; it is negligible at inflows greater than 1,000 cfs.

At station 7.7 (16th Avenue South), the variation of salinity during the tidal cycle becomes less pronounced than the salinity variation at station 12.6, and the average salinity increases with decreasing fresh-water inflow. For example, at a fresh-water inflow of 3,800 cfs the salinity at the bottom ranged from 27.8 ppt to 0.3 ppt during a tidal cycle, whereas at an inflow of 297 cfs the salinity ranged from 27.8 ppt to 15.4 ppt. The estuary at this station has fresh water at all points in the vertical profile only with the combination of very low tide and high rates of fresh-water inflow.

At station 1.9, the farthest downstream primary sampling station, the estuary is always saline regardless of tide and the rate of fresh-water inflow. The salinity variation during the tidal cycle at this station follows the same pattern as that at station 7.7, although the variation is smaller even at the higher rates of fresh-water inflow.

CIRCULATION AND MIXING

SALT-WEDGE ADVECTION

Vertical salinity profiles indicate that very little of the fresh water in the upper layer of the estuary mixes downward into the saline-water wedge. Most of the mixing between the saline and fresh water occurs at the interface of the two layers, where saline water is entrained upward into the overriding fresh-water layer (fig. 13). This pattern of circulation in estuaries has been defined by Pritchard (1955) as that of the classical salt-wedge estuary. Confirmation of the absence of downward mixing was indicated by the results of a fluorescent dye study in August 1966. (See section on "Flushing Time.")

In this type of estuary, the net movement of water in the saline wedge is upstream. The upstream movement of the saline water is theoretically necessary to replace the water that has been entrained upward into the fresh-water layer along the interface.

The theoretical circulation pattern for the estuary was confirmed by a velocity study made in June 1965 during one complete tidal cycle at a fresh-water flow of 425 cfs. The surface and the bottom velocities obtained from this study are plotted in figure 16. The net area under the two curves was computed in order to determine the net velocity of each layer. The net velocity of the bottom layer was 0.09 fps (feet per second) upstream, and the surface-layer velocity was 0.13 fps downstream.

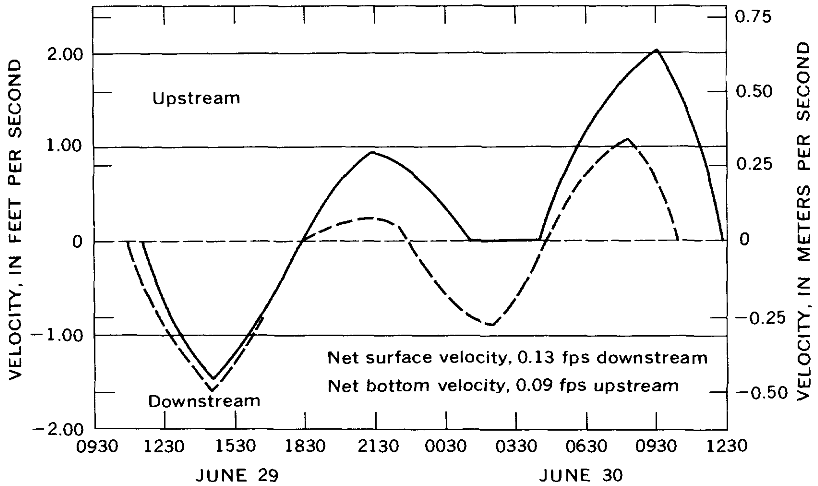


FIGURE 16.—Surface- and bottom-velocity plots at station 7.7 (16th Avenue South), June 29–30, 1965. Solid line, surface velocity; dashed line, bottom velocity.

The net circulation of the estuary—upstream in the bottom layer and downstream in the upper layer—and the mixing from the bottom layer to the upper layer places the upstream part of the Duwamish River estuary in the category of Pritchard's salt-wedge estuary even at low rates of fresh-water inflow. Vertical salinity profiles in the lower estuary, however, are indicative of the partially mixed type of estuary at low rates of fresh-water inflow.

A two-parameter system of estuary classification which may be useful for water-management purposes has been developed by Hansen and Rattray (1966) and is shown in table 1. This system, which categorized estuaries into four general types, is based upon a "stratification number" as well as a "circulation number." The stratification number is given as $\delta S/S_0$ and a circulation number U_s/U_f where

δS=top-to-bottom salinity difference, in parts per thousand.
S_0=mean cross-section salinity, in parts per thousand.
U_s=surface velocity, in feet per second.
U_f=fresh water discharge divided by the cross-section area, in cubic feet per second per square foot.

TABLE 1.—*Estuary classification*

[Modified from Hansen and Rattray, (1966)]

Type	Circulation	Sub type	Stratification
1	Well-mixed estuary, net flow seaward at all times; upstream salt transfer by diffusion.	A	Slight.
	Do	B	Appreciable.
2	Net flow reverse at depth; upstream salt transfer by diffusion and advection.	A	Slight.
	Do	B	Appreciable.
3	Similar to type 2 except advection accounts for 99 percent of upstream salt transfer.	A	Slight.
	Do	B	Appreciable.
4	Salt wedge, with appreciable stratification.		

The values used for these four parameters are the mean values over the total tidal cycle.

Data from the June 1965 velocity study and from various vertical salinity profiles lead to the following conclusions in terms of the Hansen and Rattray classification system (table 1):

1. The part of the estuary upstream from station 5.6 for any measured fresh-water inflow is in the type 4 category (salt wedge).
2. At fresh-water inflows greater than 1,000 cfs, the entire estuary would be type 4; at lesser inflows the part downstream from station 5.6 grades into type 2B. According to the classification system, the type 2B estuary, although appreciably stratified, has diffusion, as well as advection, as a mode of salt transfer and mixing.

Longitudinal stratification profiles of the Duwamish River estuary are shown in figure 17. Three rates of fresh-water inflow are plotted against the stratification numbers of Hansen and Rattray (1966, p. 322).

DISPERSION

The use of dyes to study dispersion and water movement has been reported by many workers. Most of the studies used fluorescein, pontacyl pink, or one of the rhodamine compounds. Rhodamine B was used in the work reported in this section. The details on instrumentation, standardization, and dye have been reported by Fischer (1968), who also provided an excellent discussion of the physical and hydraulic factors that produce dispersion.

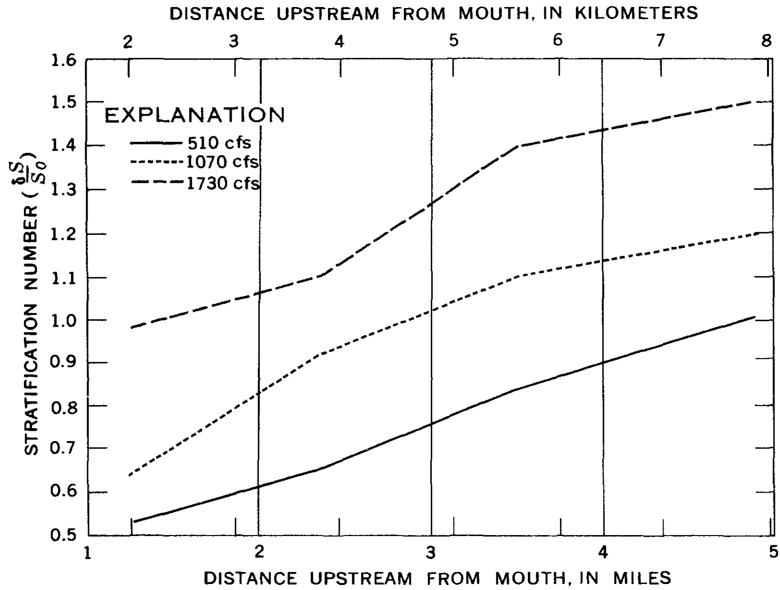


Figure 17.—Longitudinal stratification profiles for selected fresh-water inflow rates.

The use of a dye to study time of travel and dispersion in the Duwamish River estuary posed three problems. First, the geometry of the estuary is such that a very large amount of dye must be inserted into the relatively small-volume upstream section so that the dye can be detected in the large-volume lower part of the estuary. Second, during low flows in the summer, the river contains adult salmon migrating upstream to spawn and juvenile salmon migrating downstream to Puget Sound. A search of the literature provided no indication as to what concentration of rhodamine B might be toxic to salmon; therefore, the concentrations of dye that were used in the early studies were too weak, and the result was that those studies failed. Third, background fluorescence in the Duwamish estuary varies with water temperature, salinity, and quantity of phytoplankton. In general, the background fluorescence amounted to 0.1–0.2 μg/l (microgram per liter) of apparent rhodamine B. In most of the studies, therefore, 0.1 μg/l was considered to be the minimum detectable amount of dye, and concentrations below that were considered background fluorescence.

The rate of dispersion in a stream is described quantitatively by means of a dispersion coefficient. In an early dye study in this investigation. Williams (1967) calculated dispersion coefficients of 100 and 200 to 400 square feet per second for stations 12.6 and 7.7, respectively. River flow during the study was about 700 cfs. Williams used two different methods for calculating the coefficient at station 12.6. The first method used the statistical Pearson type-III distribution (Godfrey and Fredrick, 1963), which gave a coefficient of 113 square feet per second. The second method used the formula of Taylor (1954), which gave a coefficient of 104 square feet per second. Williams rounded the coefficients to 100 square feet per second.

In reporting on the more intensive studies made in the summer of 1965, Fischer (1968) developed a method for predicting longitudinal dispersion from lateral dye distribution and velocity profiles at a single station. Dispersion coefficients for two experiments gave measured values of 70 and 90 square feet per second, whereas dispersion coefficients predicted by Fischer's method gave values of 84 and 91 square feet per second. The dispersion coefficients reported by Fischer were computed from data collected on an outgoing tide, when the estuary behaves essentially like a fresh-water river, and the coefficients apply only to the upper 9.7 km of the study area.

FLUSHING TIME

Flushing time is the average length of time required for the river water and its contained pollutants to move through the estuary. Because it determines the residence time of oxygen-depleting pollutants, the flushing time is one of the more important factors (along with the quality and rate of inflowing fresh water, tidal action, and concentration of the pollutants) controlling the DO levels in the estuary. The method proposed by Ketchum (1951b) was used to compute the flushing time of the estuary.

Ketchum's method requires a division of the estuary into segments whose lengths correspond to "the average excursion of a particle of water on the flooding tide" (Ketchum, 1951b, p. 200); the method includes the assumption that the intertidal volume of water (and any contained pollutants) in each segment moves downstream to the next segment during each successive tidal cycle. The method also assumes vertical homogeneity. The Duwamish River estuary, however, is not homogeneous vertically, and some of the data had to be modified to fit Ketchum's method. Because the saline wedge does not enter into the mixing process except through entrainment at the interface, a theoretical "bottom" was used in the flushing-time calculations. The theoretical bottom was placed at that depth of the water below which salinity is virtually constant. The cumulative-volume curve used in the computation varied because of the differences in depth to the theoretical bottom with different rates of streamflow. Volumes of estuary segments were computed at mean high and mean low water. The volume of the estuary used in the computation ranged from 242.1×10^6 cu ft (cubic feet) at mean high water for a discharge of 500 cfs to 323.0×10^6 cu ft at mean high water for 7,000 cfs.

The total volume escaping from each segment can be calculated by dividing the river flow per tidal cycle by the fraction of fresh water in that segment of the estuary (Ketchum, 1951b, p. 206). The percentages of fresh water for three segments of the estuary, for virtually the entire range of fresh-water inflow, are shown in table 2. Fresh-water percentages calculated by Ketchum's method are shown along with actual percentages from field salinity measurements. The lengths of the hypothetical segments, which are based on tidal-excursion distances, vary with the rate of fresh-water inflow.

As shown in table 2, at inflows greater than 1,000 cfs the calculations by Ketchum's method were in good to fair agreement with the actual data. At lesser inflow rates, however, some of the calculated percentages disagreed substantially from the actual percentages, especially in segment 2, which is farthest downstream. This departure between calculated and actual percentages in the lower part of the estuary also was described by Ketchum (1951b, p. 206) for Raritan Bay in New Jersey.

TABLE 2.—*Lengths of hypothetical estuary segments and percentages of contained fresh water for various rates of river inflow*

[Method of Ketchum, (1951a)]

River discharge (cfs)	Segment 0			Segment 1			Segment 2		
	Fresh water (percent)		Length (ft)	Fresh water (percent)		Length (ft)	Fresh water (percent)		Length (ft)
	Calculated	Actual		Calculated	Actual		Calculated	Actual	
510	100	98	28,800	44	63	18,000	22	46	18,800
540	100	95+	29,600	45	47	19,400	24.2	32	16,400
745	100	99+	34,600	50	53	18,000	28	32	16,700
570	100	95+	34,500	51	49	19,200	28	28	15,600
750	100	95+	37,700	42	45	18,000	26	31	17,900
800	100	100	35,400	52	61	18,300	29	47	16,600
800	100	100	35,400	52	68	18,300	27	46	16,600
890	100	100	36,400	55	61	18,800	31	44	16,500
900	100	99+	36,600	52	72	19,300	31	44	16,600
930	100	100	37,000	52	80	19,700	31	60	16,600
950	100	99+	37,000	54	59	19,800	32	36	16,300
1,070	100	98+	38,600	58	59	20,300	33	43	16,100
1,150	100	98+	39,700	60	75	20,500	...	....	.....
1,260	100	97+	41,000	59	69	20,200	...	....	.....
1,800	100	100	48,200	67	69	18,600	...	....	.....
1,900	100	97+	49,400	77	76	17,200	...	....	.....
3,000	100	94+	58,600	....	....	.....	...	....	.....
3,000	100	97+	58,600	....	....	.....	...	....	.....
3,900	100	97	63,700	....	....	.....	...	....	.....
5,900	100	94	71,600	....	....	.....	...	....	.....

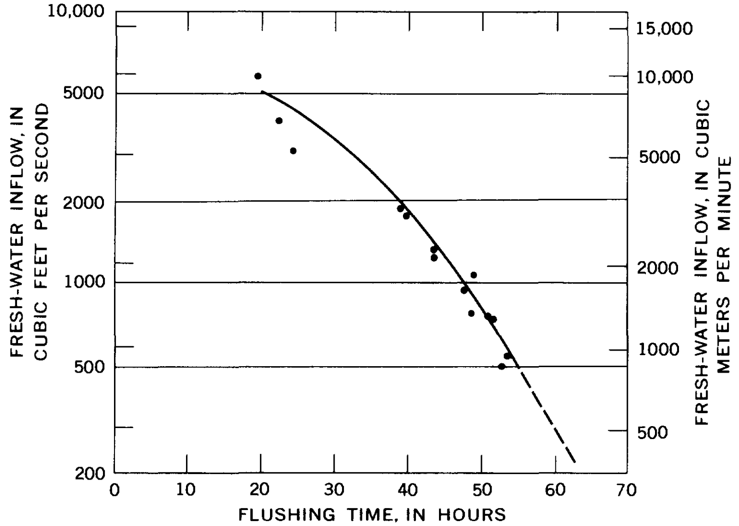


FIGURE 18.—Flushing time of Duwamish River estuary, from station 21.0 to mouth.

The curve in figure 18, derived from the data in table 2, represents at this stage of the investigation the best available estimate of flushing time for the Duwamish estuary. A comparison is available from a previous investigation made by Brown and Caldwell Engineers (1958). Their calculations of a flushing time of 3.0 days at 200 cfs, using an estimated mean mixed depth of 16 feet at mean high water, corresponds well with the 65 hours, or 2.7 days, at 200 cfs shown on the curve in figure 18.

The change in the lower estuary at fresh-water discharge less than 1,000 cfs from a salt-wedge type to a partially mixed type probably accounts for the failure of Ketchum's method in the low-inflow range. At the lower discharges the interface between the wedge and mixed layer becomes so diffuse that it is nearly impossible to establish accurately a theoretical bottom for the mixed layer. Therefore, because the critical DO levels occur during the low-discharge period, the use of this method to compute flushing time has been abandoned.

Several authors have proposed other methods of mathematical models intended to evaluate the salinity distribution and (or) flushing time in an estuary. The method of Ippen and Harleman (1961) was found to be unsatisfactory because calculated results using this method did not compare well with the Duwamish field data. A possible reason is that the diffusion coefficient of Ippen and Harleman, determined at the ocean entrance, is assumed to be constant, whereas this value increased in an upstream direction when computed from data for the Duwamish River estuary.

Arons and Stommel (1951) have proposed a "mixing-length theory of tidal flushing" for computing the salinity distribution in an idealized estuary where mixing is predominantly due to tides. Their equation takes the form

$$\overline{S}/S_0 = {}_eF(1-L/X),$$

where

$\overline{S}$=mean salinity, in parts per thousand;
S_0=ocean salinity, in parts per thousand;
L=length of the estuary, in feet, from a point where salinity=0 to a point where salinity=S_0;
X=distance along the estuary length, in feet; and
F=a "flushing number" presumed to be characteristic of a given estuary, dimensionless.

Longitudinal salinity profiles at selected discharges as predicted by the Arons and Stommel method were compared with actual profiles measured in the estuary. That the predicted salinity did not compare well with the measured salinity was not surprising because $\overline{S}$ in the equation is intended to be the mean salinity in the vertical over the tidal cycle, whereas the measured values of salinity were not tidal-cycle means. This method, however, seems to hold enough promise to warrant further evaluation after data for a sufficient number of tidal cycles have been collected.

In August 1966 another dye study was made to determine how long the relatively fresh surface-water layer remains in the lower estuary. The dye was released at 0500 hours on August 29, 1966, at station 13.2. Figure 19 shows the predicted tide curves for the study period. Fresh-water inflow for the preceding 5 days had increased gradually; the mean daily discharge at station 21.0 had increased from 291 cfs on August 24, 1966, to 307 cfs on August 28, 1966. During the study, inflow decreased from 301 cfs on August 29, 1966, to 289 cfs on September 1, 1966.

Samples of river water were collected for determination of dye concentrations at stations 1.9, 3.7, 4.5, 5.6, 6.9, 7.7, 9.5, and 10.4. Samples were taken 3 feet below the surface and 3 feet above the bottom. Station 10.4 was not sampled during lower low water, for shallow water prevents access by boat. The dye entered the study reach in about 2 hours and at the first lower low water, about 6 hours after the dye release, almost the entire dye cloud was in the study area (fig. 20). During successive tides the dye cloud moved out of the estuary (fig. 21). In four successive cycles between lower low waters, the maximum dye concentration decreased from 18 μg/l to 0.4 μg/l. A plot of peak dye concentration found during subse-

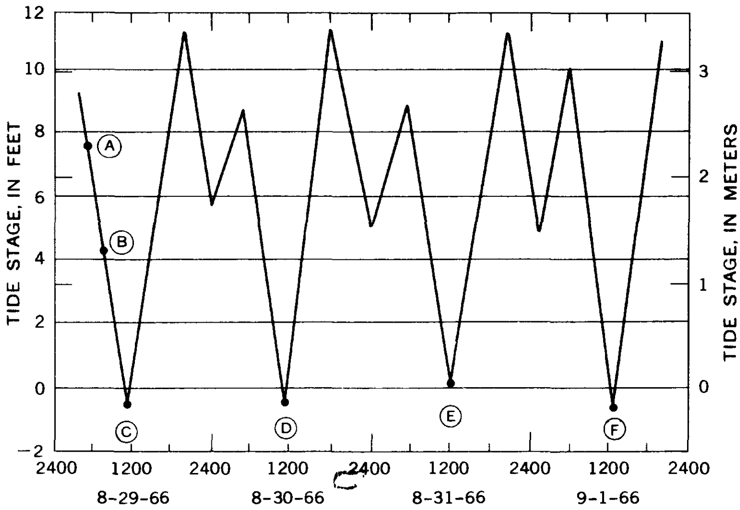


FIGURE 19.—Generalized predicted tide stage for the Duwamish River estuary at station 6.9, for period August 29–September 1, 1966. Point A indicates dye release; points B through F refer to tide stages for figures 20 and 21.

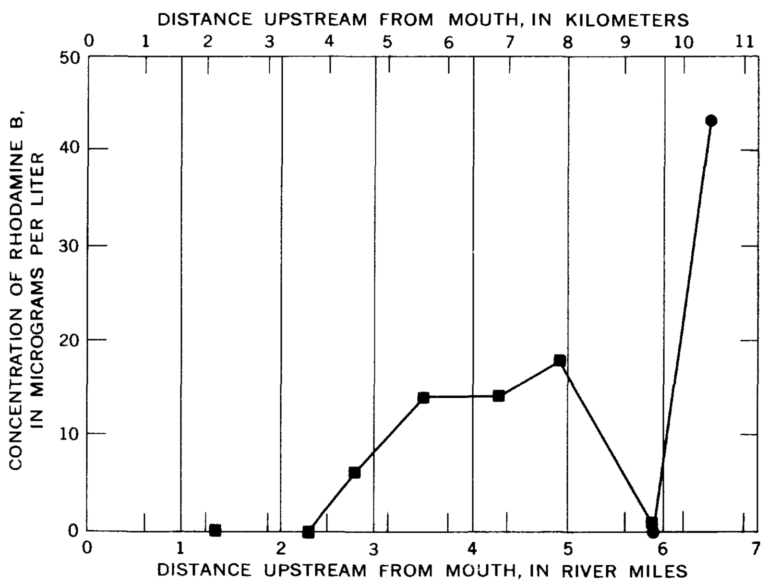


FIGURE 20.—Longitudinal configuration of dye clouds in the Duwamish River estuary, August 29, 1966. Circles, dye cloud just entering study area about 2 hours after dye release; squares, dye cloud at lower low water about 6 hours after dye release.

quent lower low water yielded a curve (fig. 22) that upon extrapolation suggests the dye would be nearly gone within 5 days. Rhodamine B was not detected in the bottom samples collected at stations 1.9, 3.7, and 5.6; this fact suggests that no mixing took place between the surface and bottom waters during this study.

In both the 1965 and 1966 dye studies, data were collected during nearly identical conditions of tide stage and fresh-water inflow. Comparison of the 1965 upper river data with the 1966 lower river data indicates that some of a pollutant introduced at station 21.0 would remain in the estuary a minimum of 7 days.

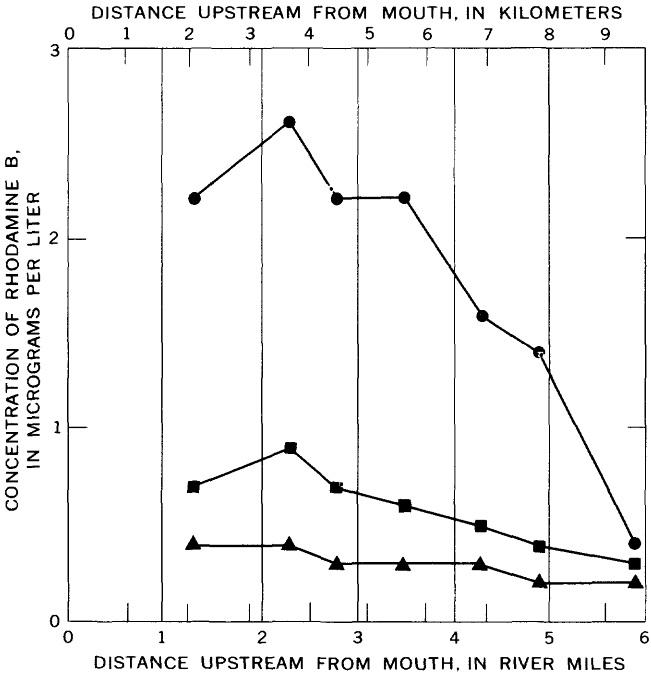


FIGURE 21.—Longitudinal configuration of dye clouds at successive times of lower low water in the Duwamish River estuary: circles, August 30, 1966, about 26 hours after dye release; squares, August 31, 1966, about 51 hours after dye release; triangles, September 1, 1966, about 77 hours after dye release.

DISSOLVED OXYGEN

Dissolved oxygen has been a key parameter in this and previous studies of the Duwamish River estuary. Inasmuch as the degradation of the more common wastes requires their oxidation, the variation in content of DO in stream or estuarine water is a significant indicator of the general amount and persistence of pollutants. Furthermore, the DO is especially significant in this and similar streams that have commercially and recreationally important fish populations. Changes in DO content not only directly affect the respiration of the fish and shellfish, but also influence them indirectly by changing the ecological system of which they are a part.

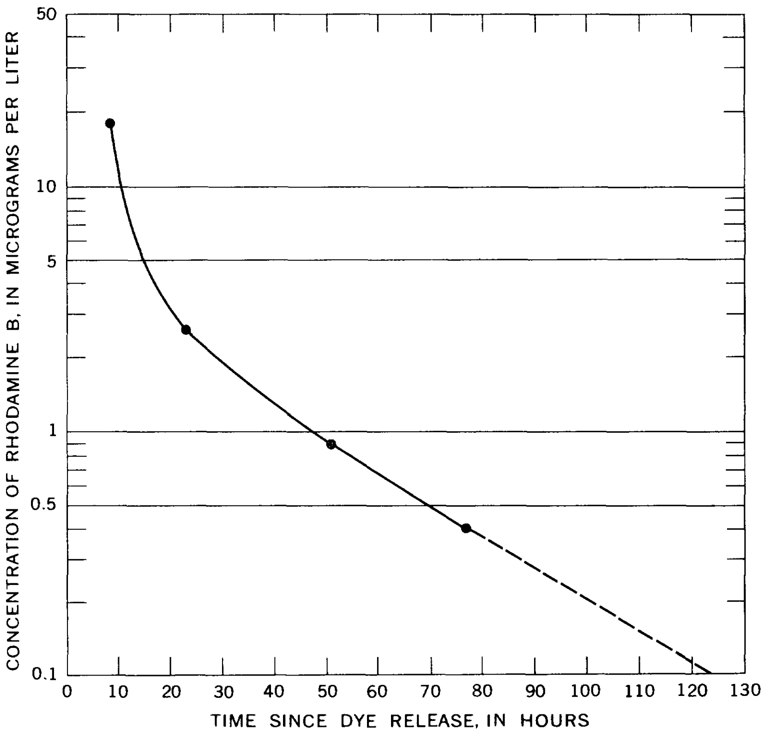


FIGURE 22.—Plot of peak concentrations of rhodamine B found during successive times of lower low water, August 29–September 1, 1966.

The DO of stream or estuary water is depleted by the oxidation of natural materials as well as manmade wastes and is added naturally by aeration at the air-water surface, by mixing with water having more DO and (or) by photosynthesis of aquatic plants. (See sections on "Phytoplankton" and "Biochemical Oxygen Demand.") Commonly the DO concentration in a stream water will decrease progressively for a certain distance downstream from a point of waste entry because the rate of oxygen depletion by oxidation of the wastes is greater than the rate of oxygen enrichment by reaeration or photosynthesis. The concentration of oxygen usually begins to increase again at a sufficient distance downstream as the oxygen-depletion rate becomes less than the oxygen-enrichment rate. This longitudinal decrease and subsequent increase in DO is usually referred to as a "DO sag."

PREVIOUS DATA

Previous investigations by other agencies and individuals provide data for comparison with the DO data from the present study and provide a possible indication of changes over the years. Sample collection by these earlier investigators, however, was random with respect to tides and time. Significant DO data from the survey made by the Engineering Department of the City of Seattle during the period November 1948–April 1950 (table 3) show monthly mean values of DO in milligrams per liter and of percentage saturation for the four stations that most nearly correspond with those for stations of the present investigation.

During the 1948–50 period the data show that a DO sag near the bottom was centered about the 16th Avenue South station 7.7, and the minimum DO concentration of 3.7 mg/l recorded during that study was found near the bottom at that location during August 1949. Although the surface samples show no sag, there is a steady decline in percentage saturation of DO in the surface layer in the downstream direction. The relationship between DO content and fresh-water inflow during the critical summer period (May–October) at 16th Avenue South for 1949 is shown in figure 23. Mean-daily fresh-water inflow during August and September 1949 was 262 cfs. Under the conditions of fresh-water flow during that survey, no serious oxygen depletion in the lower Duwamish River estuary was evident.

In the sanitary survey of the Green-Duwamish River made by the Washington State Pollution Control Commission during the summer of 1955 (Peterson and others, 1955), the river was sampled at 13 stations from Auburn (river kilometer 52.6) to the Spokane Street station (river kilometer 1.9). The samples were taken from the surface only, at approximately weekly intervals. The fresh-water inflow during the sampling period June–October (fig. 24) was greater than that during the previous (1948–50) investigation by the City of Seattle. Minimum DO concentrations observed on the surface also were higher than those of the previous investigation. The minimum DO concentration observed at station 7.7 during the study by the Pollution Control Commission was 6.0 mg/l.

During the investigation in the summer and fall of 1956 by R. W. Okey (written commun., 1957), samples were taken from the top

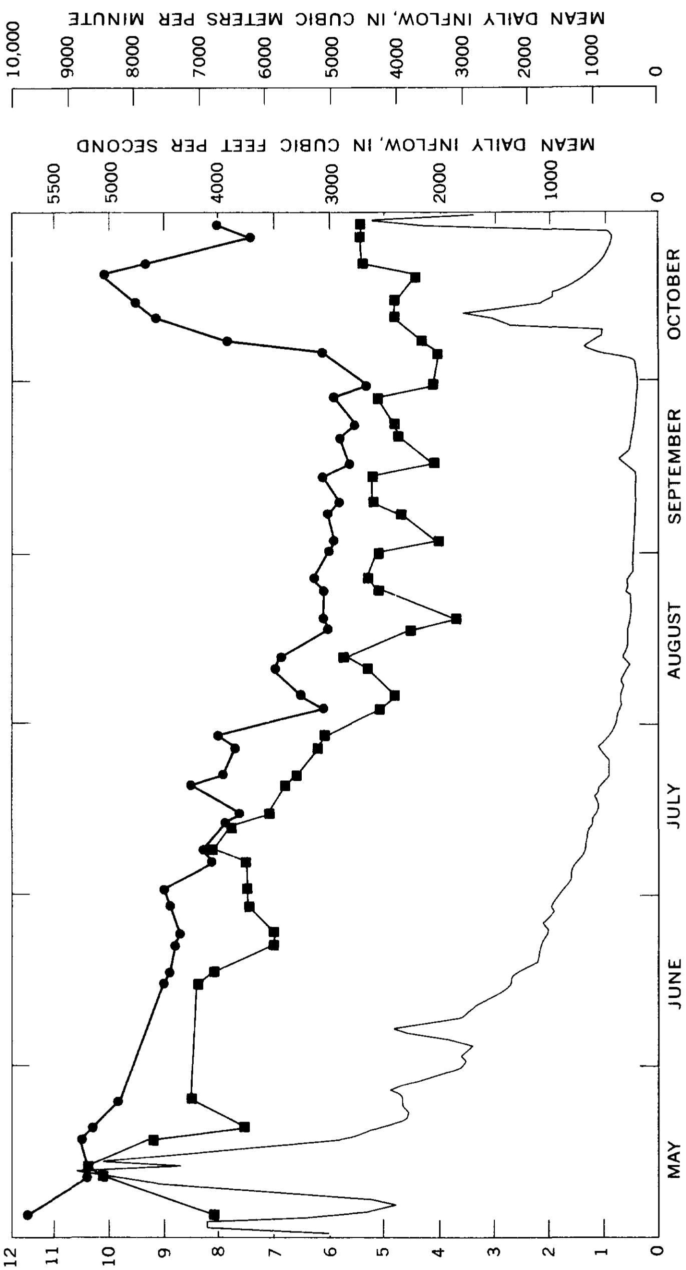


FIGURE 23.—Fresh-water inflow and DO content at station 7.7, May–October 1949. Circles, DO at the surface; squares, DO at the bottom; solid line, fresh-water inflow.

TABLE 3.—*Monthly mean DO in near-surface and near-bottom*

[Reported from previous studies as follows: November 1948–April 1950 by City of Seattle; by R. W. Okey

Year	Month	Station 12.6				Station 9.5			
		Surface		Bottom		Surface		Bottom	
		mg/l	Percent saturation at field temperature	mg/l	Percent saturation at field temperature	mg/l	Percent saturation at field temperature	mg/l	Percent saturation at field temperature
1948	November	10.9	89	....	....	9.5	80	....	....
	December	11.6	89	....	....	11.2	84	....	....
1949	January	12.2	90	....	....	11.6	85	....	....
	February	11.0	86	....	....	10.6	84	....	....
	March	11.0	90	....	....	10.7	72	....	....
	April	11.0	94	....	....	10.9	94	....	....
	May	10.7	94	11.4	98	10.5	92	9.0	84
	June	9.1	87	8.6	84	8.9	85	7.6	80
	July	8.2	82	8.1	80	8.1	83	7.1	76
	August	6.8	71	6.4	68	6.3	68	5.0	55
	September	6.9	69	6.8	69	5.8	61	4.7	52
	October	9.6	83	8.9	78	8.4	76	4.8	48
	November	10.1	87	9.1	79	9.4	82	5.2	53
	December	11.3	89	10.7	84	10.7	85	6.4	62
1950	January	11.9	86	11.8	86	11.9	87	7.5	67
	February	11.3	90	11.1	88	11.1	89	8.2	76
	March	10.8	88	10.7	86	10.7	88	8.4	78
	April	11.0	93	10.9	91	10.7	91	9.2	86
1955	June	10.4	94	....	....	10.2	95	....	....
	July	9.1	88	....	....	9.0	88	....	....
	August	7.6	80	....	....	7.0	77	....	....
	September	7.3	72	....	....	6.3	67	....	....
	October	9.4	86	....	....	8.4	78	....	....
1956	July	8.1	85	7.8	86	8.0	86	7.1	78
	August	6.1	67	6.1	67	7.5	82	7.1	77
	September	6.1	63	6.0	62	6.1	66	5.7	61
	November	11.4	93	11.8	97	10.2	89	6.1	60

samples at selected stations on the Duwamish River estuary

June–October 1955 by Washington State Pollution Control Commission; July–November 1956 (written commun., 1957)]

Station 5.6				Station 1.9			
Surface		Bottom		Surface		Bottom	
mg/l	Percent saturation at field temperature	mg/l	Percent saturation at field temperature	mg/l	Percent saturation at field temperature	mg/l	Percent saturation at field temperture
10.0	85	....	....	8.8	78	....	....
10.9	84	....	....	10.3	85	....	....
11.3	84	....	....	10.0	80	....	....
10.4	84	....	....	10.0	84	....	....
10.7	90	....	....	10.5	89	....	....
10.8	94	....	....	10.4	92	....	....
10.4	92	7.9	79	10.1	92	8.4	83
8.6	85	7.9	84	8.4	85	8.4	89
8.4	86	7.3	79	8.3	87	7.6	80
6.2	68	5.5	61	6.4	72	5.9	66
5.8	62	5.1	57	5.7	62	5.7	64
7.9	74	5.1	55	7.0	68	5.5	59
9.2	82	5.5	56	8.6	78	5.9	60
10.3	84	6.6	66	9.9	83	7.0	69
11.6	85	7.4	71	11.2	84	8.0	75
10.7	86	8.0	76	10.6	86	8.4	79
10.6	88	10.5	73	10.6	88	9.1	83
10.7	92	8.9	83	10.5	91	9.5	87
10.0	93	....	....	9.6	94	....	....
8.8	88	....	....	8.3	86	....	....
7.0	75	....	....	6.8	79	....	....
5.9	62	....	....	5.8	66	....	....
8.2	75	....	....	7.4	73	....	....
8.2	91	7.5	82	7.6	84	7.4	80
6.8	78	6.5	71	6.6	73	6.0	65
5.7	62	5.5	59	5.2	56	5.4	57
10.2	89	6.1	60	6.7	63	6.4	63

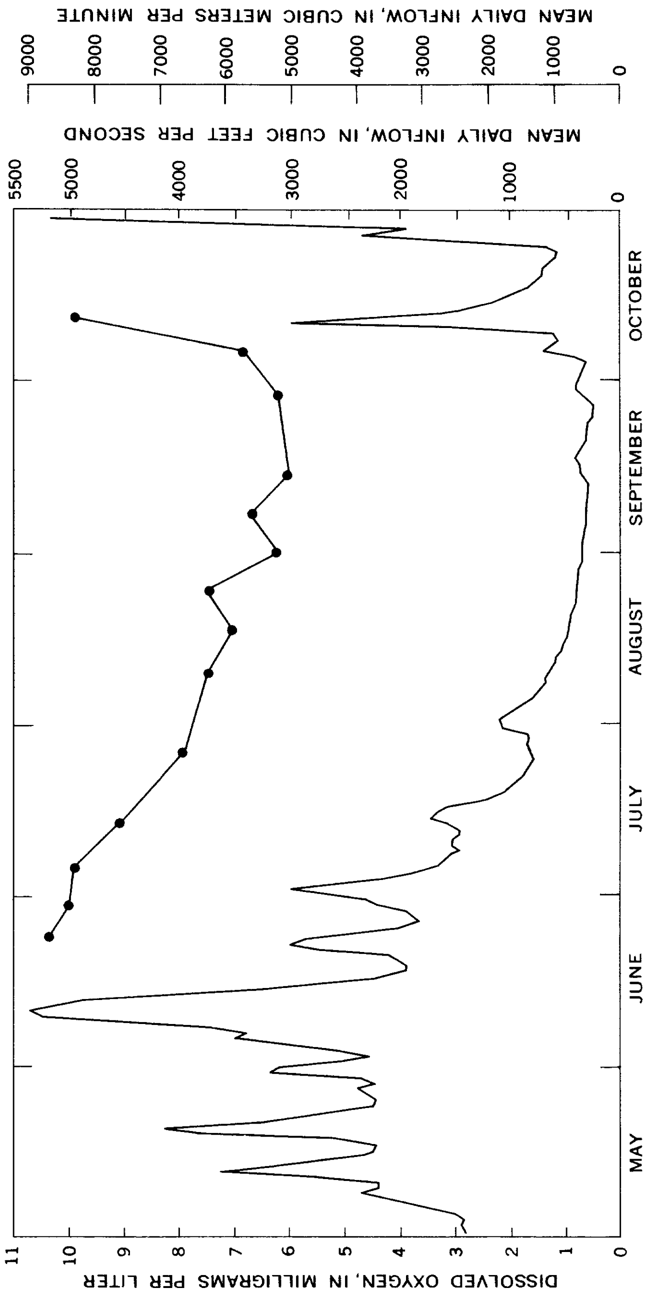


FIGURE 24.—Fresh-water inflow and DO content at station 7.7, May–October 1955. Circles, DO at the surface; solid line, fresh-water inflow.

and bottom at seven stations from 50.8 to 1.9 km above the estuary mouth at approximately biweekly intervals. The minimum observed DO, 4.9 mg/l, again occurred at station 7.7 and in the bottom layer (fig. 25). Mean fresh-water inflow during the critical period August–September was 258 cfs. Although fresh-water inflow was similar, the minimum observed DO was 1.2 mg/l higher in 1956 than the minimum observed by the City of Seattle 7 years earlier. This difference, however, probably is due mostly to the difference in sampling frequency. On the basis of the data available from the previous studies, therefore, no progressive decrease in DO content in either the upper (fresher) or lower (saline) layers of the estuary was apparent.

ANNUAL VARIATION

The present investigation has extended the collection of DO information through the period 1962–66; the data were collected by Metro and the Geological Survey. Monthly mean DO values for the years in which these data were available, at the sites where automatic water-quality monitors are presently located, are plotted in figure 26. The relationship of the DO level to fresh-water inflow can be clearly seen in this figure. Minimum DO conditions occur during periods of minimum inflow, and conversely, maximum levels occur during periods of maximum inflow. Figure 26 also suggests that the annual minimum DO concentrations in the study reach have generally declined since the pre-1960 studies. For example, lesser minimum values of DO are shown for all four sampling locations during 1965–66; even though minimum fresh-water inflow rates during those years were about the same as, or slightly greater than, those during 1949, 1955, and 1956. However, records are not sufficient yet to determine conclusively that the annual minimum DO levels in the Duwamish River are declining.

CORRELATION STUDIES

RENTON JUNCTION

The Renton Junction station (sta. 21.0) is the farthest upstream sampling point and provides the initial DO information for the study reach. Figure 27 shows the daily mean DO and the daily standard deviation for the period February–September 1966. The mean daily standard deviation is 0.35 mg/l of DO. The daily variation about the mean DO for this station is smaller than those for the other three automatic monitoring sites.

The daily mean DO between February and September 1966 was regressed against daily mean inflow, logarithm of daily mean inflow,

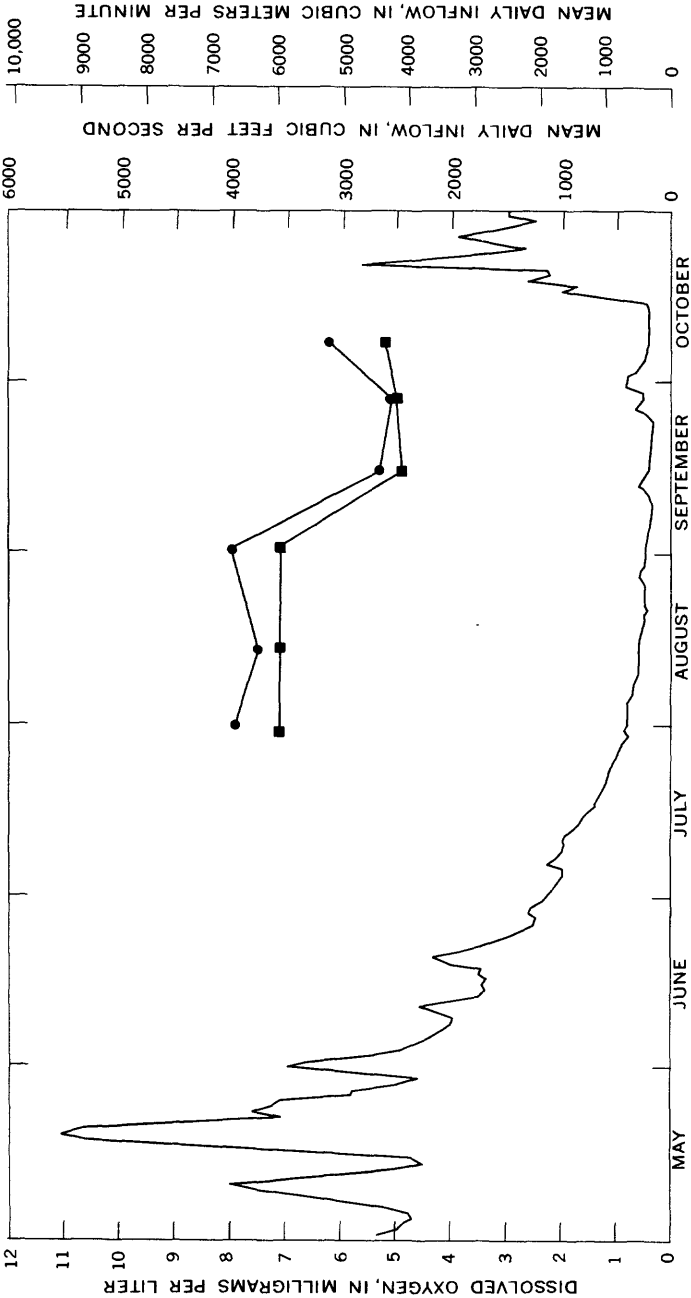


FIGURE 25.—Fresh-water inflow and DO content at station 7.7, May–October 1956. Circles, DO at the surface; squares, DO at the bottom; solid line, fresh-water inflow.

daily mean water temperature, and tidal-prism thickness. The water temperature and fresh-water inflow proved to be the most significant variables and are the only two used in the regression equation

$$\text{Daily mean DO (mg/l} = 8.79 - 0.09 \text{ temperature (°F)} + 2.01 \log_{10} \text{inflow (cfs)}.$$

The standard error of estimate for this regression analysis is 0.70 mg/l DO.

Concentrations of DO at this station have been considered to be adequate at all periods of discharge. Concentrations less than 6.0 mg/l are rare.

EAST MARGINAL WAY

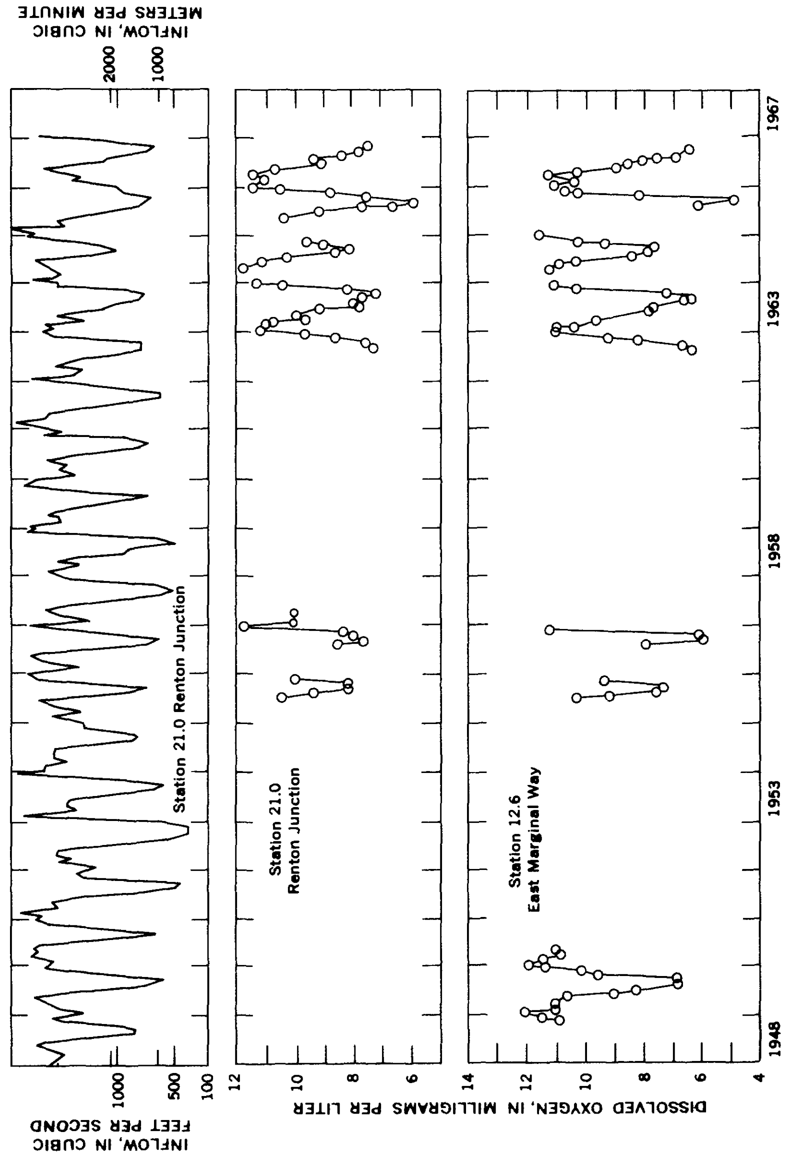
The station at East Marginal Way (sta. 12.6) is downstream from the Renton Treatment Plant. The presence of salt water at this location is dependent upon discharge and tide stage. Concentrations of DO here are generally less than at Renton Junction, 8.4 km upstream. The daily mean DO curve in figure 28 shows the seasonal trend of lower DO concentrations during the late summer months when the fresh-water inflow is low. The greater variability during late summer, however, is due largely to the influence of salt-water intrusion. The minimum DO concentration is rarely less than 4.0 mg/l. Using the same independent variables (fresh-water inflow and temperature) against daily mean DO, regression analysis was performed on the data for February to September 1966. The standard error of estimate is 1.04 mg/l for the regression equation

$$\text{Daily mean DO (mg/l} = 5.16 - 0.08 \text{ temperature (°F)} + 2.73 \log_{10} \text{fresh-water inflow (cfs)}.$$

The deviation of the daily mean DO is only slightly greater than that obtained for the Renton Junction data.

SIXTEENTH AVENUE SOUTH

DO samples at station 7.7 at 16th Avenue South were taken from both top and bottom waters. Surface DO concentrations at this station generally are less than those at the upstream stations except during periods of phytoplankton bloom, when they may be greater. Concentrations as great as 13.2 mg/l have been recorded at the surface during bloom conditions. Minimum surface DO concentrations during the bloom have declined to as low as 2.5 mg/l; mean surface DO concentrations, however, are rarely less than 3.0 mg/l. Multiple-regression analysis suggests that fresh-water inflow and temperature are the major variables contributing to the variations in surface DO concentration. Daily mean DO and standard deviation for the February–September 1966 data are shown in figure 29.



INFLOW, IN CUBIC METERS PER MINUTE
2000
1000
INFLOW, IN CUBIC FEET PER SECOND
1000
500
100
Station 21.0 Renton Junction
Station 21.0
Renton Junction
Station 12.6
East Marginal Way
DISSOLVED OXYGEN, IN MILLIGRAMS PER LITER
12
10
8
6
14
12
10
8
6
4
1948
1953
1958
1963
1967

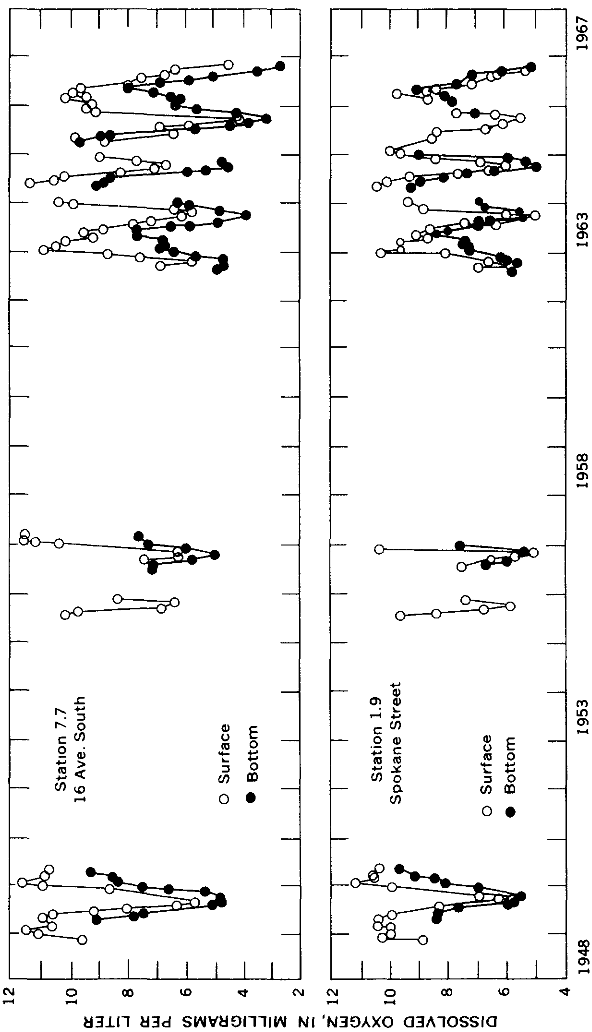


FIGURE 26.—Fresh-water inflow for the period 1948–66, and monthly mean DO content at selected stations for periods of data collection.

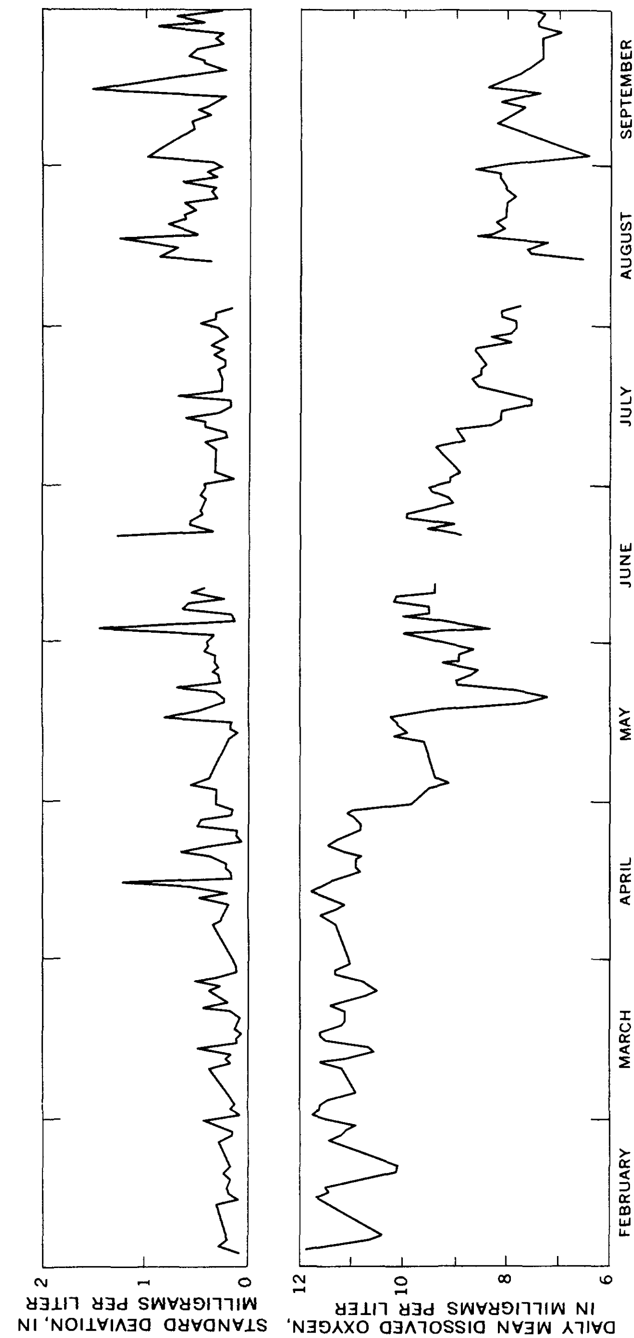


FIGURE 27.—Daily mean DO content and daily standard deviation at station 21.0 for period of available data, February–September 1966.

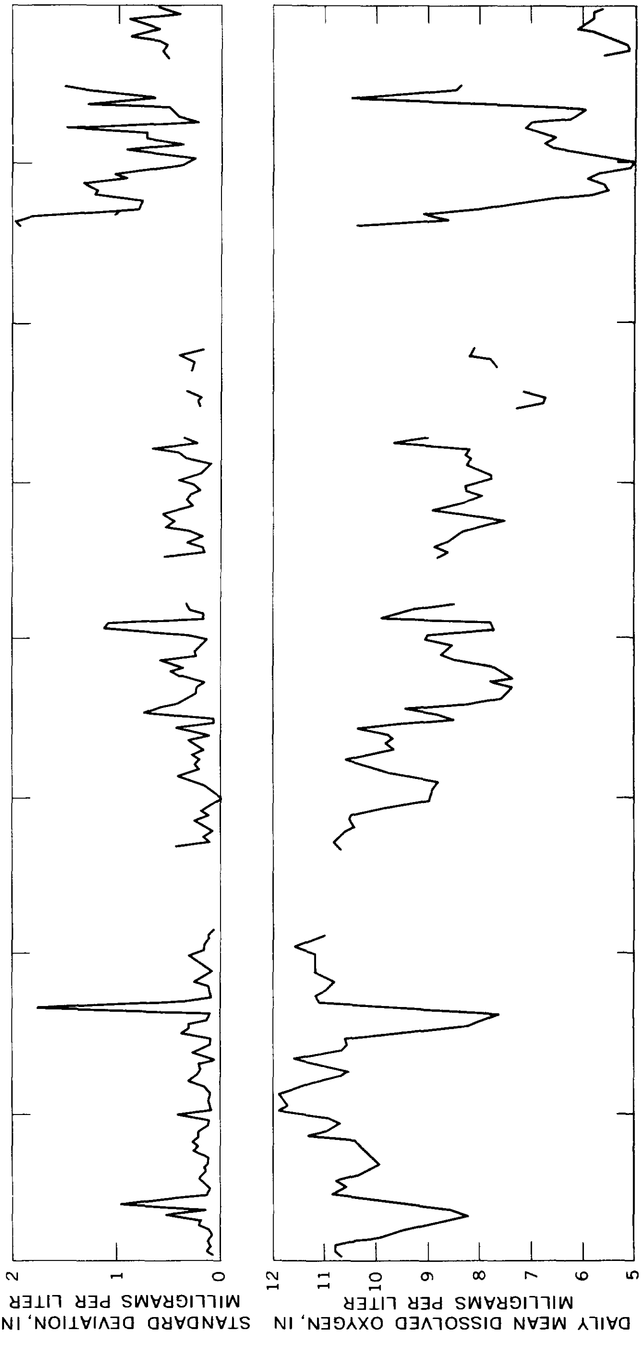


FIGURE 28.—Daily mean DO content and daily standard deviation at station 12.6, for period of available data, February–September, 1966.

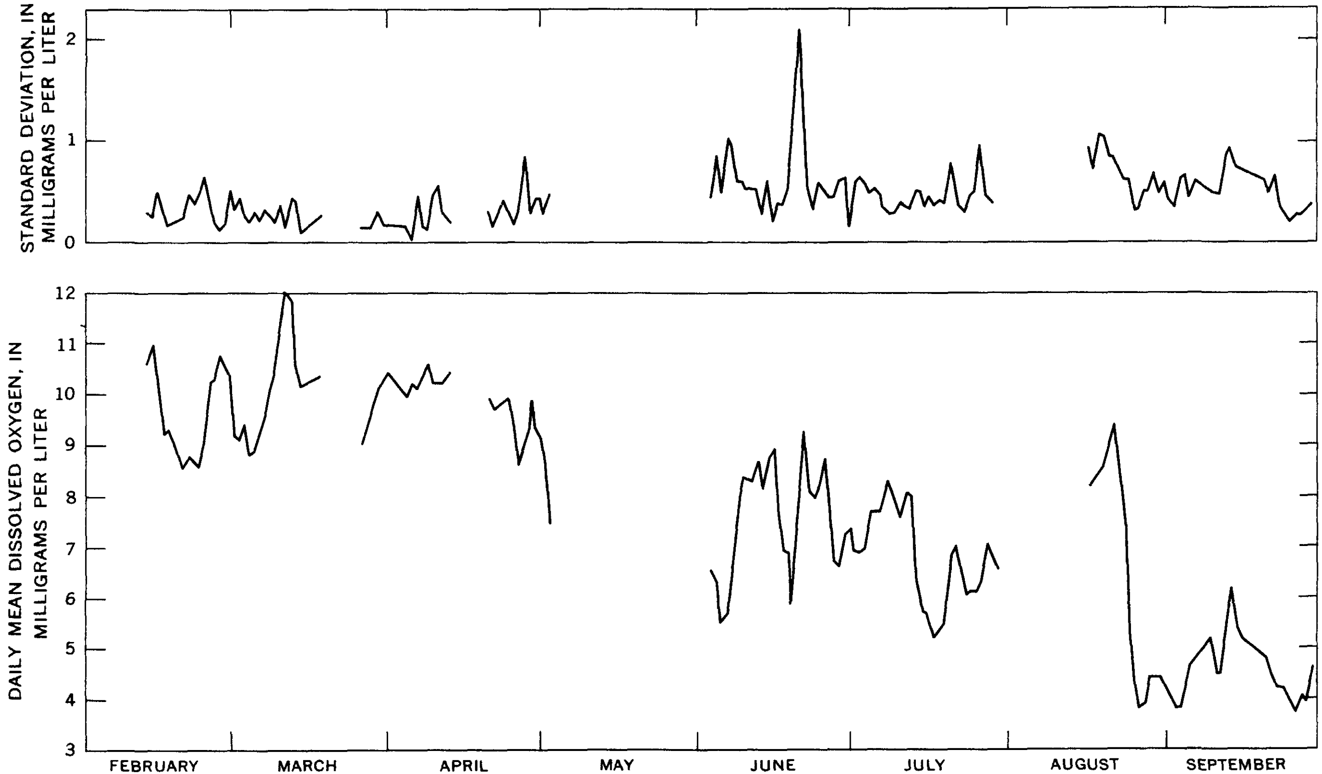


FIGURE 29.—Daily mean DO content and daily standard deviation at the surface at station 7.7, for period of available data, February—September 1966.

Deviation of DO concentrations from the daily mean at this station was the highest of all of the four surface-sampling stations. Mean daily standard deviation here was 0.47 mg/l.

The bottom DO samples taken at this station are from the area of minimum DO conditions in the estuary. Daily mean DO concentrations of less than 2.0 mg/1 and minimum concentrations as low as 0.8 mg/l have been recorded during the late summer months of low fresh-water inflow. The February–September data for the bottom samples are plotted in figure 30. The mean daily standard deviation (0.79 mg/1) here is the highest recorded for all the sampling locations.

Multiple-regression analysis indicates that bottom DO concentrations in this part of the estuary can be estimated from the tidal-prism thickness and fresh-water inflow. The standard error of estimate for the regression equation is 0.61 mg/l.

$$\text{Daily mean DO (mg/l)} = (-12.45) + 0.18 \text{ tidal-prism thickness (ft)} + 5.26 \log_{10} \text{inflow (cfs)}.$$

SPOKANE STREET

The Spokane Street station, at river kilometer 1.9, is the farthest downstream DO monitoring site. Samples are collected for DO from both the surface and bottom at this location. Mean surface DO concentrations there also generally were less than those at the upstream surface-sampling stations. Figure 31 shows a plot of the available 1966 daily mean DO data from the surface samples at this station. Surface DO concentrations generally followed the annual streamflow patterns, with minimums generally occurring during the late summer months. Daily mean concentrations of less than 3.0 mg/l were rare. As at the other stations, the major factors influencing the surface DO concentrations at the Spokane Street station were fresh-water inflow and water temperature. The variation about the daily mean DO concentration was of the same order as for the Renton Junction and East Marginal Way stations.

Bottom DO concentrations at the Spokane Street station were greater than the bottom concentrations upstream at 16th Avenue South; summer minimums here usually exceeded 2.0 mg/l and rarely declined to 1.0 mg/l. Daily mean data for February to September 1966 are plotted in figure 32. Here again the bottom DO concentrations could be estimated from the fresh-water discharge and tidal-prism thickness.

AREA OF CRITICAL DISSOLVED OXYGEN

Minimum DO conditions occurred near the bottom of the estuary between river kilometer 7.7 (16th Avenue South) and river kilome-

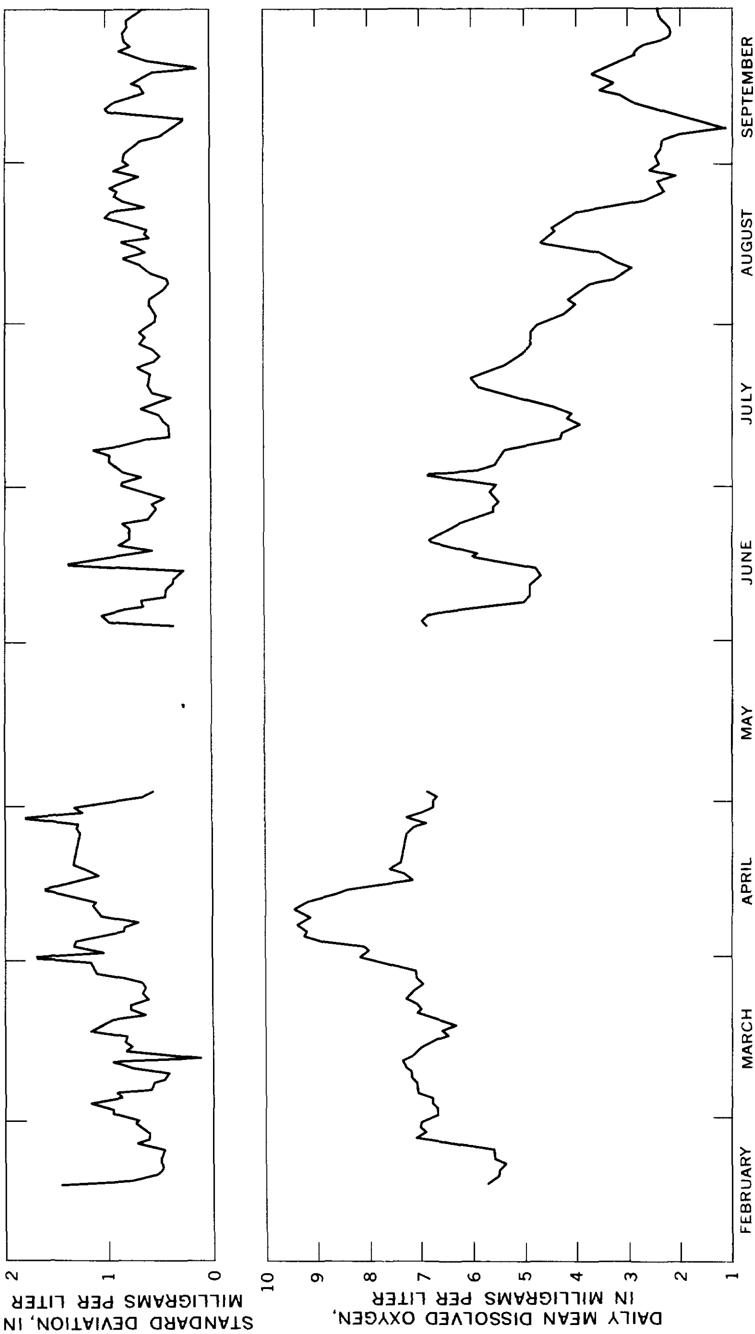


FIGURE 30.—Daily mean DO content and daily standard deviation at the bottom at station 7.7, for the period of available data, February–September 1966.

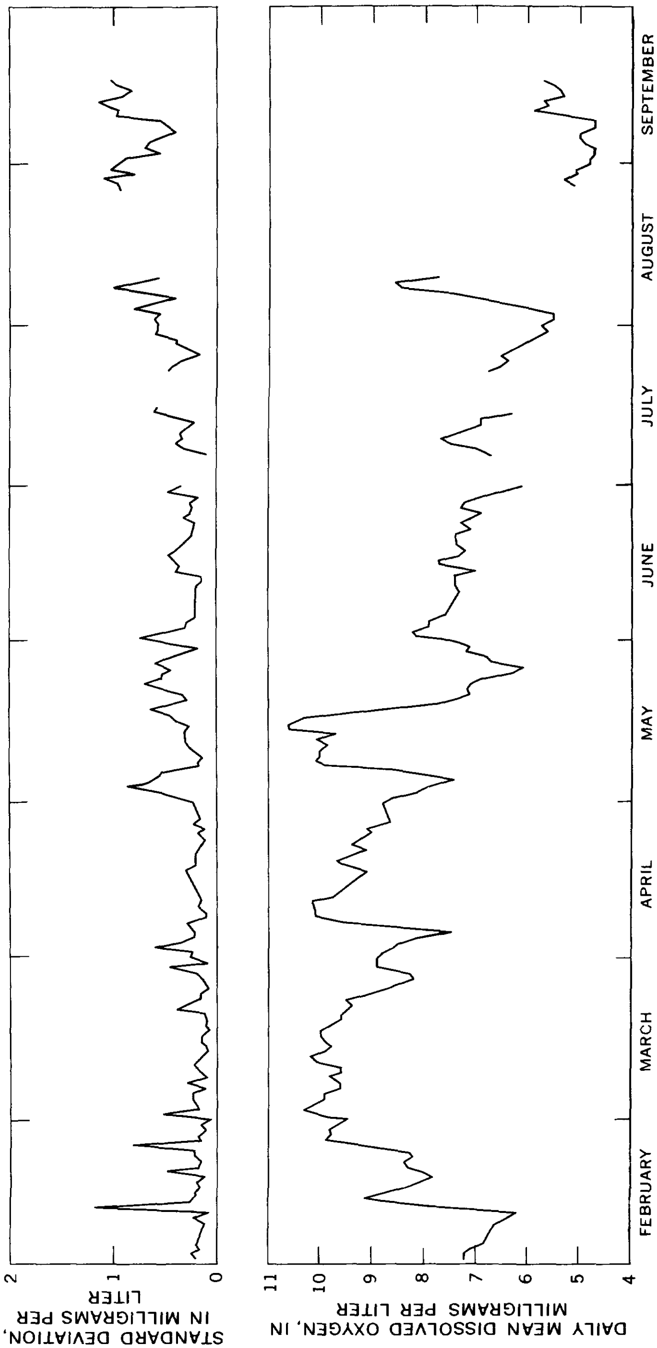


FIGURE 31.—Daily mean DO content and daily standard deviation at the surface at station 1.9, for the period of available data, February–September 1966.

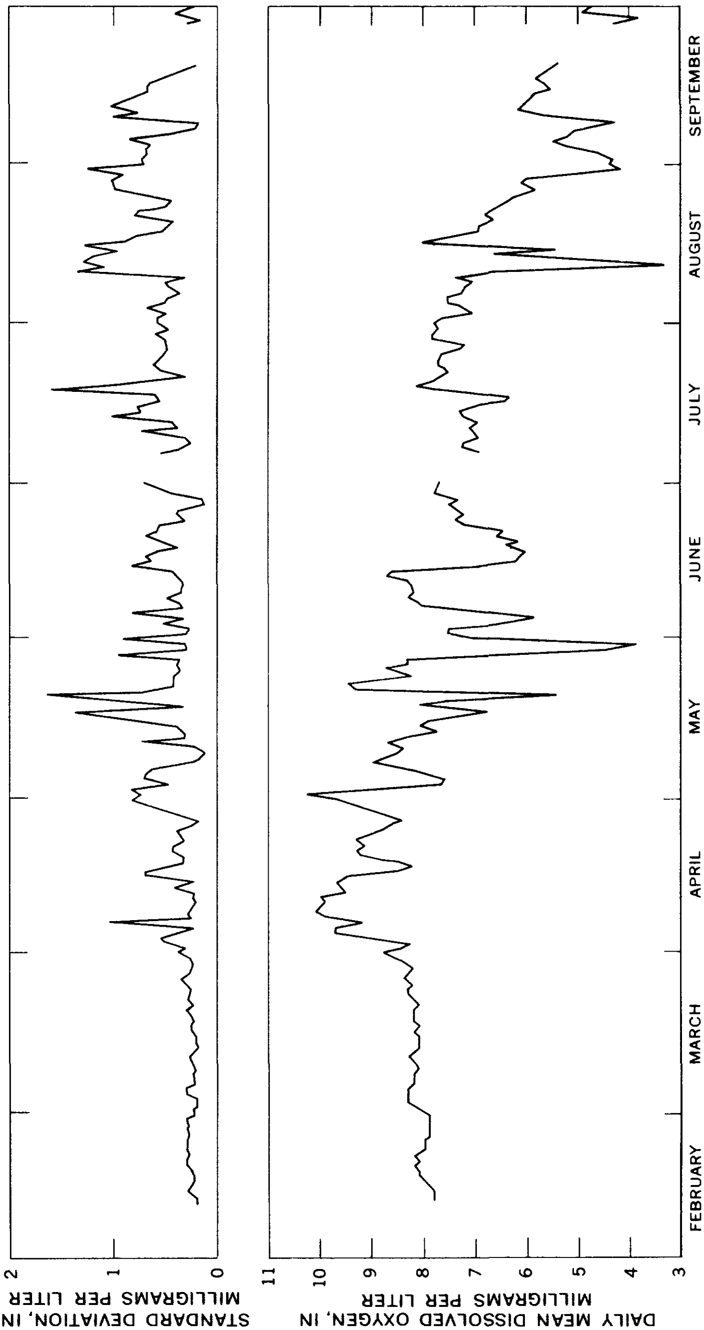


FIGURE 32.—Daily mean DO content and daily standard deviation at the bottom at station 1.9, for the period of available data, February–September 1966.

ter 10.4 (Boeing Bridge). Very low DO conditions occurred during the late summer months only when fresh-water discharge was less than 400 cfs. Although streamflow rates play a highly significant role, minimum tidal exchange must occur concurrently with low flow to produce the very low DO conditions. The length of time that the flow rate remains less than 400 cfs is also quite important. The longer the flow remains below this rate, the lower will be the minimum DO concentration. The mean daily inflow, tidal-prism thickness, and minimum daily DO concentration of bottom water at river kilometer 7.7 for June to September 1966 are plotted in figure 33. This figure shows the important influence of the duration of a period of inflow at rates less than 400 cfs. The figure also shows that

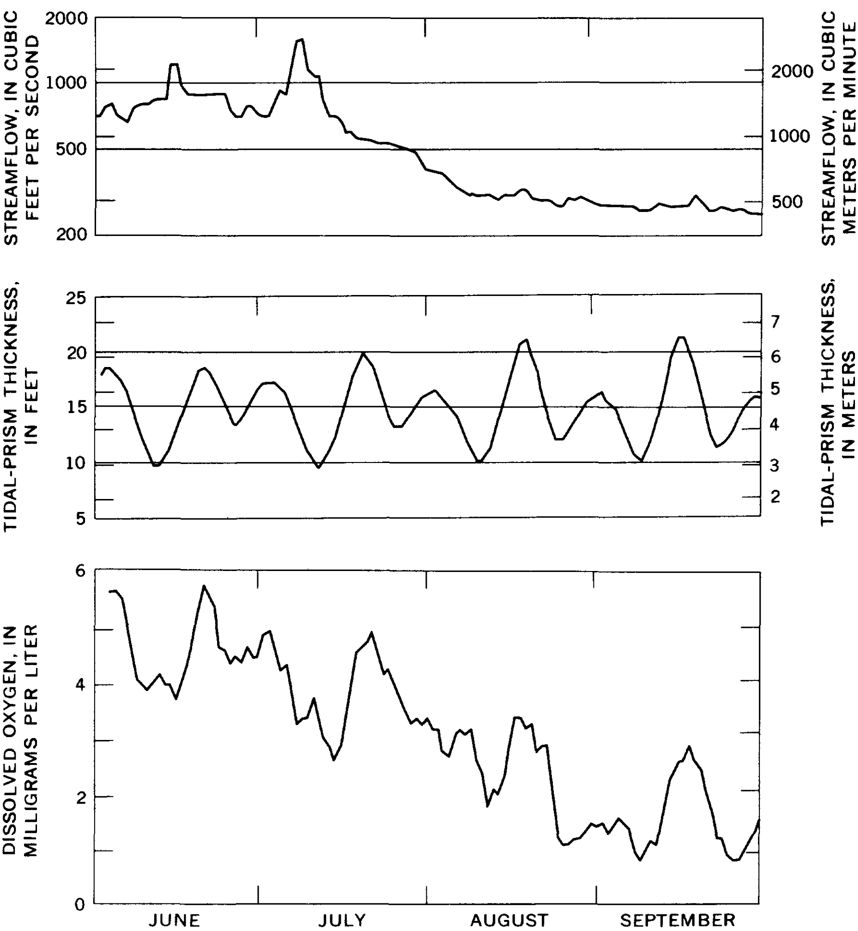


FIGURE 33.—Mean daily fresh-water inflow, tidal-prism thickness, and minimum bottom DO, at station 7.7, June–September 1966.

the cyclic variation in DO concentration corresponds very well to the variation of the tidal-prism thickness, for the lower minimum concentrations coincide with the days of minimum tidal exchange.

The minimum possible DO concentrations apparently are related to the retention time. As described previously, the bottom water is removed by entrainment into the upper layer with little or no mixing of the surface layer downward. This method precludes any reaeration by downward mixing. When the lower rates of fresh-water inflow coincide with minimum tidal exchange, removal of bottom waters by entrainment is reduced, and retention time of the contained oxygen-demanding materials is increased. However, because the quantitative relation between minimum DO and retention time in the estuary has not been firmly established, this relation is undergoing further investigation.

PHYTOPLANKTON

Frequently the introduction of nutrients (nitrogen and phosphorus compounds) into an aquatic environment has caused nuisance blooms of phytoplankton. A study of the factors controlling phytoplankton growth in the estuary was made to evaluate the influence of the effluent from the Renton Treatment Plant. The following material on phytoplankton is summarized from a comprehensive report by Welch (1969).

Phytoplankton blooms occurred in August 1965 and 1966 after the discharge of effluent from the Renton Treatment Plant started in June 1965. A pre-effluent bloom in 1963 is indicated by supersaturated oxygen values that occurred at station 7.7 in the euphotic zone (upper, light-receiving zone). No bloom occurred in 1964 when summer fresh-water inflow was twice as large as the summer inflow during bloom years. Chief factors observed to control the occurrence of a bloom in the estuary are fresh-water inflow rate, tidal-prism thickness, water temperature, and solar radiation.

Nutrient concentrations do not control the occurrence of the bloom inasmuch as nitrogen and phosphorus compounds always are present in sufficient quantities for a bloom to exist. Also, because no noticeable decrease in nutrient concentration was observed during the bloom, it is apparent that nutrient limitation was not the cause of the bloom decline. An increase in nurients, however, may increase the biomass produced during the bloom.

Retention time during the warm season probably is more significant in triggering a bloom. A low fresh-water inflow rate and small tidal-prism thickness increase retention time. If this combination happens during a period when solar radiation is optimum, the surface-water temperature increases and causes thermal stratification. The stratification decreases the mixing depth and increases the amount of light available for plankton cells, and a bloom occurs.

Welch and Isaac (1967) demonstrated that chlorophyll *a* is a good indicator of phytoplankton productivity in the Duwamish River estuary. Figure 34 shows the hydrographic conditions during the 1965 and 1966 blooms, which are indicated by large chlorophyll *a* concentrations at station 7.7. Figure 34 shows that the same hydro-

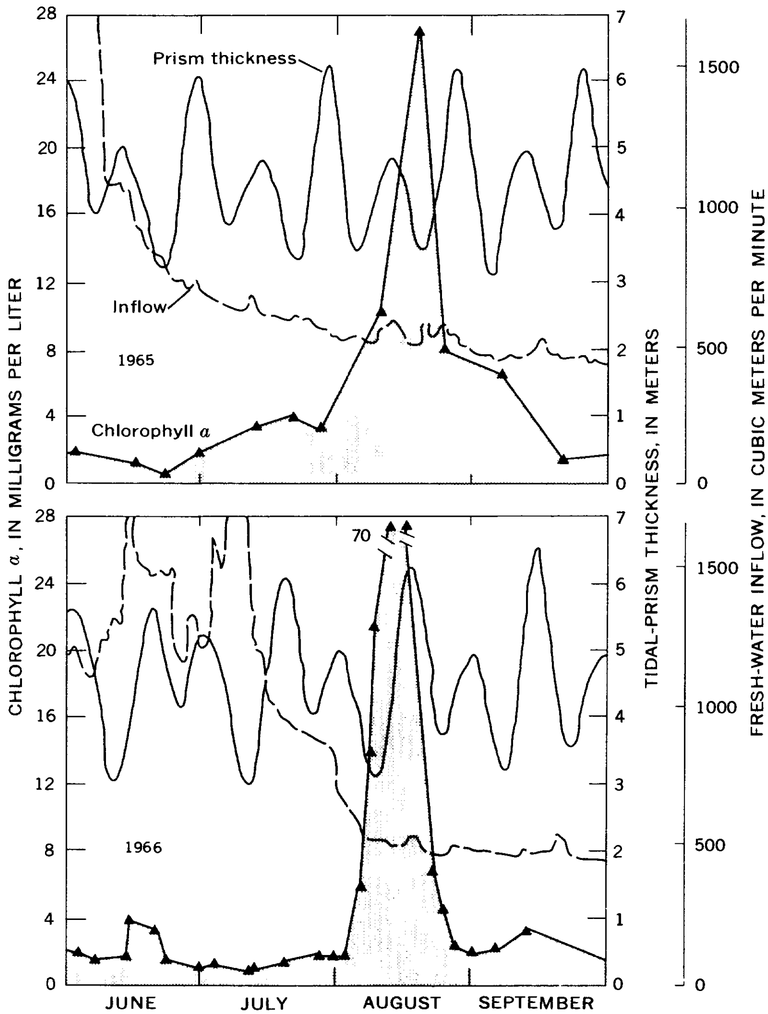


FIGURE 34.—Relation of phytoplankton bloom-time, as indicated by chlorophyll *a* concentration to fresh-water inflow and tidal-prism thickness, during 1965 and 1966 (after Welch, 1969).

graphic conditions that occurred in August of both years were repeated in September of both years, but the small chlorophyll *a* values in September 1965 and 1966 indicate that no blooms occurred during either September. The lack of a September bloom probably was due to the fact that solar radiation and surface-water temperature both were much less in September than in August.

Welch (1969) concluded that effluent from the Renton Treatment Plant probably was not the sole cause of the phytoplankton blooms but that the increase in nutrients from the plant could increase the biomass of the blooms. The relations he described between chlorophyll *a* and BOD show that phytoplankton both alive and dead may be an important source of BOD in the estuary. If the effluent from the sewage treatment plant increases the bloom biomass, it could result in a greater BOD, and the greater BOD would further decrease the DO content of the bottom water.

The present (1967) program is oriented toward a better understanding of what environmental factors control the magnitude and timing of the phytoplankton bloom. Some of these factors, such as tidal-prism thickness, fresh-water inflow, solar radiation, and water temperature, are relatively easy to determine but are difficult to relate to the blooms, particularly to their influence on the magnitude of the bloom. The role of the nutrients from the Renton Treatment Plant is made even more obscure, of course, because those nutrients are superimposed upon the various nutrients from other sources that are present in the estuary.

BIOCHEMICAL OXYGEN DEMAND

EXPERIMENTS

As stated in the discussion of methods and equipment, a part of this investigation was devoted to experiments seeking methods of determining BOD values that would closely represent conditions in the estuary.

Because the four automatic-monitor water-quality stations have a continuous source of river water, incubation of BOD samples at river temperature was determined to be more nearly representative than the laboratory procedure. Incubation troughs were constructed and installed at the four monitor stations. (See section on "Special Equipment.") Many of the initial experiments, however, failed because of pump failure, and there was some difficulty in making the BOD bottles lightproof.

In the tests a 4-liter sample was taken in a sampler and subdivided into an initial-DO sample, 10 BOD samples, and a second initial-DO sample at the end of sample drawoff. For the next 5 days the DO content was determined on a sample air at 1-day intervals. The average DO concentration for the two samples then was used to plot the DO uptake for 5 days. The graphical method of Thomas (1960) for determining the ultimate first-stage BOD demand was tried, but the plots of DO uptake versus time were poor, mainly because BOD values were small in comparison to possible errors in determining the residual DO in the BOD sample.

Large differences in BOD values between the two samples of a pair were noted occasionally. One reason for this could be that while the samples were being drawn off, some settling of particulate organic material could take place, so that some samples received more biodegradable substances than did others. An experiment was made to determine what influence the order of sample withdrawal from the sampler had on the BOD value found. A sample was collected at Renton Junction (sta. 21.0) and, after agitation, eight consecutive BOD samples were drawn off and incubated for 5 days. The time taken to draw off the eight BOD samples was less than 2 minutes and, except for very heavy material, only a very small amount of settling could have taken place during that short time. Samples 1, 3, and 8 have BOD values above the median (0.30 mg/l), and samples 4, 5, and 7 had values below the median. The maximum BOD was 0.90 mg/l (sample 1), and minimum was 0.10 mg/l (sample 4). The results did not show any correlation of BOD with the order of sample withdrawal.

The negative results of these tests led to another experiment wherein the samples were collected from nine stations in the estuary rather than from just one. As before, the sample was divided into an initial-DO sample, eight consecutive BOD samples, and another initial-DO sample. In addition, a sample was taken at the same time for a determination of specific conductance. Results were similar to those from the previous test and show what variation in BOD values occur when a 4-liter sample is subdivided. Figure 35 shows the minimums, maximums, and means for the nine sets of samples. The greatest variation between subdivided samples occurred in the sample collected at station 17.9 and the least variation occurred in the sample collected at station 1.9 from 3 feet above the bottom. Although the specific conductance increased progressively in a downstream direction, no correlation was apparent between BOD and specific conductance.

One influence on BOD was found to be the initial DO in the BOD sample. Aerated and unaerated samples gave different results. In unaerated samples which had an initial DO of less than 4 mg/l, the average BOD was 1.5 mg/l. The average BOD for aerated samples was 2.6 mg/l. Zobell (1940, p. 218) suggested that this type of relation was due to the fact that, during the period of incubation,

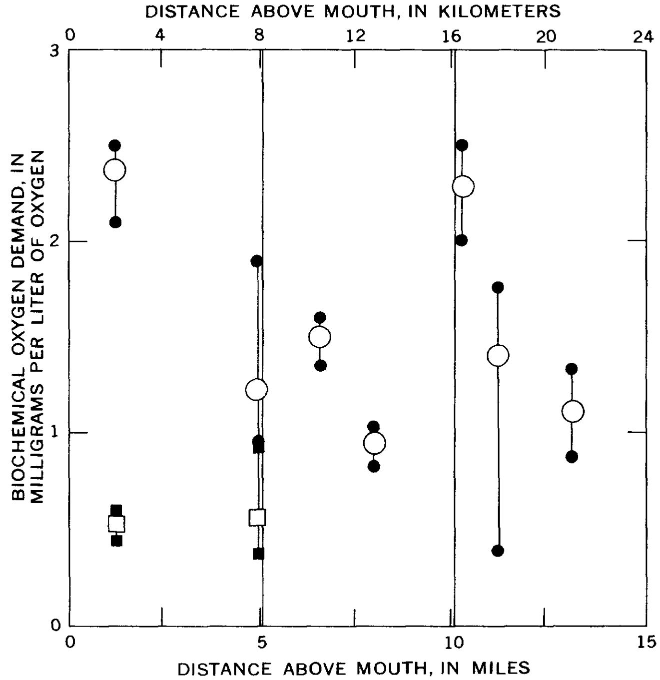


FIGURE 35.—Variation of minimum, mean, and maximum BOD to distance above river mouth, at a mean daily inflow of 710 cfs. Black circles, surface samples; black squares, bottom samples; open circles and squares, mean values for surface and bottom samples, respectively.

the bacteria were using oxygen faster than it could diffuse into localized microspheres of oxidizable material.

The preceding discussion indicates that accurate data on the BOD actually occurring in the river are very difficult to obtain; therefore, the data presented in this section should be considered as only semiquantitative.

LONGITUDINAL PROFILES

Figure 36 shows selected longitudinal BOD profiles for rates of fresh-water inflow ranging from 293 to 1,760 cfs.

The figure indicates that below station 21.0 surface BOD increases downstream and generally reaches a maximum near or between stations 12.6 and 17.9. The increase can be attributed to waste discharges into the river upstream from station 12.6. The increase is small, with the maximum observed (1.9 mg/l) occurring between stations 21.0 and 12.6. Downstream from station 12.6 the surface BOD decreases or remains about the same when fresh-water inflow rates are large (figs. 36 *A*, *F*). When fresh-water inflow

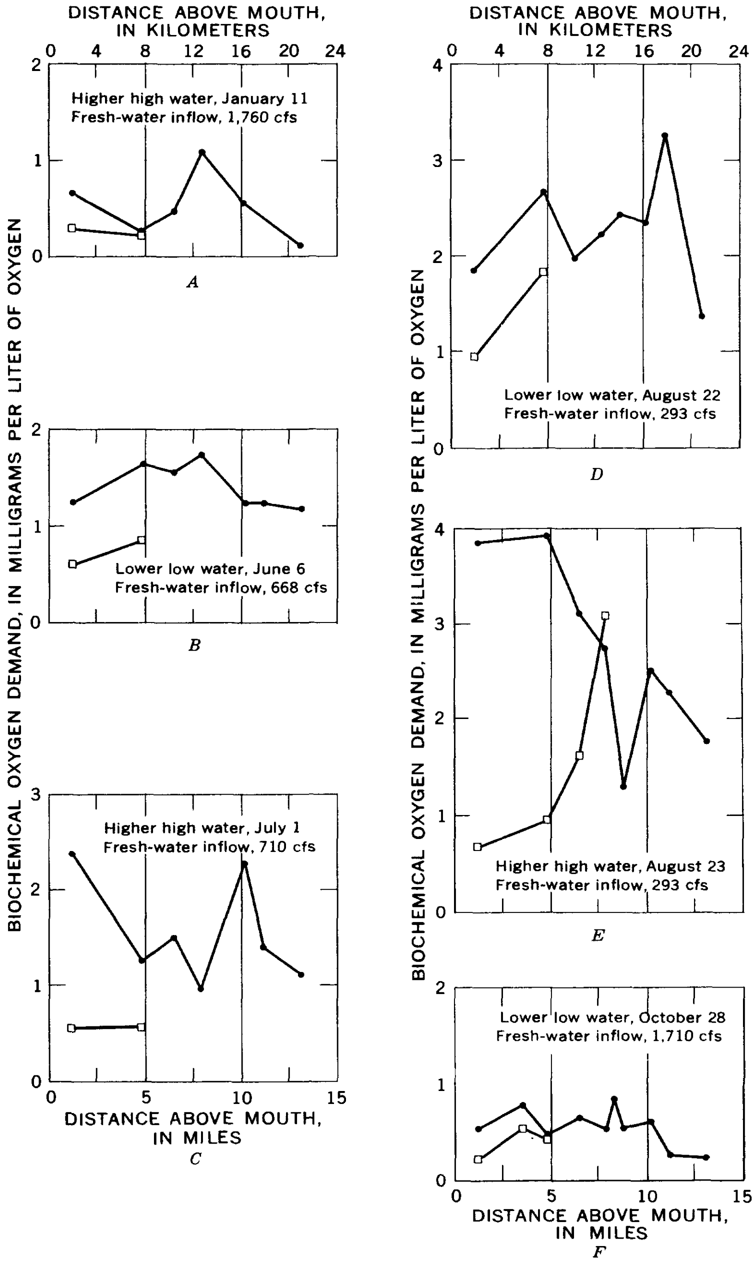


Figure 36.—Longitudinal distribution of BOD at higher high water or lower low water at various rates of fresh-water inflow, January–October 1966. Circles, surface BOD; squares, bottom BOD.

rates are large and water temperatures are cold, the bottom BOD values are small (figs. 36 *A–C*, *F*). When inflow rates are moderate or small, the effect of tides is apparent.

Figures 36*B* and *C* show the effect of tide when fresh-water inflow is moderate. At low tide (fig. 36*B*) the surface BOD shows a slight decrease downstream from station 12.6. Figure 36*C* shows a fairly rapid downstream increase in the surface BOD, reflecting a "compression" effect of the high tide. Under the conditions represented by that figure, the maximum surface BOD occurred at station 16.2, whereas at low tide (fig. 36*B*) the maximum occurred 3.6 km farther downstream at station 12.6. The relatively large surface BOD (about 2.4 mg/l) at station 1.9 (fig. 36*C*) represents water returning from the previous ebbtide that contained wastes discharged into the estuary by industries downstream from station 1.9. To a lesser degree this also is shown in figure 36*A*.

Figures 36*D* and *E* show the increase in BOD values observed during the die-off stage of a phytoplankton bloom. (See fig. 34.) Although part of the BOD increase is due to planktonic material from the bloom, the decreased fresh-water inflow during late summer also is responsible for part of the observed increase. The maxi-

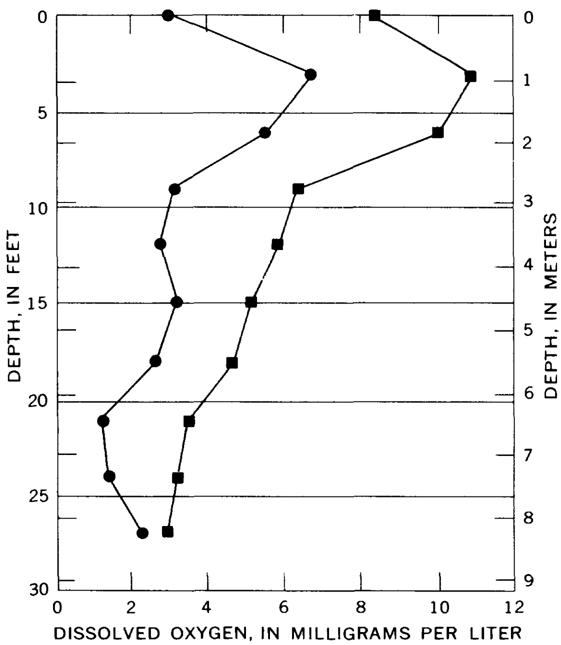


FIGURE 37.—Vertical distribution of DO (squares) and BOD (circles) at station 9.5 during a phytoplankton bloom, August 9, 1966.

mum BOD in the bottom layer (about 3 mg/l) was observed at station 12.6 (fig. 36*E*). Maximum bottom values occurred when minimum tidal-prism thickness coincided with low fresh-water inflow; under these conditions, water velocities are not large enough to prevent the organic detritus from settling to the bottom. A device has been constructed for sampling the amount of detritus that settles to the bottom. Hopefully, the analyses of samples thus collected will define the amount of BOD in detritus and will help to delineate the hydrographic conditions needed for the maximum settling rate of detritus.

Although BOD values are generally greater for the surface layer than for the bottom layer, the DO in the surface layer is considered adequate for the maintenance of aquatic life. Figure 37 shows the relation of DO and BOD to depth at station 9.5.

The bottom water, on the other hand, receives virtually no additional DO except for small quantities that diffuse downward from the water above. Therefore, even though BOD is small in the bottom water, the DO can be depleted to values considered detrimental to aquatic life because the bottom water is essentially unaerated. (See p. C47.)

CHEMICAL CHARACTER OF THE FRESH WATER

MAJOR CONSTITUENTS

In a river basin in its pristine state the dissolved-solids content of the waters traversing the basin is controlled largely by the geology of the basin and by the precipitation. In general, man's activities in a watershed increase the dissolved-solids content by such influences as municipal and industrial waste disposal, changes in overland drainage, and changes in land-use patterns.

Chemical-quality data have been collected routinely at four locations in the Duwamish River basin (fig. 3) and have been published by the U.S. Geological Survey (1960–63, 1964, 1965, 1966). Selected comprehensive analyses of fresh-water samples from those stations are presented in table 4.

The analyses of the water of Green River at Palmer (table 4) indicates that the water comes from a near-pristine watershed. The water is a dilute calcium bicarbonate type. Silica is the major constituent, and nitrate and phosphate values are generally about what could be expected from an unpolluted stream (Hem, 1959, p. 117).

It can be seen from table 4 that mineralization increases progressively between the two downstream sampling stations (Green River near Auburn and Duwamish River at sta. 16.2). A similar downstream increase occurred between the Green River stations at Palmer to near Auburn. At the Auburn sampling site, chemical

TABLE 4.—*Chemical analyses of water at selected stations in the Duwamish River basin*

[Results in milligrams per liter except as noted]

Location	Mean discharge (cfs)	Date of *collection*	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Orthophosphate (as PO_4)	Dissolved solids (residue on evaporation at 180°C)	Hardness (as $CaCO_3$)	Specific conductance (micromhos at 25°C)	pH
Green River at Palmer ..	554	7– 8–59	13	5.5	0.5	2.4	0.1	22	1.6	1.2	0.1	0.4	0.02	36	16	44	7.3
	205	8–12–59	14	6.0	.8	2.6	.5	27	2.3	1.2	.1	.3	.00	38	18	54	7.4
	802	9–25–59	14	5.5	.3	2.5	.4	22	2.1	1.0	.2	.2	.03	38	15	45	7.2
	1,450	10–16–59	14	5.0	.5	2.4	.4	22	1.9	1.0	.1	.1	.00	36	14	43	7.0
	1,080	2–19–60	14	4.0	.9	2.1	.1	20	1.9	.8	.1	.2	.03	30	14	41	7.0
	2,220	3–22–60	13	3.5	.5	2.0	.1	17	2.3	.8	.1	.1	.03	32	11	34	7.3
Big Soos Creek above fish hatchery.	414	2– 6–63	12	8.0	2.5	5.4	1.0	31	11	2.5	.1	3.7	.06	68	30	88	7.0
	24	9– 3–63	19	10	3.5	4.8	.8	51	6.0	2.0	.3	.7	.06	76	40	101	7.4
	52	11–15–63	17	9.0	3.2	4.4	1.8	36	9.8	3.5	.2	3.0	.09	76	36	93	6.8
	313	1–14–64	12	7.5	3.2	5.2	1.0	36	9.2	2.5	.1	2.9	.04	64	32	91	7.1
	23	8–27–64	16	9.5	3.7	4.9	.9	50	6.2	2.0	.1	1.2	.07	71	38	101	7.5
	47	7–11–66	15	11	3.8	5.5	.8	53	7.4	2.0	.1	1.0	....	74	43	109	7.2
Green River near Auburn.	3,320	2– 6–63	13	5.0	1.2	2.9	.3	22	4.0	1.2	.1	1.1	.04	44	18	50	7.0
	260	9– 3–63	16	10	2.7	4.9	.9	47	4.8	3.0	.1	.8	.03	70	36	95	7.1
	695	11–15–63	14	6.5	1.9	3.7	.7	29	4.4	2.0	.1	1.5	.06	47	24	65	6.9
	1,760	1–14–64	14	7.0	1.3	3.4	.6	29	4.2	1.5	.0	1.7	.03	49	23	63	7.1
	970	8–27–64	13	9.0	2.7	4.4	.5	43	4.2	2.0	.0	1.2	.04	59	34	90	7.0
	1,020	7–11–66	12	6.3	1.6	3.4	.4	30	3.0	1.2	.1	.4	....	43	22	60	7.1
Duwamish River at Tukwila.	4,040	2– 6–63	13	5.5	1.6	3.6	.8	24	5.6	2.2	.1	1.1	.10	52	20	60	6.9
	309	9– 3–63	18	12	3.9	12	1.4	58	5.8	12	.1	1.8	.28	99	46	148	7.1
	755	11–15–63	15	8.5	3.0	4.7	1.7	34	9.8	3.5	.1	3.4	.18	71	33	94	6.7
	2,000	1–14–64	15	8.5	2.4	5.5	1.1	36	7.0	4.2	.1	2.9	.15	68	31	93	6.8
	450	8–27–64	16	12	3.9	13	1.1	59	5.6	15	.0	2.1	.19	97	46	162	7.0
	1,060	7–11–66	12	7.1	2.0	6.0	.8	34	3.8	4.8	.1	1.7	....	57	26	84	6.8

analyses of the 70 samples collected monthly since July 1959 show that the dissolved solids range in concentration from 33 to 71 mg/l and consist principally of calcium and bicarbonate.

The addition of surface-water inflow between Auburn and station 21.0 is chiefly from Big Soos Creek, which enters the Green River about 500 feet downstream from the Auburn sampling site. The discharge from Big Soos Creek averages less than 10 percent of the flow of Green River at Auburn. Although the dissolved-solids concentration in water of Big Soos Creek is larger than that in the Green River, the water also is of the calcium bicarbonate type, similar to that of the Green River (table 4). Although small in terms of tons, nitrate concentrations are generally greater in Big Soos Creek, because of considerably more human activity in that watershed than in the Green River watershed upstream from the Auburn station.

A long-term chemical-quality sampling site is at station 16.2, downstream from the outfall of the Renton Treatment Plant and on the reach of the Duwamish River that is affected by salt water. Data from station 16.2 show the water there to be slightly more mineralized than that from the Auburn station. During periods of low fresh-water inflow and high tides, traces of salt water (specific conductance values greater than 250 micromhos) have been detected as far upstream as station 17.9.

The salt water found in the downstream reaches of the estuary may be represented simply as various percentages of Elliott Bay water diluted by Green River water. A graph of specific conductance values versus chloride values (fig. 38) shows the linear relation between the two. The graph was used to estimate chloride values for correcting the DO values used in calculating percentage saturation of DO.

Nitrate in water is one of the indicators of pollution caused by man's activities and is a nutrient for the microorganisms in the estuary. Inspection of nitrate values (table 4) indicates that nitrate concentrations increase significantly between Auburn and station 16.2. To determine whether the increase was real or attributable to differences in rate of streamflow, the nitrate values were weighted with water discharge by the equation

$$\frac{\Sigma\ (\mathrm{mg/l\ NO_3})_1(\mathrm{cfs})_1+(\mathrm{mg/l\ NO_3})_2(\mathrm{cfs})_2+{*}{*}{*}+(\mathrm{mg/l\ NO_3})_n(\mathrm{cfs})_n}{\Sigma\ (\mathrm{cfs})_1+(\mathrm{cfs})_2+{*}{*}{*}+(\mathrm{cfs})_n}$$

where n=the number of samples.

A plot of the yearly nitrate values for the two sampling stations (fig. 39) indicates that nitrate values have increased slightly in

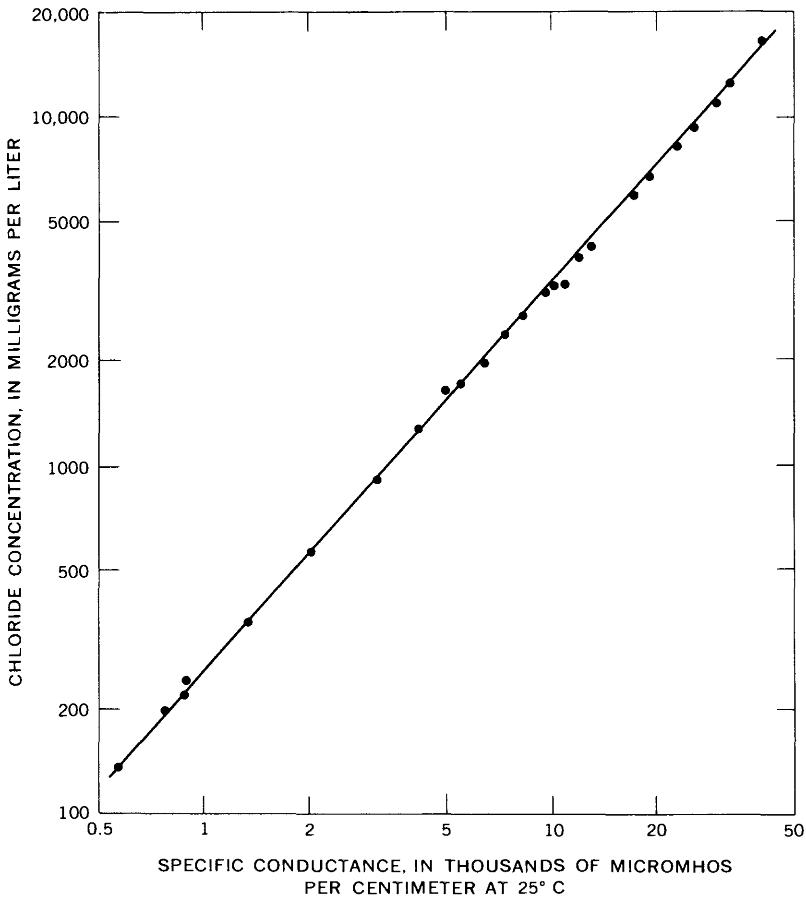


FIGURE 38.—Relation of chloride concentration to specific conductance in the Duwamish River estuary.

the Green River near Auburn since 1962 and progressively in the Duwamish River at station 16.2 since 1964. The indicated increase in nitrate concentration is attributed principally to wastes from increased industrial activity and to increased urbanization along this 46.7-km reach of the river, rather than from the Renton Treatment Plant effluent. Data from Metro (G. D. Farris, written commun., 1969) show that the average discharge of effluent from the plant during 1966 was 18.7 cfs and that the effluent had a discharge-weighted average nitrate concentration of 3.1 mg/l. At this rate and concentration, the effluent could have increased the discharge-weighted average nitrate concentration at station 16.2 by only 0.05 mg/l. Because the observed increase in nitrate concentration in the river between Auburn and station 16.2 was 1.4 mg/l in 1966,

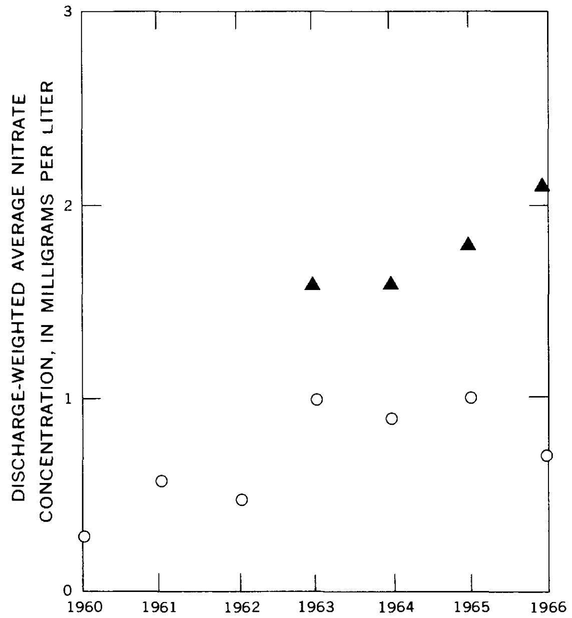


FIGURE 39.—Increase in discharge-weighted average nitrate concentrations. Circles, upstream concentrations in the Green River near Auburn; triangles, downstream concentrations in the Duwamish River at station 16.2.

the contribution from the Renton Treatment Plant could have accounted for less than 5 percent of the increase.

Plottings of discharge-weighted values of phosphate, another nutrient compound, failed to give significant results.

TRACE ELEMENTS

Trace elements, as defined in this discussion, are minor elements that usually are present in fresh or sea water in concentrations so low that they are measured in micrograms per liter. Only in recent years have investigators looked into the role that these minor constituents have in biological processes of fresh- and salt-water phytoplankton. Most studies have been in laboratories under controlled conditions and have used pure cultures of algae to determine whether a minor constituent is essential for algal growth. Wiessner (1962) presented an excellent sumary of what he called inorganic micronutrients (minor constituents). He points out the extreme difficulty of proving that a minor constituent is essential for algal growth.

Durum and Hafty (1961) presented trace-element data for principal rivers of the United States and Canada, and Livingstone (1963) gave trace-element data for rivers and lakes of the world. Their data indicate that large ranges in trace-element concentrations exist in many rivers. Sverdrup, Johnson, and Fleming (1942, p. 176–177) summarized trace-element data for sea water. The variation in concentrations of minor constituents in river water makes it extremely difficult to relate their occurrence to environmental parameters, such as precipitation.

In spite of the difficulties involved, it was felt that work should be done to determine if some relation existed between phytoplankton and minor constituents in the Duwamish River. As initially set up, the program of sampling for the minor constituents in the fresh water entailed defining the quantity and distribution of these constituents and how they relate to the microorganisms in the estuary. A series of four weekly sampling trips was made during the summer of 1964, and surface samples were collected for chlorophyll *a*, *b*, and *c*, numbers of phytoplankton, specific conductance, and trace elements. Evaluation of the data leads to the conclusion that the minor-constituent concentrations are so large that phytoplankton uptake cannot be detected.

TABLE 5.—*Range in concentration of trace elements in the Green-Duwamish River prior to discharge of effluent from the Renton Treatment Plant*

[In micrograms per liter]

Element[1]	Station 1.9		Station 7.7		Station 12.6		Station 21.0	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Aluminum	≦1.4	13	<1.3	24	1.7	58	1.6	37
Iron	4	24	3.9	138	2.6	>70	3.4	>70
Manganese	2.4	76	<1.2	100	<1.2	33	<1.2	18
Titanium	< .50	....	< .50	....	< .50	1.8	< .50	1.4
Chromium	<1.2	....	<1.2	....	<1.2	6.0	<1.2	6.0
Nickel	1.0	7.4	.66	4.7	.43	2.4	< .39	2.5
Copper	<1.2	13	<1.2	8.1	<1.2	5.4	<1.2	10
Zinc	< .50	....	< .50	....	< .50	≦5.7	< .50	11
Cobalt	<1.2	....	<1.2	2.3	<1.2	....	<1.2	9.7
Cadmium	<1.2	5.4	<1.2	....	<1.2	6.9	<1.2	....
Bismuth	< .25	....	< .25	....	< .25	....	< .25	.71
Molybdenum	< .25	16	< .25	3.6	< .25	3.8	< .25	....
Vanadium	< .25	5.7	< .25	.94	< .25	.89	< .25	.85

[1] Also detected—lead, beryllium, gallium, and germanium.

The trace elements (summarized in table 5) can generally be separated into three categories: (1) elements, such as lead, that were detected but in concentrations not large enough for quantitative definition, (2) the element molybdenum, the only one whose occurrence could be readily observed as relatable to specific conductance

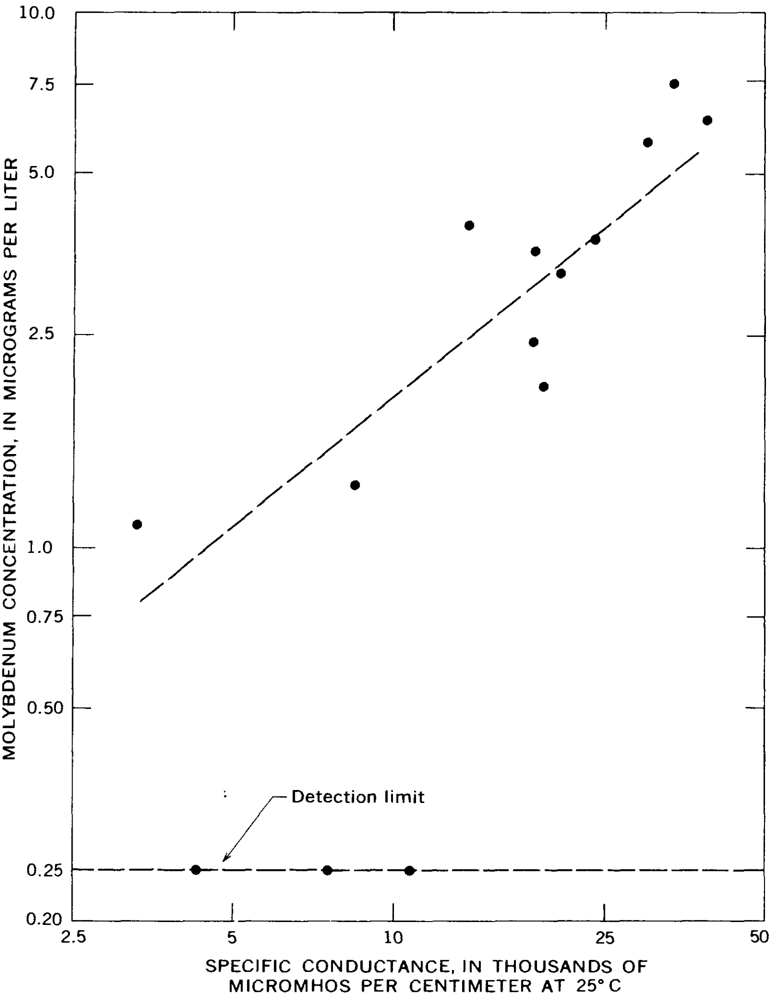


FIGURE 40.—Relation of molybdenum concentration to specific conductance in the Duwamish River estuary.

(fig. 40), and (3) elements, such as aluminum, iron, manganese, copper, nickel, and vanadium, whose concentrations appear to have been a random distribution with respect to specific conductance.

In the downstream part of the estuary, the occurrence of some minor constituents can be related to specific conductance. For many of the elements, however, the relations are obscured by the addition of other variables, such as wastes from municipal and industrial sources.

The trace-element concentrations in the fresh-water samples showed no correlation to rate of fresh-water inflow. Also, the longitudinal distribution of trace-element concentrations in the river exhibited no clear correlation with tide.

After the Renton Treatment Plant had been in operation for about 8 months, a set of samples was collected to determine which trace elements were in the treated effluent and if they could be detected in the river. Samples were collected for the measurement of trace elements and specific conductance at stations 12.6, 17.9, 21.0, and at the treated-effluent source (sta. 20.5).

TABLE 6.—*Analyses of special trace-element samples collected at selected stations, showing theoretical versus actual concentrations*

[In micrograms per liter]

Element	Station				Calculated for station 17.9	Percent difference
	12.6	17.9	20.5	21.0		
Aluminum	16	16	114	13	19	+19
Iron	>70	>70	>70	>70	----	----
Manganese	33	21	20	18	18	+17
Chromium	6.0	2.7	177	6.0	16	—490
Nickel	1.3	1.8	5.4	1.6	1.8	0
Copper	4.9	5.1	34	10	11	—116
Zinc	≦5.7	≦5.7	30	11	12	—100
Cadmium	6.9	6.6	223	<1.4	14	—112
Vanadium	.4	.3	.4	.3	.3	0

The samples were analyzed for the 17 elements listed in table 5, and nine elements were found in quantitative amounts (table 6). Data on the water discharged by the Renton Treatment Plant and the discharge of the river allowed a calculation of the theoretical amounts of trace elements that should be found in the sample collected at station 17.9. The calculated theoretical concentrations of nickel and vanadium compared very well with the concentrations actually found, and the differences between the calculated and actual concentrations of aluminum and manganese were not great enough to be significant. The calculated concentrations for cadmium, chromium, copper, and zinc suggest a loss of these elements from solution. It was felt that the comparisons, particularly for increased concentrations, could not be extended downstream to station 12.6 because of possible additions of trace elements through storm drains and minor outfalls in the reach between stations 12.6 and 17.9.

FLUVIAL SEDIMENTS

As a part of the comprehensive study, suspended-sediment samples were obtained once daily or oftener at Renton Junction kilometer 21.0. The sediment is derived principally from natural processes along the channel and alluvial plain of the Green River below Eagle Gorge, but in recent years appreciable amounts of sediment have been added to the lower Green River as a result of industrial construction between Kent and Renton Junction.

From station 0 to station 7.7 the river-bottom material is always an estuarine ooze. A transitional zone, dependent on river flow, exists between stations 7.7 and 10.4, during much of the high-flow winter months the bottom there consists of sand, whereas during the low-flow summer period the bottom consists of a typical estuarine ooze of mud and organic detritus. Upstream from station 10.4 the estuary is more typical of a meandering sand-bottom river.

Total-carbon analysis cannot be used to quantify the amount of organic material present in the bottom deposits because of the large amounts of coal in the bottom deposits. In the upstream reach between Palmer and Black Diamond, numerous coal seams, interbedded with shale or sandstone (Evans, 1912, pl. 20), have been exposed by erosion of the Green River channel. The coal seams contribute to the sediment load of the Duwamish River; for example, a bed-material sample taken at mile 12.6 contained, in addition to smaller-sized particles, a piece of coal that measured three-quarters of an inch square by one-quarter of an inch thick. Analysis of bottom deposits collected during periods of high flow in the winter and low flow during early fall show almost no difference in the percentage of carbon.

Daily mean suspended-sediment concentrations at Renton Junction usually ranged from 20 to 200 mg/l; however, during periods of high streamflow mean daily concentrations of 1,000 mg/l have been observed. The maximum observed daily suspended-sediment load was 31,000 tons on January 30, 1965, whereas minimums of less than 20 tons per day occur frequently during the low-flow periods in the summer. Yearly suspended-sediment loads vary with peak discharge, as can be seen from the following table:

Water year	Maximum discharge during the water year (cfs)	Annual suspended-sediment load (tons per water year)
1964	6,000	125,000
1965	12,000	375,000
1966	4,800	57,000

Appreciable quantities of sediment, too heavy to be carried in suspension, are moved along the riverbed. This bedload of a river (usually expressed as a percentage of the suspended sediment) increases as water discharge decreases. Two measurements of bedload at Renton Junction show that it amounted to 40 and 20 percent of the suspended-sediment load when streamflow was 1,880 and 11,600 cfs, respectively.

Scour and fill play an important part in sediment transport and, during peak discharges, the streambed may be deepened locally as much as 7 feet, as shown in figure 41. The importance of channel scour, particularly in the lower estuary, is still under investigation. It has been suggested that a buildup of oxygen-consuming deposits would result if there were little or no channel scour from one year to the next. Studies are being made to determine what rates of fresh-water inflow are needed to scour the oxygen-consuming deposits from the lower estuary.

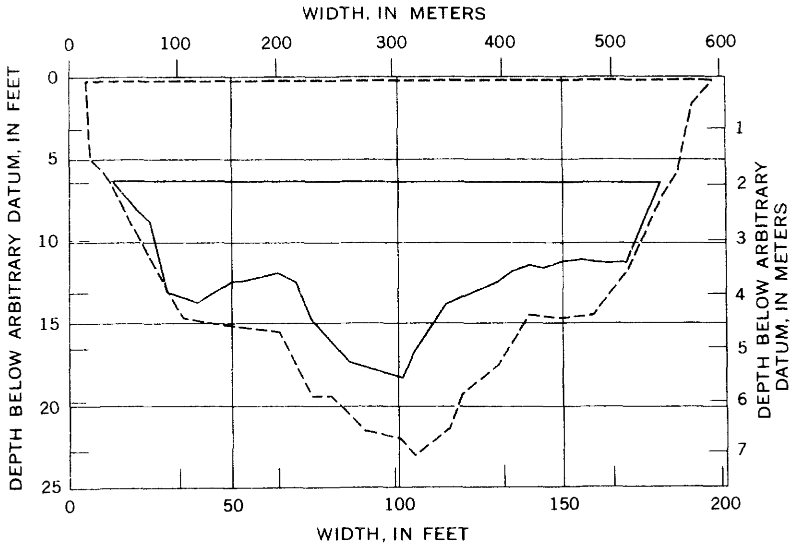


FIGURE 41.—Comparison of channel cross-section areas at station 12.6 during two rates of fresh-water inflow. Dashed line, area at 12,700 cfs; solid line, area at 1,910 cfs.

Particle-size analyses of suspended-sediment samples, collected when fresh-water inflow ranged from 540 to 12,000 cfs, show that the suspended sediment consists of 8–28 percent clay particles (<0.004 mm), 11–57 percent silt (0.004–0.062 mm), and 16–75 percent sand (0.062–2.0 mm). The unit weight of sedient transported past the daily station is estimated to be 1 ton per cubic yard. The reader is referred to the annual reports of the U.S. Geological Survey (1960–63) for more detailed information on daily sediment concentrations and particle size in the Duwamish River.

CONTINUING AND FUTURE STUDIES

During later phases of this investigation, emphasis will be on developing a more precise quantitative understanding of the hydrodynamics of the estuary and on extending the biologic aspects of the study. Additional subjects of study and work planned or already underway include the following:

1. The mixing-length theory of tidal flushing proposed by Arons and Stommel (1951) will be tested for application to the Duwamish River estuary. Salinity-velocity studies will be made during periods of different rates of fresh-water inflow and during selected tidal cycles.
2. During a period of low fresh-water inflow, the residence time of the salt-water wedge will be determined by using a fluorescent dye.
3. DO data from the water-quality monitors will continue to be supplemented by field data to determine the severity of the DO sag during the low fresh-water inflow period. The severity of the DO sag for each year will be compared to the historical (pre-1962) DO data to determine if the sag is becoming more severe for comparable low-flow periods.
4. The conditions that control the occurrence of phytoplankton blooms need better definition, especially the roles played by solar radiation and water temperature. When a bloom does occur, its magnitude and duration will be determined and compared to previous bloom data for indications of increased biomass.
5. Work on BOD is continuing. A differential respirometer has been acquired; it is felt that this apparatus will provide data on rates of BOD more accurately than is possible with the equipment used to date (1967).
6. An attempt will be made to develop a mathematical model of the estuary that satisfactorily represents the relationship of circulation and mixing to the distribution of dissolved oxygen in the estuary.

SUMMARY AND CONCLUSIONS

Major preliminary results and conclusions from the various phases of the study completed to date (1967) are:

1. The Duwamish River estuary can be classed as well stratified to partially mixed, depending on the rate of fresh-water inflow. The inflowing fresh water and any contained pollutants remain mostly in the upper 5–15 feet of the estuary and are underlain by a wedge-shaped body of salty water throughout most of the length of the estuary. The degree of stratification increases in an upstream direction and is more distinct during high rates of inflow than during lower rates of inflow. Where stratification is evident, the thickness of the upper (fresher) water also varies directly with the rate of fresh-water inflow. The volume of the estuary ranges from 205 to 592 million cubic feet for the lowest and highest recorded tides, respectively.

2. The distribution of salinity in the estuary varies with the rate of fresh-water inflow and with tide stage. For a given inflow, the salt-water wedge migrates upstream and downstream with the tide stage; for similar tide conditions, the wedge advances farthest upstream during low rates of inflow and retreats downstream during greater inflow. A fresh-water inflow greater than 1,000 cfs prevents salt-water movement to station 12.6 regardless of tide height, but during low fresh-water flows, salt water has been detected upstream beyond station 16.2. At virtually any station on the estuary, the salinity at a given depth is laterally constant.

3. Fluorescent-dye studies confirmed that there is virtually no mixing of the fresh-water downward into the salty-water layer. Most of the mixing of fresh and salty water in the estuary takes place at the interface, where salty water is entrained upward into the overriding fresh water. The erosion of salty water is balanced by a net upstream movement of the water in the salt-water wedge.

4. Three methods that use salinity to calculate flushing rates were tried and abandoned. A comparison of results of dye studies during succeeding years (1965 and 1966) indicates that some fraction of a pollutant introduced upstream at station 21.0 would remain in the lower estuary a minimum of 7 days. Dispersion coefficients for the upper layer have been determined to be on the order of 100–400 square feet per second.

5. DO in the surface layer decreases almost linearly in a downstream direction, but this layer usually contains adequate amounts for the maintenance of aquatic life. DO in both the upper and lower layers increases with increasing fresh-water inflow and diminishes with decreasing inflow. The minimum DO concentrations in the bottom layer vary also with tidal-prism thickness, although the rate of fresh-water inflow is the dominant factor. Bottom DO concentrations decrease in an upstream direction. The minimum recorded DO values, obtained during late summer, consistently occur in the bottom layer at station 7.7; however, results from manual sampling showed that a seasonal DO sag oscillates between stations 10.4 and 7.7. At low rates of fresh-water inflow and minimum tidal exchange, DO content in the minimum reach has been less than 1 mg/l at times.
6. Information available from previous studies failed to indicate a decrease in DO content in either the upper (fresh-water) or lower (salty water) layer during the period 1949–56. Data from this study suggest a slight general decrease in the annual minimum DO concentrations since the pre-1960 studies, but additional data are needed to evaluate this suggested change.
7. Phytoplankton blooms occur in the estuary only when combinations of hydrographic and climatic conditions are favorable. The DO of the surface layer is increased as a result of photosynthesis of the plants composing the bloom, but the DO of the bottom layer is decreased as the plants die and settle.
8. The chief factors controlling whether or not a phytoplankton bloom will occur are: (a) fresh-water inflow rate, (b) tidal-prism thickness, (c) water temperature, and (d) solar radiation. Determination of the relative importance and critical ranges of these factors must await further study during subsequent blooms. Concentrations of nutrients (nitrogen and phosphorous) in the upper layer do not control the occurrence of a bloom, because sufficient nutrients are always present. Nutrients from the effluent of the Renton Treatment Plant may increase the biomass produced by the phytoplankton blooms, but previous data showing saturation values of DO indicate that a phytoplankton bloom occurred prior to installation of the Renton Treatment Plant. Trace-element studies have not defined any possible role that these elements play in algal growth.

9. Extensive experiments and collection of data on BOD have failed to produce a method that was satisfactory for determining quantitatively the actual BOD in the estuary. In general, BOD was greater in surface samples than in bottom samples for most tide conditions and seasons; however, the bottom samples showed the greater BOD during some periods of low fresh-water inflow.

10. The inflowing fresh water is low in total dissolved solids and is a calcium bicarbonate-type water. The general chemical character of the salty water in the estuary may be represented simply as various percentages of the fresh water of the Duwamish River and the salt water of Elliott Bay. Once-monthly analyses suggest that the nitrate concentrations in the inflowing fresh water increased during the period 1960–66. Nitrate concentrations at station 16.2 increased to a greater degree than could be attributed to the Renton Treatment Plant, which began discharging effluent in 1965.

11. Daily mean concentrations of suspended sediment in the inflowing fresh water usually range from 20 to 200 mg/l at station 21.0; however, during periods of high inflow daily mean concentrations of 1,000 mg/l have been observed. A maximum sediment load of 31,000 tons per day occurred on January 30, 1965, whereas minimum amounts of less than 20 tons per day occur frequently during low-flow periods in the summer. The streambed material is eroded during periods of peak flow, and the bed may be deepened locally as much as 7 feet during such times. Bottom deposits contain large amounts of coal particles from upstream sources, and this coal prevents the quantitative determination of other organic material by carbon analysis.

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