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Water-Discharge

Determinations for the Tidal Reach of the Willamette River From Ross Island Bridge to Mile 10.3, Portland, Oregon

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1586-H

*Prepared in cooperation with the
U.S. Atomic Energy Commission*



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By GEORGE R. DEMPSTER, JR., and GALE A. LUTZ

HYDROLOGY OF TIDAL STREAMS

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UNITED STATES DEPARTMENT OF THE INTERIOR

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HYDROLOGY OF TIDAL STREAMS

WATER-DISCHARGE DETERMINATIONS FOR THE TIDAL REACH OF THE WILLAMETTE RIVER FROM ROSS ISLAND BRIDGE TO MILE 10.3, PORTLAND, OREGON

By GEORGE R. DEMPSTER, JR., and GALE A. LUTZ

ABSTRACT

Water-discharge, velocity, and slope variations for a 3.7-mile-long tidal reach of the Willamette River at Portland, Oreg., were defined from discharge measurements and river stage data collected between July 1962 and January 1965. Observed water discharge during tide-affected flows, during floods, and during backwater from the Columbia River and recorded stages at each end of the river reach were used to determine water discharge from two mathematical models. These models use a finite-difference method to solve the equations of moderately unsteady open-channel streamflow, and discharges are computed by an electronic digital computer.

Discharges computed by using the mathematical models compare satisfactorily with observed discharges, except during the period of backwater from the annual flood of the Columbia River. The flow resistance coefficients used in the models vary with discharge; for one model, the coefficients for discharges above 30,000 cfs (cubic feet per second) are 12 and 24 percent less than the coefficient used for discharges below 30,000 cfs.

Daily mean discharges were determined by use of one mathematical model for approximately two-thirds of the water year, October 1963 through September 1964. Agreement of computed with routed daily mean discharges is fair; above 30,000 cfs, average differences between the two discharges are about 10 percent, and below 30,000 cfs, computed daily discharges are consistently greater (by as much as 25 percent) than routed discharges. The other model was used to compute discharges for the unusually high flood flows of December 1964.

INTRODUCTION

The growth and establishment of population complexes along many river estuaries create new and intricate water-utilization problems. Water-discharge data and information about characteristics of the flow for the estuaries are essential to proper management and utilization of the water resources of these rivers.

Discharge has no simple relationship to stage in a river estuary; the influence of the tides continually changes the discharge even

though upland flow may remain constant. The determination of instantaneous discharge of river estuaries is complex and entails laborious computations, but recently the use of electronic computers has greatly simplified these computations.

The data in this report are part of a study started in June 1962 to determine the quantity and properties of sediment discharged by the Willamette River. The feasibility of using mathematical models to determine water discharges was investigated, and additional knowledge of the flow characteristics of the Willamette River was obtained.

PURPOSE AND SCOPE

The purpose of this report is to broaden the limited information about the riverflow at Portland and to evaluate the use of mathematical models for determining water discharge in a tide-affected part of the Willamette River. The report presents observations of several flow parameters and demonstrates the use of two mathematical models to determine the discharge for the Willamette River at Portland; the applicability of these models is shown by comparing computed and observed discharges for short-term records and by comparing routed and computed daily discharges for a partial water year. The routed discharges are based on summations of upland streamflows which were routed to Portland.

ACKNOWLEDGMENTS

The investigative work was done in cooperation with the U.S. Atomic Energy Commission. The investigation was planned and started in 1962 under the supervision of L. B. Laird, district chemist, Quality of Water Branch, and continued under the supervision of G. L. Bodhaine, district engineer, Quality of Water Branch. This report was prepared under the supervision and guidance of W. L. Haushild, research hydrologist, Water Resources Division.

Appreciation is expressed to the River Forecast Center, Weather Bureau, U.S. Department of Commerce, and the North Pacific Division, U.S. Corps of Engineers, for furnishing river-stage information.

GENERAL DESCRIPTION OF THE STUDY REACH

The Willamette River, the largest tributary of the lower Columbia River, flows in a northerly direction and discharges into the Columbia River approximately 12 miles downstream from the center of Portland (fig. 1). Both the Columbia and Willamette Rivers are navigable to Portland by ocean-going vessels. The navigable channels are maintained by dredging. The Willamette River is deep from Portland to the mouth and gradually widens and then narrows between about

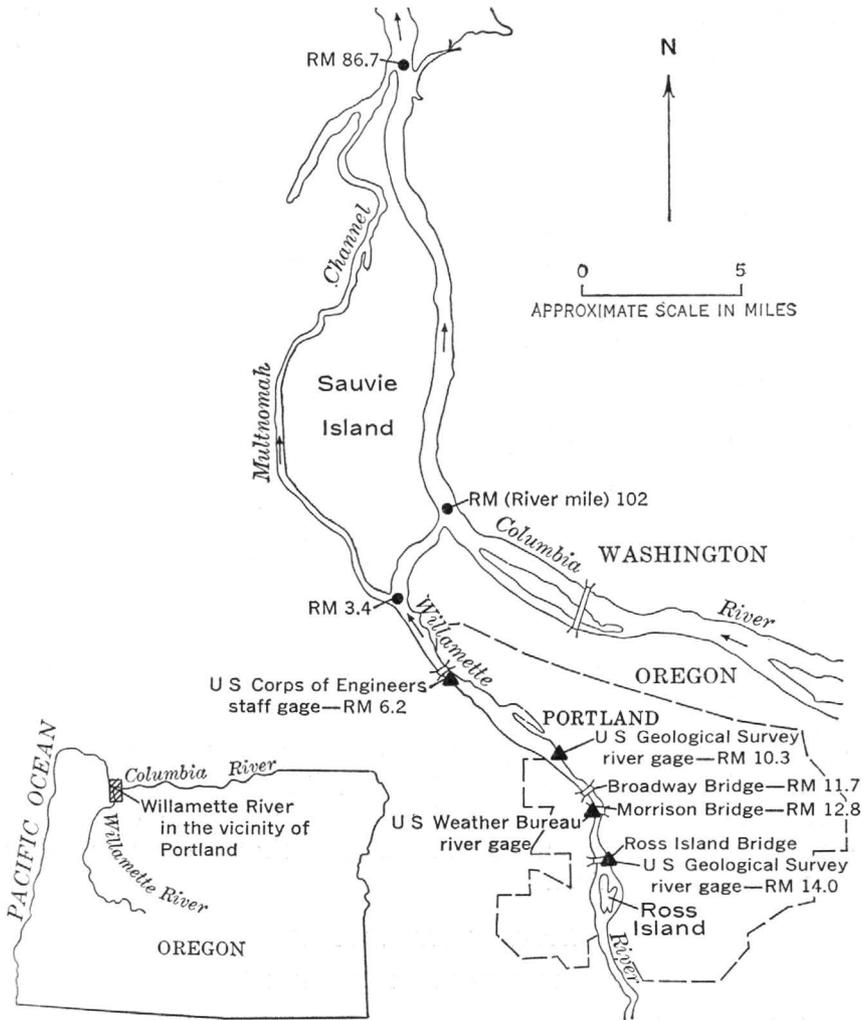


FIGURE 1.—Willamette River in the vicinity of Portland, Oreg., showing measurement locations (Ross Island and Broadway Bridges), gage locations, and geographic features.

river mile 10 and the mouth. River miles used in this report are the same as those given in "River mile index, Willamette River, Columbia River basin, Oregon" (Hydrology Subcommittee, Columbia Basin Inter-Agency Committee, 1963).

The study reach for the Willamette River extends from Ross Island Bridge, river mile 14.0, downstream to river mile 10.3. The channel width in this 3.7-mile-long reach is nearly uniform and averages about 1,200 feet. Channel depths and sideslopes are irregular because of dredging operations and rock outcrops. Although water depths

in local areas are greater than 60 feet, average water depth in the reach during low water is about 35 feet. The flow is confined within nearly vertical banks to river stages of approximately 30 feet above mean sea level. At stages greater than 30 feet, the river overflows its banks. Many wharves and pilings have been built along both riverbanks, and 10 bridges span the river within the city limits of Portland.

CAUSES OF UNSTEADY FLOW

Tides from the Pacific Ocean affect flow in the Columbia River inland for 146 river miles and cause the main part of the Willamette River (fig. 1), which flows into the Columbia River at mile 102, to be tide affected to Willamette Falls, which is nearly 15 miles upstream from the center of Portland. Upstream from the confluence of the Columbia and Willamette Rivers, the flows of the two rivers mutually affect each other. The extent to which they are tide affected varies inversely with discharge of both rivers and directly with the magnitude of the tides at the Columbia River mouth. When discharges of both rivers are low, tide effects are large and flow reverses in the Willamette River at Portland; as discharges of these rivers increase, tide effects diminish. Unsteady flow, however, nearly always exists in the Willamette River because the discharges of both rivers vary continuously. Also, discharges of both rivers are regulated to varying degrees by upstream hydroelectric dams (not shown in fig. 1). Annual mean discharge of the Columbia River is about five to seven times that of the Willamette River; discharge is maximum during the summer months for the Columbia River and during the winter months for the Willamette River.

DATA COLLECTION

DISCHARGE MEASUREMENTS

Discharge and hydraulic data are based on 127 discharge measurements of the Willamette River at Portland obtained during the period July 1962 to January 1965. Seventy-one of the measurements resulted from a series of consecutive measurements made during each of three complete tidal cycles on October 18-19, 1962, October 15-16, 1963, March 16-17, 1964, and during one-half of a tidal cycle on August 27, 1964. A series of consecutive measurements made during all or part of a tidal cycle is called a tidal-cycle measurement. A tidal cycle in the Willamette River is the approximate 25-hour period during which the tide ebbs and floods twice. The first tidal-cycle measurement was made at Broadway Bridge, river mile 11.7, and the three other tidal-cycle measurements were made at Ross Island Bridge, river mile 14.0. The

remaining 56 discharge measurements were made at the Broadway Bridge. Measurement locations (highway bridges) are shown in figure 1, and the discharge and hydraulic data are given in table 1.

The discharge measurements were made during streamflow conditions that ranged from low tide-affected flows to the near record flood during December 1964. Generally, one field crew measured discharge; however, for the tidal-cycle measurements, two or three field crews were used to minimize measuring time, and each crew observed depths and velocities in accordance with a preplanned schedule. Depths and velocities were observed at approximately 1-hour intervals during the first tidal-cycle measurement and at 1.5-hour intervals during each succeeding tidal-cycle measurement. Other discharge measurements were usually completed in about 1 hour, but some measurements required as much as 3 hours to complete. Total measurement time depended upon the difficulty experienced while measuring and the number of field crews working.

Velocities and depths were observed by suspending Price current meters and appropriate sizes of sounding weights from the highway bridges. Concurrently, flow direction at the water surface was observed to be upstream, downstream, or at an angle to the measuring cross section. Velocity was observed at 0.2 and 0.8 of the depth below the water surface. Studies made during this investigation and in another tide-affected river (Miller, 1962, p. 6-8) indicate that the two-point method is valid if the vertical distribution of velocity is approximately parabolic; to achieve this distribution, measurement locations must be far enough upstream from the ocean to provide such a vertical distribution. Velocities and depths in the cross sections were observed at 20 verticals at the Broadway Bridge (river mile 11.7) and at 28 verticals at Ross Island Bridge (river mile 14.0). The same verticals were used for each measurement.

RIVER-STAGE RECORDS

Prior to September 1963, stage was continuously recorded at the Morrison Bridge, at river mile 12.8; also stage was read each hour from a staff gage at river mile 6.2 (fig. 1). Because the Morrison Bridge is approximately midway between both the discharge measurement locations and the ends of the study reach, mean stage at Morrison Bridge was used for all discharge measurements given in table 1. River stages at Morrison Bridge are referred to a local datum (mean sea level minus 1.55 ft.).

Beginning in September 1963, stage was synchronously recorded every 15 minutes (96 readings per day) at Ross Island Bridge (river mile 14.0) and river mile 10.3. These stages were referred to mean sea level. The stages were recorded digitally to facilitate translation

of stage data into a form that is usable in the mathematical models. The frequency of commercial alternating-current power, which was transformed to direct-current power to operate the recorders, was virtually constant; therefore, synchronism between stage readings at both recorders was excellent. Recording of stages was interrupted occasionally by failures in commercial power or the instrumentation system.

DATA PRESENTATION

MEASUREMENT CROSS SECTIONS

Water depths in the river cross section were obtained at each measurement location, and concurrent river stages were available from nearby recorders. Streambed elevation, in reference to mean sea level, at each vertical was determined by adjusting water depth for the stage at the time of sounding. Average cross sections were defined from the average of all streambed elevations at each vertical. Small deviations of streambed elevations from the average elevations at the verticals within the cross sections indicated that the streambed did not change significantly during the study period. Average cross sections for Ross Island Bridge (river mile 14.0) and Broadway Bridge (river mile 11.7) are shown in figures 2 and 3 respectively.

WATER VELOCITY

LATERAL VELOCITY DISTRIBUTIONS IN THE REACH

During parts of any ebb and flood tide, water may flow downstream at one depth and (or) lateral location within a river cross section and upstream or nearly parallel to the cross section at another depth or lateral location. The resulting flow pattern is a complicated mixture of many different flow paths that become most complicated when the flow reverses direction. The data indicate that some uncertainty existed concerning velocity and flow direction for about 2 hours during each flow reversal; therefore, velocities determined by use of the two-point method and flow directions throughout the depth determined from the flow direction at the water surface may not be representative of actual conditions for short periods of time.

Average cross sections at Ross Island and Broadway Bridges and lateral velocity distributions for several different times during a tidal cycle are shown in figures 2 and 3. The distributions of lateral velocities are for an instant in time but illustrate that distributions change continuously with time. The velocity distributions at Ross Island Bridge (fig. 2) are affected by the flow division caused by Ross Island, which is a short distance upstream near the east bank (fig. 1). Maximum velocities were observed in the deeper part of the cross section

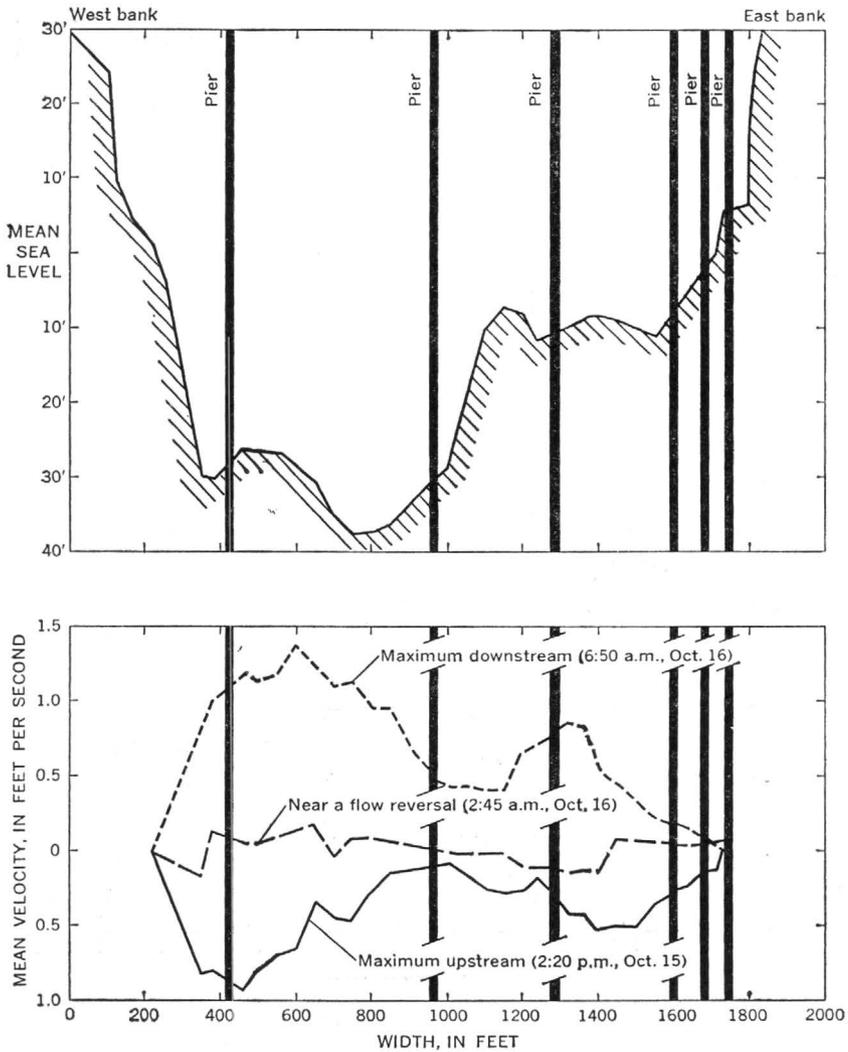


FIGURE 2.—Cross section of Willamette River at Ross Island Bridge (river mile 14.0) and the variation of the lateral distribution of velocity, October 15-16, 1963.

near the west bank. An upstream velocity of nearly 1 fps (foot per second), shown in figure 2, was observed during the tidal cycle of October 15-16, 1963. At Broadway Bridge (fig. 3), the velocities are more uniformly distributed. The cross section at Broadway Bridge is symmetrical in shape, and maximum velocities were observed near midchannel. Although water flows upstream at Broadway Bridge, it was never observed to do so during water discharge measurements at this location.

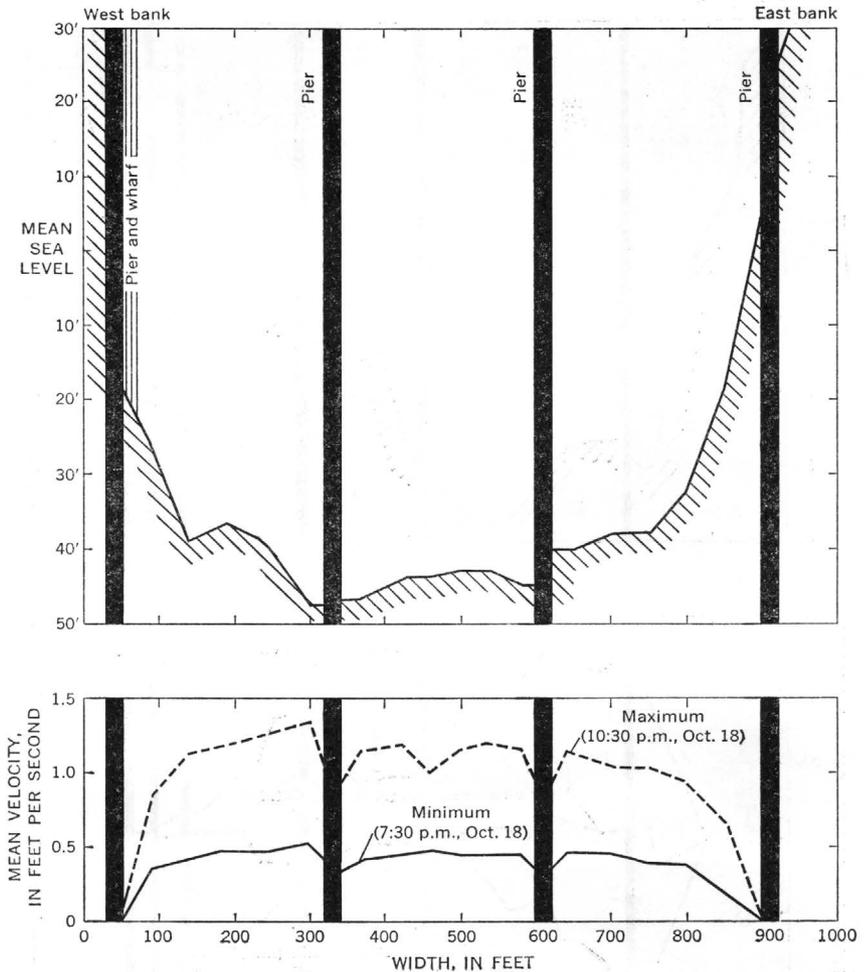


FIGURE 3.—Cross section of Willamette River at Broadway Bridge (river mile 11.7) and the variation of the lateral distribution of velocity, October 18-19, 1962.

DISCHARGE-VELOCITY RELATIONSHIPS

The average discharge-velocity relations shown in figure 4 illustrate the variation of mean and maximum velocity with discharge. Mean velocities were computed by dividing the measured discharges by the cross-sectional areas. At river stages less than approximately 7 feet above mean sea level, the cross-sectional areas at Ross Island and Broadway Bridges (river miles 14.0 and 11.7) are about equal. Flow between the two locations is confined between fairly straight and vertical banks. Because the cross-sectional areas are nearly the same for the same discharge, the mean velocities (table 1) at both

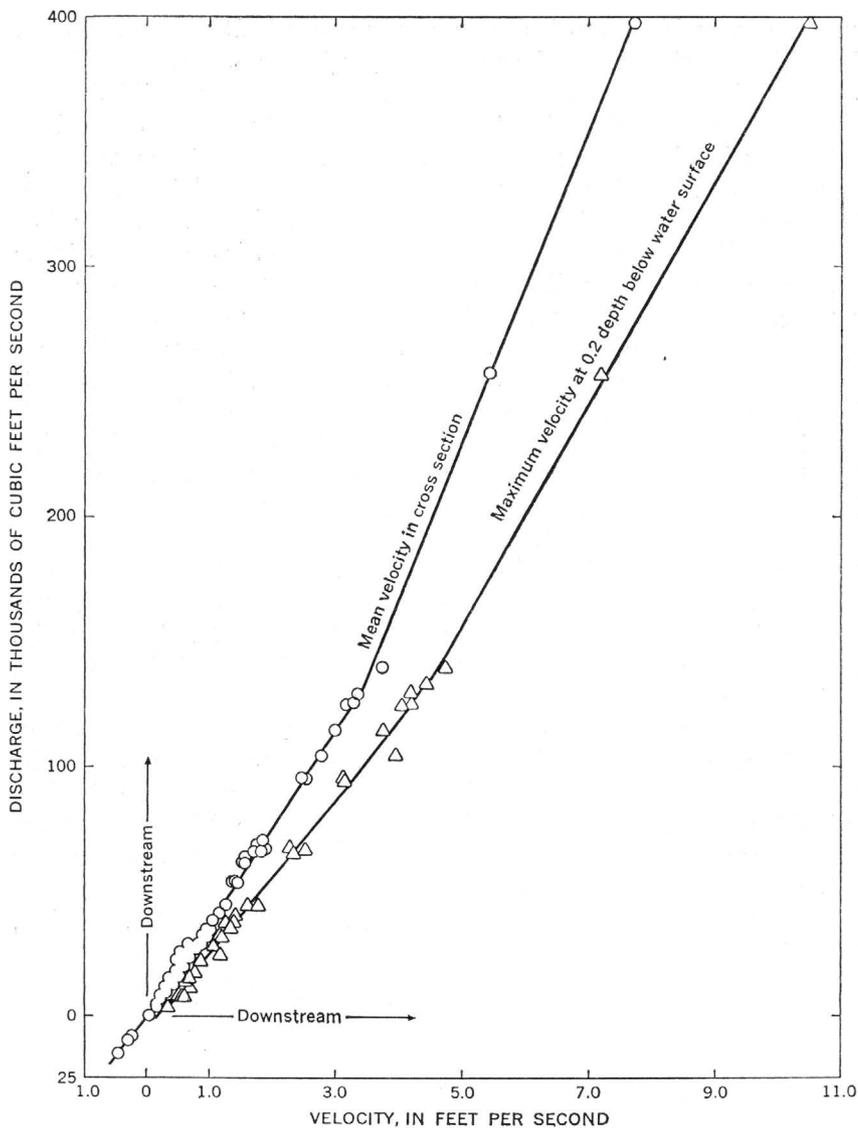


FIGURE 4.—Average relations of velocity to discharge determined from data at Ross Island Bridge (river mile 14.0) and Broadway Bridge (river mile 11.7).

locations are about equal for equal discharges, and velocities from both locations are plotted together in figure 4. For stages greater than 7 feet, discharge, area, and mean-velocity data at Broadway Bridge were used. The maximum velocities are among the velocities observed at 0.2 of the depth below the water surface near midchannel at Broadway Bridge. Mean velocities in the reach ranged from an

upstream velocity of 0.5 fps to a downstream velocity of nearly 8 fps. Coincidental with mean downstream velocity of 8 fps, a 0.2-depth velocity of more than 10 fps was observed at Broadway Bridge.

The average relationships in figure 4 show that stream velocities increase with increasing discharge. The linearity of the velocity-discharge relationships within each range represented is partly due to the relatively small increase in cross-sectional area between low and high discharges. The cross-sectional area varies from 31,000 to 40,000 square feet for discharges less than 140,000 cfs (cubic feet per second) and increases to only about 52,000 square feet at a discharge of 400,000 cfs. Because the flow is unsteady, some values are scattered about each average relation, and the velocity can be different for the same discharge. The average deviation of mean velocities from the relation shown is 0.05 fps, and the maximum deviation is 0.15 fps. The average deviation of velocities at 0.2 of the depth is about 0.15 fps, and the maximum deviation is 0.3 fps. The velocities determined from figure 4, therefore, could be in error by a large percentage, particularly at low discharges. The high discharges and velocities in figure 4 are for the December 1964 flood in the Willamette River basin (Rantz and Moore, 1965, p. 34-47). Concurrently, flows in the Columbia River were above normal for that time of year, and the change in the slopes of the relations in figure 4 above 140,000 cfs may be, in part, due to unusually high backwater from the Columbia River. If Columbia River discharges had been lower during the 1964 flood and Willamette River discharges had remained high, velocities would probably have been greater in the Willamette River than they were, and the relations might have been singular relations throughout the entire range of discharge.

Several mean and 0.2-depth velocities, converted to miles per day, from figure 4 follow:

<i>Discharge (cfs)</i>	<i>Mean water velocity (miles per day)</i>	<i>Water velocity at 0.2 depth (miles per day)</i>
5,000	2.0	5.4
10,000	4.6	8.2
25,000	11.3	16.4
50,000	21.6	29.6
100,000	42.7	56.0

These velocities represent an estimated mean and maximum distance that water entering the study reach may travel in 1 day. When the discharge is 5,000 cfs, most of the water entering the reach at Ross Island Bridge (river mile 14.0) may leave the reach at river mile 10.3 about 2 days later. Flow time of water through the reach decreases with increase in discharge. Use of different techniques and more detailed studies are needed to determine precise flow times of water for the tide-affected part of the Willamette River.

WATER-SURFACE SLOPE**COMPUTATION OF SLOPE IN THE REACH**

Water-surface slopes in the river reach were computed by subtracting the simultaneous measurements of water-surface elevations either for Morrison Bridge (river mile 12.8) and river mile 6.2 or for Ross Island Bridge (river mile 14.0) and river mile 10.3 and then dividing that difference by the distance between the two respective gages. Computed slopes in feet per mile at the midtime of each discharge measurement are given in table 1. Slopes determined from water-surface elevations at only two points in a reach are approximate if the water surface is curved, as it usually is in a river estuary.

SLOPE-DISCHARGE RELATION

The relation between approximate water-surface slope and discharge is shown in figure 5. Slopes in the reach range from 0.05 foot per mile in the upstream direction to 0.7 foot per mile in the downstream direction. Although the range of discharge and slope is quite large, discharges are low enough that slopes are less than 0.10 foot per mile during about 90 percent of each year. The inset in figure 5 uses the data of October 15-16, 1963, to illustrate the variation of slope and discharge during a tidal cycle. The "loop" curve shown in the inset shows that slope (determined by method used in this report) does not relate directly with discharge (or velocity) when flow is tide affected.

FLOW HYDROGRAPHS

Stage, discharge, mean-velocity, and water-surface-slope hydrographs of the Willamette River at Portland for all tidal-cycle measurements are shown in figures 6-9. The open circles (figs. 6-9), which indicate individual measurements, represent data given in table 1 and are plotted at the clock time midway between the start and finish of a discharge measurement. In figure 6, the discharge hydrograph was defined by using the data in table 1. In figures 7-9, the observed discharge hydrograph for each tidal-cycle measurement was obtained by (1) computing the discharge for 15 or 16 subsections of the cross section, (2) plotting individual discharge hydrographs for each subsection throughout the tidal cycle, and (3) summing the discharges of all subsections at 15-minute intervals by using the hydrographs defined in (2). This technique more accurately defines the discharge hydrograph if discharges are changing rapidly and (or) measuring times are excessively long. The differences between discharges determined by the latter method and the discharge values for the individual measurements (open circles) can be seen in figures 7-9. The total time, in hours, during which consecutive discharge measurements

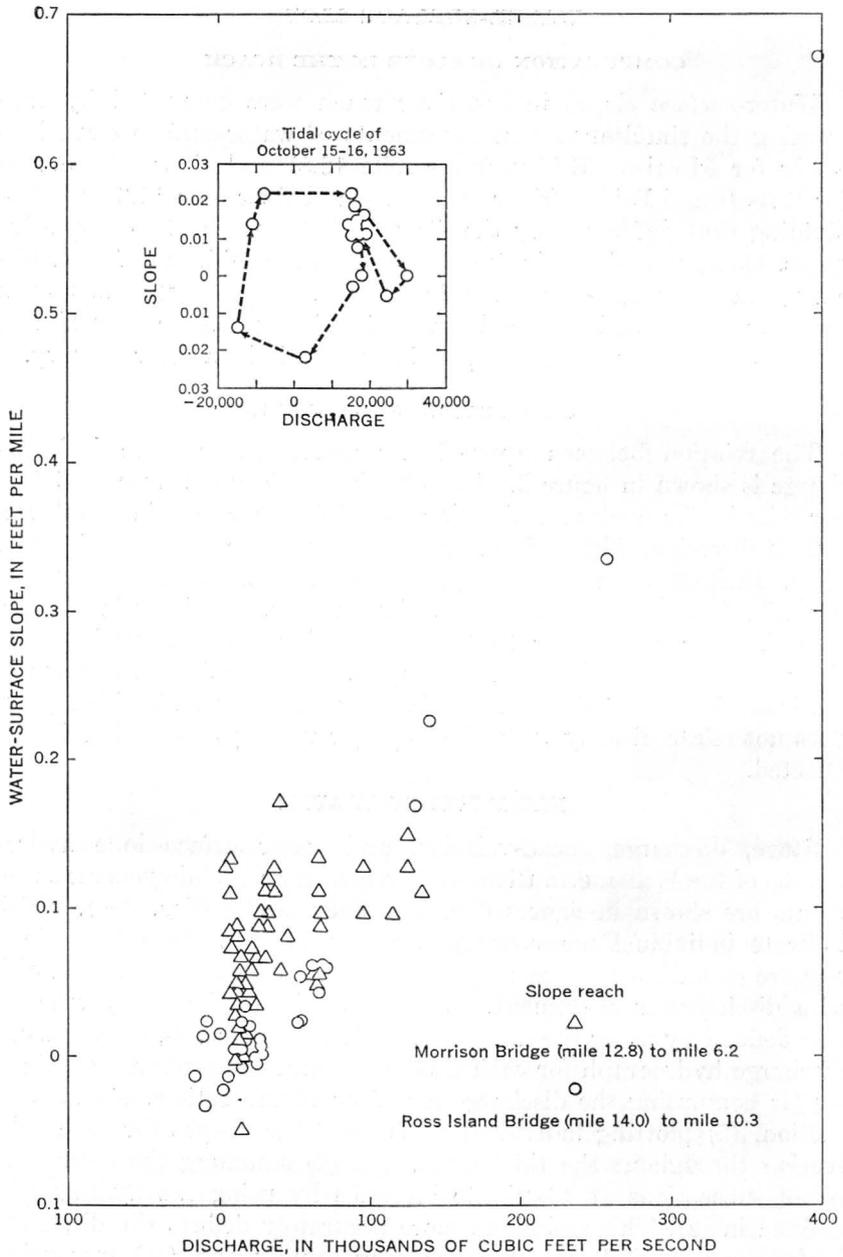


FIGURE 5.—Variation of water-surface slope with discharge.

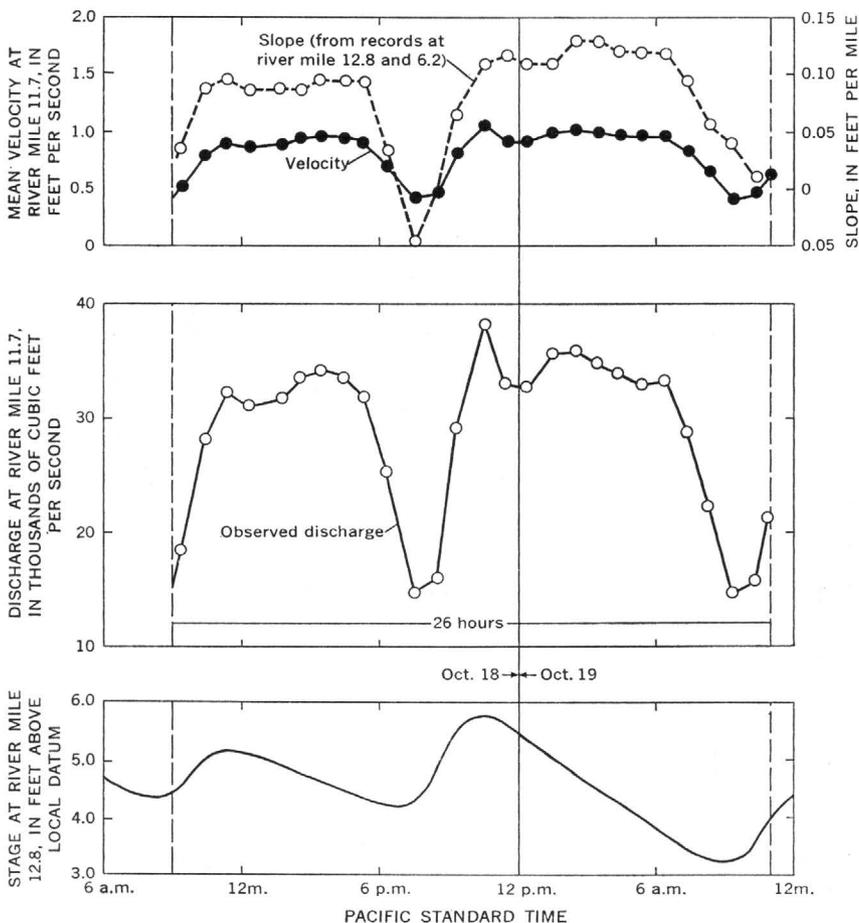


FIGURE 6.—Stage at Morrison Bridge (river mile 12.8), discharge and mean velocity at Broadway Bridge (river mile 11.7), and slope of Willamette River, October 18-19, 1962.

were made for each tidal-cycle measurement is given in each figure. The computed discharge hydrographs in figures 7-9 are the discharges determined by using the mathematical model discussed in later sections of this report.

The tidal-cycle measurements are summarized in the following table:

Measurement location (river mile)	Dates	Number of measurements	Measuring duration (hr)	Mean discharge (cfs)	Range of discharge (cfs)
11.7	Oct. 18-19, 1962.....	27	26.0	28,600	14,600-38,200
14.0	Oct. 15-16, 1963.....	18	25.5	12,500	-115,100-30,000
14.0	Mar. 16-17, 1964.....	17	24.0	63,900	54,500-71,100
14.0	Aug. 27, 1964.....	9	10.5	10,300	-19,300-19,400

¹ Negative sign indicates flow in the upstream direction.

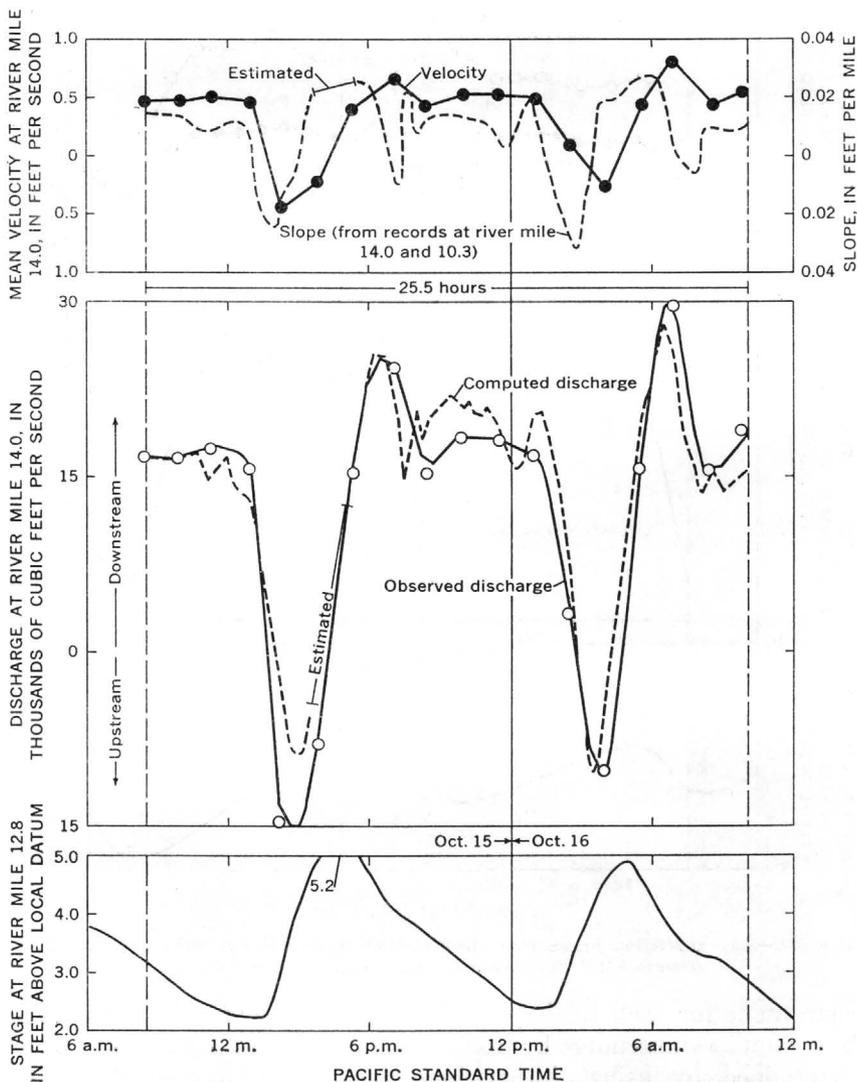


FIGURE 7.—Stage at Morrison Bridge (river mile 12.8), discharge and mean velocity at Ross Island Bridge (river mile 14.0), and slope of Willamette River, October 15-16, 1963.

The discharge data in figures 7 and 9 and the preceding table clearly show that tides sometimes cause the Willamette River at Portland to flow in the upstream direction (reverse flow). During tidal flows, the discharge varies from moment to moment and rapidly changes during the incoming floodtide. From the time of minimum downstream discharge or maximum reverse flow (which occurs from 1 to 3 hours prior to the peak stage of the floodtide) through ebb tide, discharge

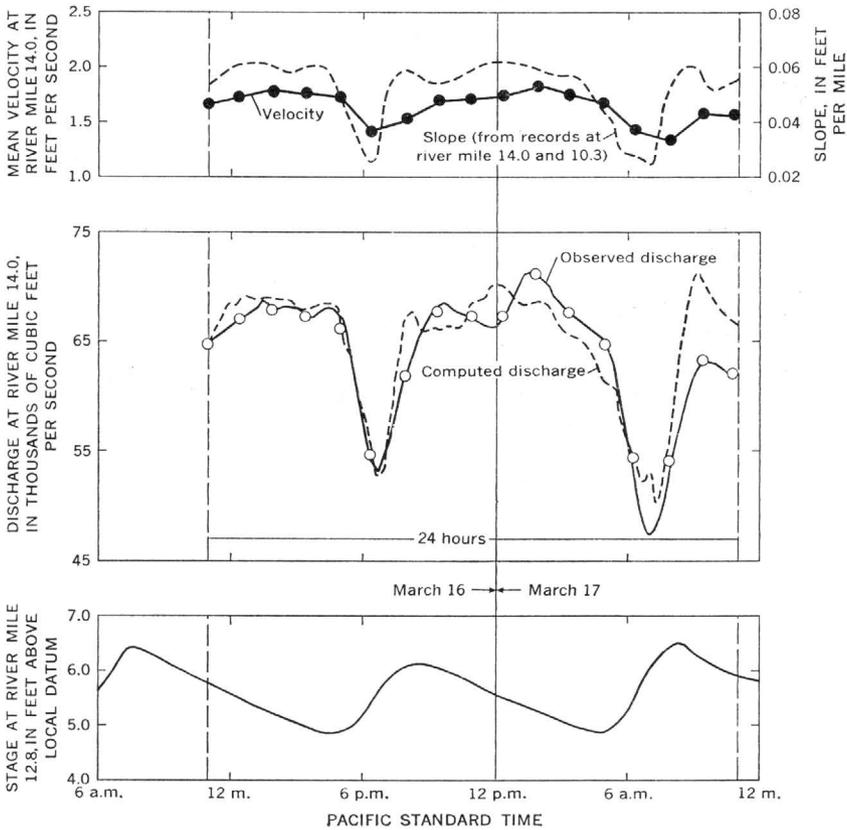


FIGURE 8.—Stage at Morrison Bridge (river mile 12.8), discharge and mean velocity at Ross Island Bridge (river mile 14.0), and slope of Willamette River, March 16-17, 1964.

increases in the downstream direction, and water is released from storage until the next floodtide. The mean velocity of flow varies similarly to discharge and indicates the degree of unsteadiness of the flow.

Besides the stage, discharge, and velocity hydrographs, the temporal variation of water-surface slope for the four tidal-cycle measurements is shown in figures 6-9. In figure 6, slope is defined by using the stage data in table 1 for Morrison Bridge (river mile 12.8) and river mile 6.2. In figures 7-9, slope is defined by using simultaneous 15-minute interval stages for Ross Island Bridge (river mile 14.0) and river mile 10.3. How slopes vary during tidal cycles and how discharges and velocities respond to changes in slope are illustrated in figures 6-9; they show that the momentum of the river water either sustains or retards changes in flow as slope in the reach decreases or increases. The slope, discharge, and velocity data partly illustrate the complexity of the flow system.

HYDROLOGY OF TIDAL STREAMS

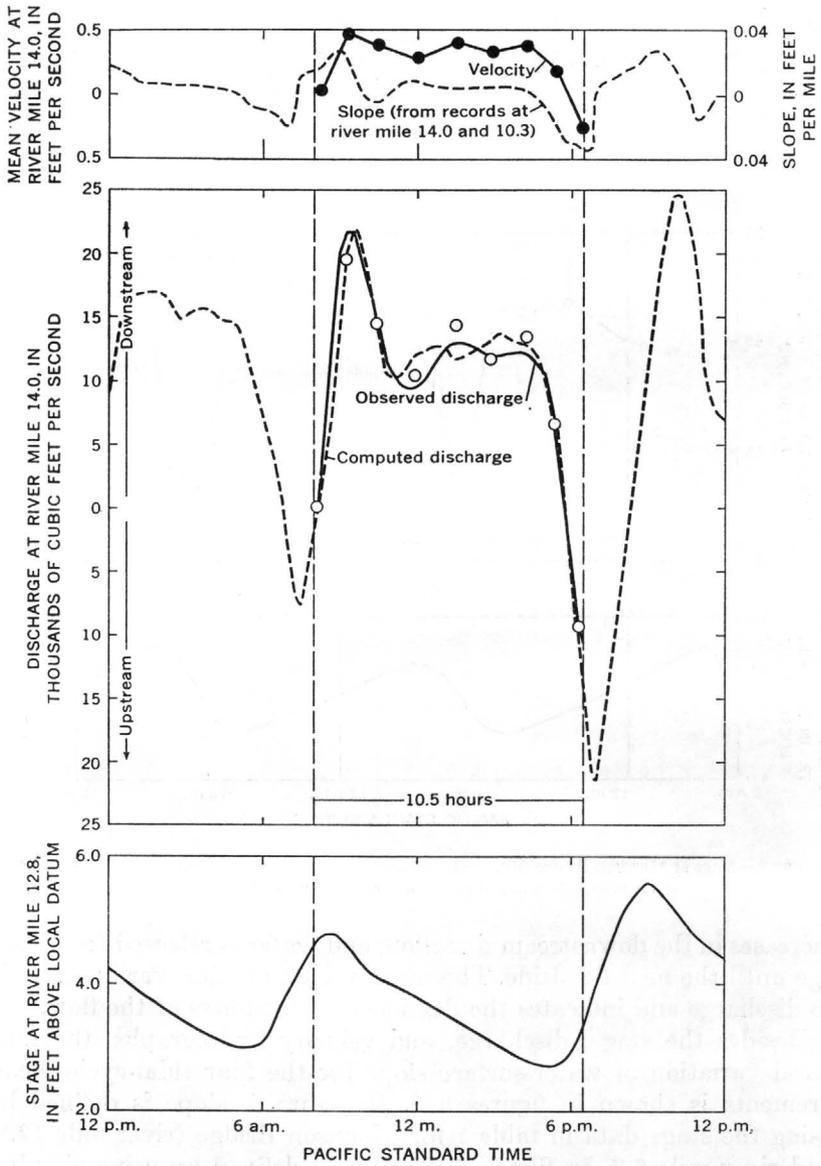


FIGURE 9.—Stage at Morrison Bridge (river mile 12.8), discharge and mean velocity at Ross Island Bridge (river mile 14.0), and slope of Willamette River, August 27, 1964.

**GENERAL DESCRIPTION OF MATHEMATICAL MODELS
FOR FLOW IN TIDAL RIVERS**

The usual methods of determining discharge are inadequate when riverflow is affected by tides. Stage does not relate with discharge, and discharge of tidal rivers cannot be determined by use of the variable water-surface slope method when storage in the reach and accelerative forces are too large to be ignored.

A mathematical model developed by Baltzer and Shen (1961) and another model developed by Lai (1965) are used to determine the discharge at a selected location along a river estuary. Each model is an approximate numerical solution of two first-order quasi-linear partial differential equations of two dependent and two independent variables representing unsteady open-channel flow. A detailed discussion of the differential equations is beyond the scope of this report; however, a brief explanation of general principles is given. The equations of continuity and motion are used to represent moderate, unsteady open-channel flow. The equation of continuity (conservation of mass) states that the net change in discharge in a reach is equal to the change in storage in the reach. The equation of motion (conservation of momentum) states that the resultant force acting on an element of water in a given direction is equal to the time rate of change of momentum of the water contained in the element. The derived set of differential equations expressing these principles are the generalized mathematical model. A power series—specifically a Taylor series reduced to the special case of a Maclaurin series—is used as the analytical technique by Baltzer and Shen to expand the equation of motion and continuity about a selected reference point. Lai solved the equations of motion and continuity implicitly by setting up and solving simultaneously as many equations as there are unknowns. In both methods of solutions the resulting equations are expressions in difference form, from which a change in discharge for an increment of time is derived. Subsequently, incremental changes in discharge are used in obtaining a continuous record of discharge. The discharges are determined from the model by use of an electronic digital computer.

The conditions considered to be valid in the development of the mathematical models are as follows: (1) The flow is moderately unsteady and is interpreted to be one dimensional, (2) the water is of homogeneous density, (3) the channel is prismatic and has a very small bottom slope, (4) the velocity of flow is uniform over the cross section, and (5) the variables in the equations and their derivatives are continuous functions with respect to distance and time. The flow therefore is idealized to represent the time-dependent bulk flow passing through an incremental length of a prismatic channel having finite but temporally variable cross-sectional dimensions.

DATA REQUIRED AND COMPUTATION PROCEDURE

The data required for a reach include simultaneous water stages at each end of the reach; average relations of channel width and area to depth; reach length; and amount of side inflow or outflow in the reach. Water stages are observed simultaneously at short intervals of time. Corrections to stage necessitated by incorrect recording or changes in elevation of either the stage sensor or its reference datum are applied to the stage records. In the power-series method, average relations of channel width and area to depth are defined from cross sections at a suitable number of locations in the reach. With the implicit method, relations of channel width and area to depth for each end of the reach are used. Reach length is determined by using accurate maps or by using appropriate distance-measuring techniques. The amount of side inflow or outflow in the reach is either known or estimated.

In addition to these data described, a flow-resistance coefficient(s) must be determined by using observed discharges. It is found either by solving the equations of the mathematical models in reverse order or by using a trial-and-error procedure. In the trial-and-error procedure, an estimated value of the resistance coefficient is used to compute discharges that are then compared with observed discharges. Computations are repeated until a "best fit" of computed with observed discharge is obtained. In this report, determining the "best fit" by use of the trial-and-error procedure is called a calibration. Flow resistance for unsteady flow is approximately the same as that for steady flow; therefore, the Manning equation may be used in making the first estimate of the flow-resistance coefficient.

Discharge is determined from the mathematical models by adding a computed discharge change during a short time interval (incremental discharge) to the previously determined (or known) discharge at the beginning of the time interval. By using this technique, the incremental and resultant discharges for all times are determined. The computer program provides for the computation of instantaneous discharges, or volumes of flow within a day, or daily mean discharges. Discharge is computed for one end of the reach, usually where the discharge is measured. The generalized sequence of steps used in the computation follows:

1. Read stage data.
2. Determine channel geometry (channel width and area).
3. Compute channel conveyance (related to channel geometry and inversely proportional to resistance coefficient).

4. Compute incremental discharge, ΔQ (add side inflow or subtract side outflow).
5. Compute discharge from the expression

$$Q_m = Q_k + \Delta Q,$$

where

Q_m = discharge at any time and

Q_k = discharge at one time increment prior to Q_m (the initial Q_k may be estimated because of the rapid convergence due to the damping effect of channel friction (Baltzer and Shen, 1961, p. 89; Lai, 1965, p. 28)).

APPLICATION OF MATHEMATICAL MODELS FOR DETERMINING DISCHARGE OF THE WILLAMETTE RIVER AT PORTLAND

ASSUMPTIONS AND REQUIRED DATA

To apply the mathematical models to the Willamette River at Portland, several assumptions were made and certain information was required. Flow was assumed to be moderately unsteady and of homogeneous density. Side inflow or outflow in the reach, which consists of surface runoff from local drainage, flow from a few sewer outfalls, and effluent or influent flow of ground water, was neglected in the models. Stage at 15-minute intervals of time was recorded at Ross Island Bridge (river mile 14.0) and river mile 10.3. Reach length was determined from maps. Average relations of channel width and area to depth were defined from five cross sections in the reach. Two of these cross sections were at the ends of the reach, and three were about equally spaced in between. Observed discharges were used to calibrate the models.

CALIBRATION OF THE MODEL

Discharges computed by the power-series method were compared with observed discharges determined for two tidal-cycle measurements when flows were low and for one tidal-cycle measurement and one other measurement when flows were high enough in the Willamette River to diminish the tidal effect. The computed discharges for three of the four sets of measurements are shown in figures 7-9. In figure 9, the discharge for the whole calendar day was computed. In figures 7-9, computed discharges generally agree well with observed discharges. The results of the additional calibration, when tidal effect was very small or probably did not exist

in the reach, are not presented graphically. Values of the resistance coefficients and computed and observed mean discharges for the four sets of data are summarized in the following table:

Date	Time interval (hr)	Mean discharge			Flow resistance coefficient
		Computed (cfs)	Observed (cfs)	Percent difference	
Oct. 15-16, 1963 (fig. 7)-----	25.5	13,300	12,500	+6.4	0.0450
Jan. 23, 1964-----	2	140,000	140,000	0	.0395
Mar. 16-17, 1964 (fig. 8)-----	24	65,000	63,900	+1.7	.0340
Aug. 27, 1964 (fig. 9)-----	10.5	10,200	10,300	-1.0	.0450

Data in the preceding table show that flow resistance varies with discharge. The flow-resistance coefficients for high discharges are 12 and 24 percent less than those for low discharges.

Although the computed mean discharge may agree closely with observed mean discharge when one resistance coefficient is used for the entire tidal cycle, the instantaneous computed discharges within the tidal cycle (figs. 7-9) can differ from observed discharges considerably unless a different resistance coefficient is used for different parts of the tidal cycle. For tide-affected flow, a varying resistance coefficient would reduce deformation of the computed discharge hydrograph and asynchronism of phase between the computed and observed discharge. For the data shown in figures 7-9, differences between the computed and observed instantaneous discharges were not completely resolved by the calibrations. However, because computed and observed discharges were nearly in phase for low and high discharges during the tidal cycle and mean computed and observed discharges closely agreed, one resistance coefficient was used for the entire tidal cycle.

Computed discharges were compared with observed discharges for the period of backwater during the annual flood of the Columbia River (May through August). Discharges of 28,400 and 23,600 cfs, observed respectively on June 2 and June 18, 1964, at Broadway Bridge (river mile 11.7), were assumed to equal the discharges at Ross Island Bridge (river mile 14.0). The means of the computed and observed discharges were nearly equal; however, the calibrations were considered unsatisfactory because maximum differences between computed and observed discharges were about 20 percent, and computed discharge varied irregularly, whereas observed discharge was nearly constant. Differences between computed and observed discharges may be caused by the low values of water-surface slope in the reach. Differences between simultaneous stages at the ends of the reach were of the same magnitude as the errors in these stages. The flow-resistance coefficients of 0.0370 and 0.0335, determined from the calibra-

tions for discharges affected by backwater from the annual flood of Columbia River, were different from the coefficients determined from other calibrations for the same values of discharge when flow was not affected by backwater.

During the December 1964 Willamette River flood, discharge was measured several times at Broadway Bridge (table 1). Because continuous discharges for the unusually high floodflows were wanted and observed discharges (discharges at Broadway Bridge were assumed equal to discharges at Ross Island Bridge) were available, calibrations were made by using the mathematical model in which the equations of unsteady flow were solved by the implicit method. With the implicit method, discharges can be determined accurately even when fairly long time intervals are used. Computed discharges obtained by using the implicit method agreed within 1.5 percent of observed discharges, and the values of the resistance coefficients ranged from 0.0380 at 130,000 cfs to 0.0410 at 398,000 cfs. These coefficient values are applicable only to this flood because of the concurrent high flows in the Columbia River during the flood; they are not comparable with coefficients used for the power-series method. The mathematical model based on the implicit method was used to compute bihourly flood discharges at Ross Island Bridge (river mile 14.0). Discharges from these computations are given in a flood report by Rantz and Moore (1965).

VARIATION IN DAILY FLOW PATTERN

Mean flow velocities of the Willamette River at Portland are low except during floods. When mean velocities are less than about 1 fps, both downstream and upstream flow usually occurs within a calendar day. The variations in daily flow patterns (in addition to those shown in figs. 6-9), as shown by computed discharge data at Ross Island Bridge (river mile 14.0), are presented in table 2; these data were determined from a mathematical model (power series) for a 15-day low-flow period. The selected period, September 2-16, 1964, closely follows August 27, 1964 (fig. 9), when the resistance coefficient used in the model was defined from discharges observed during one-half of a tidal-cycle measurement. For each day, the observed times and stages of high and low waters, the distribution of downstream and upstream volumes of flow within the day, the net volume of downstream flow, and the mean discharge are shown. The duration of each downstream or upstream flow within each day is unknown because the computer program did not provide this information. The times and stages of high and low waters will aid in evaluating the beginning and ending times of downstream and upstream flows when used in conjunction with the data presented in figures 6-9. The data

in table 2 show that the variation and distribution of flow during each day is related to tidal time and stage.

COMPARISON OF COMPUTED AND ROUTED DAILY MEAN DISCHARGE

A mathematical model (power series) was used to determine daily mean discharges of the Willamette River at Portland for periods during the water year October 1963 to September 1964. Daily routed discharges were compared with daily computed discharges. The stations (all in Oregon) used in routing of discharge were Willamette River at Wilsonville, Molalla River, above Pine Creek, near Wilhoit, Pudding River at Aurora, Tualatin River at West Linn, Clackamas River near Clackamas, and Johnson Creek at Sycamore. Discharge data published by the U.S. Geological Survey (1963, 1964) were used. The discharges from these upland stations were routed to Ross Island Bridge by using estimated flow times rounded off to the nearest day. Observed discharges and river stages at Portland provided some control on the accuracy of the routed discharges.

The calibration data indicate that resistance to flow varies with discharge. In the computation of daily discharges, a flow-resistance coefficient of 0.0450 was used for discharges less than 30,000 cfs (the highest downstream discharge for the two calibrations shown in figs. 7 and 9); a coefficient of 0.0340 was used for discharges between 45,000 and 75,000 cfs (the approximate range in discharges shown in fig. 8); and a resistance coefficient of 0.0395 was used for a discharge of 140,000 cfs. For discharges from 30,000 to 45,000 cfs and from 75,000 to 140,000 cfs, values of the resistance coefficient were linearly proportioned between the values for the lower and higher discharges of the applicable range of discharge. The temporal distribution of resistance coefficients used in computing daily mean discharges was based on the daily routed discharges. When proportionment of resistance coefficients was necessary, the same resistance coefficient was used for several days or longer periods and was determined from the average of routed discharges for these periods.

Daily discharge could not be determined successfully by use of the model from about mid-May through August when flow in the Willamette River was affected by varying amounts of backwater from the annual flood of the Columbia River. The two calibrations for the June data showed that the model did not give satisfactory results; however, daily discharges for the mid-May through August period were computed. The resistance coefficients used in the computations

of daily discharges were estimated on the basis of the calibrations for the June data and values of the coefficient used during the periods that preceded and followed the period mid-May through August. The estimated values of the coefficient depended upon values of routed discharge and amount of backwater. Computed daily discharges for the period of appreciable backwater differed considerably from routed daily discharges. In June, computed daily discharges were negative (flow in the upstream direction), whereas routed discharge data and storage computations showed that this was an impossibility; in July and August, the computed discharges were two to three times greater than the routed discharges.

For the 1964 water year, excluding the 3½ months of appreciable backwater from the Columbia River and some periods of unreliable stage records, daily mean discharges that were determined by using the mathematical model are compared with routed daily mean discharges (fig. 10). Figure 10 also shows the variation of daily mean stage. Average differences between computed and routed discharges greater than 30,000 cfs are on the order of plus and minus 10 percent. For the few periods when daily discharges are less than 30,000 cfs, comparisons of weekly and biweekly means indicate that computed discharges may be as much as 25 percent greater than routed discharges.

Inaccuracies in determining discharge in a river estuary can usually be reduced by selecting a reach having large water-surface slopes and reliable channel geometry and by using equipment that measures velocity and flow direction accurately. Large slopes may be obtained by using either a long reach or a reach with steep streambed gradient; a longer reach farther upstream in the Willamette River may have been better than the one used in the vicinity of Portland. Had the equipment been more sensitive to the velocity and direction of flow, the observed discharges in the Willamette River at Portland would have been more accurate. When flow-resistance coefficients vary with discharge, as they do for the Willamette River, the computer program could be improved by incorporating a method to vary the resistance coefficient with discharge on a short-term basis. The computer could select, from a defined relation of resistance coefficient to discharge, a coefficient for computing the incremental discharge. Another improvement to the computer program would be an output that shows the time of each flow reversal. These improvements in the computer program would increase the reliability and usability of discharges computed for a tidal reach.

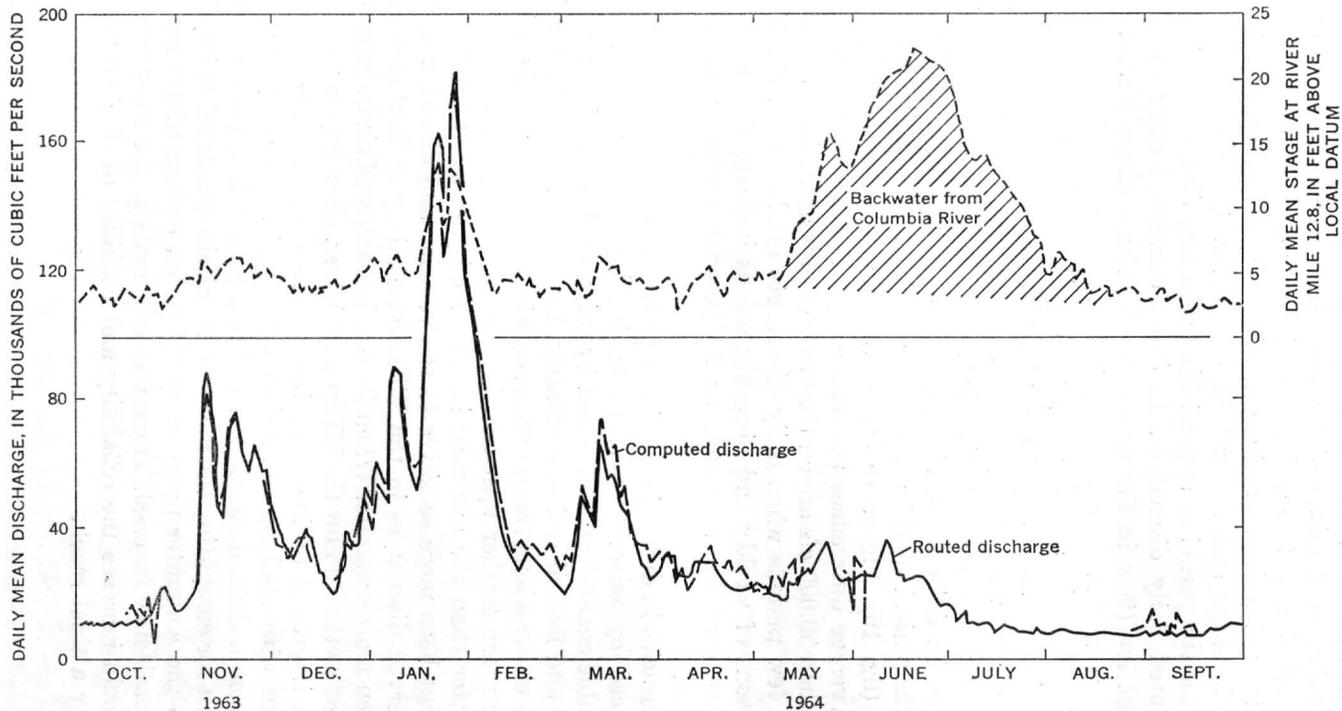


FIGURE 10.—Daily mean discharge at Ross Island Bridge (river mile 14.0), and stage at Morrison Bridge (river mile 12.8), October 1963 through September 1964.

SUMMARY AND CONCLUSIONS

Tides sometimes cause flow and velocity to reverse direction when discharge in the lower tide-affected part of the Willamette River is low. Mean velocities in a study reach at Portland ranged from an upstream velocity of 0.5 fps to a downstream velocity of 8 fps. Mean velocities in the downstream direction are less than 1 fps for about 5 months of low discharge each year. The data indicate that when the discharge of the Willamette River is 5,000 cfs, most of the water entering the reach at Ross Island Bridge (river mile 14.0) may leave the reach at river mile 10.3 about 2 days later.

Discharges at Portland were computed for short time periods, several hours to 26 hours, by use of a mathematical model at 15-minute intervals for tide-affected flows and for flows when the tidal effect was diminished. Observed discharges also were available for these same time periods. The computed discharges generally agreed well with observed discharges. Mean discharges for the data ranged from 10,300 to 140,000 cfs, and the maximum difference between the means of the computed and observed discharges was 6.4 percent. Computed discharges during backwater from the annual flood of the Columbia River did not consistently agree with observed discharges because, in part, the values of water-surface slope for the reach were extremely low. In the calibration of the mathematical models, a "trial-and-error" procedure was followed; in this method, a flow-resistance coefficient was varied until the coefficient that gave the best agreement between computed and observed mean discharges was determined. Resistance to flow varied with discharge; values of flow-resistance coefficients for one model were 0.0450 for mean discharges of 10,300 and 12,500 cfs, 0.0340 for 63,900 cfs, and 0.0395 for 140,000 cfs.

A mathematical model was used to determine daily mean discharge for about two-thirds of the year October 1963 to September 1964. Computed daily mean discharges for the remainder of the year, including the period of backwater from the annual flood of the Columbia River, were unreliable. Differences between daily means of reliable computed discharge and routed discharge were about plus or minus 10 percent for discharges greater than 30,000 cfs. For discharges less than 30,000 cfs, a comparison of weekly and biweekly mean discharges indicated that computed discharges consistently were greater (as much as 25 percent) than routed discharges. Results from computations of downstream and upstream flow volumes indicate that the variation and distribution of these flow volumes within each day are related to tidal time and stage.

Discharges determined by using the mathematical models were in reasonable agreement with comparable observed and routed dis-

charges for a reach with complicated flows. Discharge for the Willamette River at Portland probably could be more accurately determined if a longer reach were selected farther upstream. The mathematical models should be applicable for determining the discharges of many rivers, tidal or otherwise, that are subject to unsteady flow. Application of the mathematical model would be improved by incorporating into the computer program (1) a method by which the computer selected values of the resistance coefficient from a relation of resistance coefficient to discharge and (2) a method of providing the time of flow reversals.

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TABLES 1-2

TABLE 1.—Discharge measurement data of Willamette River at Portland, Oreg.

[Minus sign denotes flow in upstream direction]

Measurement	Location (bridge)	Date	Time (Pst)		Width (ft)	Area (sq ft)	Discharge (cfs)	Mean velocity (fps)	Mean stage at Morrison Bridge ¹ (local datum, ft)	Slope ² (ft per mile)
			a.m.	p.m.						
<i>1962</i>										
1	Broadway	July 6	9:50		857	38,400	8,550	0.22	8.70	0.084
2	do	July 17	9:40		857	36,300	13,700	.38	6.90	.066
3	do	Aug. 14	9:50		850	34,800	13,600	.39	3.80	.020
4	do	Aug. 20		5:50	850	34,000	10,700	.31	2.90	— .003
5	do	Aug. 21	9:25		850	34,500	7,740	.22	3.75	.111
6	do	Aug. 28	9:45		850	34,300	13,200	.39	3.50	.088
7	do	Sept. 11	9:10		850	33,000	13,900	.43	2.00	.058
8	do	Sept. 18	8:30		850	34,400	7,130	.21	3.05	.073
9	do	Sept. 26	9:10		850	33,000	14,400	.44	1.90	.066
10	do	Oct. 1		1:15	850	31,800	15,500	.49	2.10	.043
11	do	Oct. 12	9:50		850	35,400	45,200	1.28	5.10	.081
12	do	Oct. 18	9:25		850	34,900	18,500	.53	4.60	.035
13	do	do	10:25		850	35,400	28,300	.80	5.05	.088
14	do	do	11:20		850	35,400	32,300	.91	5.20	.096
15	do	do		12:20	850	35,200	31,100	.88	5.15	.088
16	do	do		1:40	850	35,200	31,800	.90	4.95	.088
17	do	do		2:35	850	35,000	33,500	.96	4.80	.088
18	do	do		3:25	850	34,900	34,200	.98	4.65	.096
19	do	do		4:30	850	34,800	33,600	.97	4.50	.096
20	do	do		5:20	850	34,100	31,800	.93	4.35	.096
21	do	do		6:20	850	34,800	25,300	.73	4.20	.035
22	do	do		7:30	850	35,200	14,800	.42	4.30	— .049
23	do	do		8:30	850	35,600	16,100	.45	4.95	— .003
24	do	do		9:20	850	35,900	29,300	.82	5.55	.066
25	do	do		10:30	850	35,700	38,200	1.07	5.80	.111
26	do	do		11:30	850	35,500	33,000	.93	5.65	.119
27	do	Oct. 19	12:30		850	35,300	32,700	.93	5.40	.111
28	do	do	1:30		850	35,100	35,600	1.01	5.05	.111
29	do	do	2:30		850	34,700	35,900	1.03	4.80	.127
30	do	do	3:25		850	34,600	34,900	1.01	4.55	.127

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31	do	do	4:20		850	34,400	33,800	.98	4.30	.119	
32	do	do	5:25		850	34,000	32,900	.97	4.00	.119	
33	do	do	6:20		850	34,000	33,300	.98	3.75	.119	
34	do	do	7:20		850	33,800	28,700	.85	3.45	.096	
35	do	do	8:20		850	34,000	22,400	.66	3.20	.058	
36	do	do	9:20		850	34,500	14,600	.42	3.25	.043	
37	do	do	10:20		850	34,800	15,700	.45	3.55	.012	
38	do	do	10:55		850	34,800	21,200	.61	3.90	.012	
39	do	Oct. 25	9:35		850	33,600	22,800	.68	2.85	.073	
40	do	Oct. 30	10:05		850	34,200	20,100	.59	3.50	.043	
41	do	Nov. 6	9:50		850	32,200	4,830	.15	1.45	.127	
42	do	Nov. 14	9:35		850	35,400	41,200	1.16	4.65	.058	
43	do	Nov. 20		12:30	850	37,800	39,700	1.05	6.75	.172	
44	do	Nov. 26	10:30		850	38,400	115,000	2.99	9.25	.096	
45	do	Nov. 30	9:20		850	38,600	95,800	2.48	9.20	.127	
46	do	Dec. 7	9:30		850	37,300	95,100	2.55	8.20	.096	
47	do	Dec. 11	9:35		850	36,200	66,300	1.83	6.45	.111	
48	do	Dec. 12	1:20		850	36,800	68,200	1.85	6.40	.096	
<i>1963</i>											
49	do	Jan. 2		2:35	850	35,300	31,800	.91	5.05	.066	
50	do	Jan. 10		2:30	850	34,100	17,100	.50	3.85	.050	
51	do	Jan. 15	10:50		850	34,800	20,900	.60	4.00	.073	
52	do	Jan. 24		2:30	850	34,200	7,900	.23	3.80	.134	
53	do	Feb. 5		1:50	850	39,800	134,000	3.37	12.20	.111	
54	do	Feb. 20	10:30		850	35,600	67,400	1.89	5.95	.134	
55	do	Mar. 14	10:10		850	34,400	26,900	.78	4.55	.066	
56	do	Apr. 1	11:25		850	38,200	126,000	3.30	9.20	.127	
57	do	Apr. 11	11:00		850	36,500	66,900	1.83	8.10	.088	
58	do	May 9	8:35		850	39,500	125,000	3.16	13.20	.150	
59	do	June 10	9:50		850	40,700	17,400	.43	12.40	.058	
60	do	July 1		1:20	850	38,700	13,500	.35	10.60	.043	
61	do	July 12	9:15		850	37,100	11,600	.31	8.20	.088	
62	do	July 19	9:25		850	37,200	11,200	.30	7.80	.050	
63	do	July 29	9:20		850	33,600	8,140	.24	3.60	.043	
64	do	Aug. 16	9:40		850	33,600	13,400	.40	3.95	.081	
65	do	Aug. 23	9:00		850	34,100	12,500	.37	4.45	.035	

See footnotes at end of table.

TABLE 1.—Discharge measurement data o Willamette River at Portland, Oreg.—Continued

Measurement	Location (bridge)	Date	Time (Pst)		Width (ft)	Area (sq ft)	Discharge (cfs)	Mean velocity (fps)	Mean stage at Morrison Bridge ¹ (local datum, ft)	Slope ² (ft per mile)
			a.m.	p.m.						
<i>1963—Con.</i>										
66	Broadway	Aug. 30	9:35		850	31,900	11,500	0.36	1.45	0.027
67	do	Sept. 20	9:50		850	33,700	15,500	.46	3.50	— .049
68	Ross Island	Oct. 15	8:30		1,550	34,300	16,600	.48	3.20	.014
69	do	do	9:55		1,550	34,300	16,700	.49	2.70	.014
70	do	do	11:20		1,550	33,600	17,500	.52	2.40	.011
71	do	do		1:00	1,550	33,000	15,700	.48	2.20	— .003
72	do	do		2:20	1,570	34,200	—15,100	— .44	3.20	— .014
73	do	do		3:50	1,580	36,400	—7,990	— .22	4.90	.022
74	do	do		5:20	1,580	37,400	15,400	.41	5.10	.022
75	do	do		7:05	1,610	36,200	24,400	.67	4.05	— .005
76	do	do		8:25	1,610	35,600	15,300	.43	3.65	.014
77	do	do		10:00	1,600	34,900	18,300	.52	3.15	.016
78	do	do		11:30	1,590	34,400	18,000	.52	2.70	.000
79	do	Oct. 16	1:00		1,590	33,700	16,800	.50	2.40	.008
80	do	do	2:30		1,550	33,800	3,310	.10	3.05	— .022
81	do	do	4:00		1,580	37,000	—10,400	— .28	4.45	.014
82	do	do	5:30		1,570	37,200	15,600	.42	4.65	.019
83	do	do	6:50		1,580	36,200	30,000	.83	3.70	.000
84	do	do	8:30		1,580	34,800	15,400	.44	3.25	.011
85	do	do	9:50		1,580	33,900	18,800	.55	2.90	.011
<i>1964</i>										
86	Broadway	Jan. 6	10:50		850	36,100	45,300	1.25	5.95	—
87	do	Jan. 23	10:00		850	37,600	140,000	3.72	9.70	.226
88	Ross Island	Mar. 16	11:00		1,645	39,000	64,700	1.66	5.75	.054
89	do	do		12:25	1,645	38,700	67,000	1.73	5.50	.060
90	do	do		2:00	1,635	38,000	67,900	1.79	5.25	.057
91	do	do		3:30	1,635	38,100	67,400	1.77	5.00	.063
92	do	do		5:00	1,615	38,000	66,100	1.74	4.90	.044
93	do	do		6:25	1,635	38,700	54,500	1.41	5.40	.024
94	do	do		7:55	1,640	40,300	61,900	1.54	6.05	.060
95	do	do		9:25	1,640	39,900	67,800	1.70	6.00	.054

96	do	Mar. 16	10:55	1,640	39,400	67,300	1.71	5.75	.060
97	do	Mar. 17	12:20	1,640	38,600	67,300	1.74	5.50	.060
98	do	do	1:50	1,630	38,900	71,100	1.83	5.25	.060
99	do	do	3:20	1,625	38,200	67,600	1.77	5.00	.057
100	do	do	4:55	1,625	38,400	64,800	1.69	4.85	.049
101	do	do	6:15	1,625	38,100	54,300	1.43	5.40	.024
102	do	do	7:50	1,660	40,100	53,900	1.34	6.40	.054
103	do	do	9:30	1,660	40,000	63,300	1.58	6.20	.054
104	do	do	10:50	1,660	39,500	62,000	1.57	5.95	.057
105	Broadway	June 2	7:40	870	43,000	28,500	.66	15.05	.011
106	do	do	9:05	870	42,400	28,500	.67	15.10	.008
107	do	do	10:20	870	42,500	27,900	.66	15.10	.003
108	do	do	11:55	870	43,200	29,300	.68	15.20	.008
109	do	do		870	42,600	28,600	.67	15.20	.003
110	do	do		870	43,100	28,200	.65	15.20	.005
111	do	June 18	8:30	870	48,000	24,100	.50	21.70	-.003
112	do	do	10:10	870	47,900	23,300	.49	21.70	.000
113	do	do	11:50	870	48,000	24,400	.51	21.75	.000
114	Ross Island	Aug. 27	8:10	1,620	37,300	159	.04	4.65	.016
115	do	do	9:15	1,620	38,200	19,400	.51	4.60	.019
116	do	do	10:25	1,620	36,300	14,500	.40	4.15	-.008
117	do	do	11:55	1,620	36,200	10,500	.29	3.80	.005
118	do	do		1,610	35,200	14,400	.41	3.40	.005
119	do	do		1,600	34,800	11,700	.34	3.10	.008
120	do	do		1,600	34,500	13,500	.39	2.80	.003
121	do	do		1,600	34,200	6,600	.19	2.70	-.014
122	do	do		1,605	35,500	-9,300	-.26	3.20	-.033
123	Broadway	Oct. 1	9:35	850	32,800	16,200	.49	2.20	-----
124	do	Dec. 24		885	51,600	398,000	7.71	27.40	.673
125	do	Dec. 29	10:10	882	47,300	257,000	5.43	22.10	.335
<i>1965</i>									
126	do	Jan. 4	10:10	850	38,700	130,000	3.36	11.20	.169
127	do	Jan. 8	10:15	850	37,600	105,000	2.79	9.20	-----

¹ Local datum equals mean sea level minus 1.55 ft.

² Approximate water-surface slopes were computed for measurements 1-67 from stages at Morrison Bridge (river mile 12.8) and river mile 6.2 and for measurements 68-127 from stages at Ross Island Bridge (river mile 14.0) and river mile 10.3.

TABLE 2.—Times and stages of high and low waters, downstream and upstream volumes of flow, net volume of flow, and discharge of Willamette River at Portland, Oreg., for each day during September 2–16, 1964

Day	High tides			Low tides			Chronological proportion of daily flow into downstream and upstream volumes ² (millions of cu ft)				Daily net volume of flow (millions of cu ft)	Daily mean discharge (cfs)	
	Time (Pst)		Stage ¹ (ft)	Time (Pst)		Stage ¹ (ft)							
	a.m.	p.m.		a.m.	p.m.								
2	2:00		4.9	12:00	m.	1.6	-9	669	-48	530		1,142	13,200
		3:30	3.7		11:00	2.0							
3	3:00		5.1		1:00	1.8	-35	832	-4	580		1,373	15,900
		4:30	4.2		12:00	2.2							
4	4:00		5.5		2:00	2.3	23	-56	599	-85	409	890	10,300
		5:30	4.8										
5	5:00		5.9	1:00		2.7	50	-120	567	-62	485	920	10,600
		6:00	5.1		2:30	2.6							
6	6:00		5.5	2:00		2.4	146	-78	607	-71	423	1,027	11,900
		6:30	4.8		3:00	2.0							
7	6:30		4.9	2:30		1.6	145	-117	502	-116	320	734	8,500
		7:30	4.8		3:30	1.5							
8	7:00		4.8	3:30		1.7	167	-104	587	-73	368	945	10,900
		8:00	5.0		3:30	1.8							
9	8:00		4.5	4:00		1.9	268	-54	536	-125	273	898	10,400
		8:30	4.8		4:00	1.6							
10	9:00		4.2	5:00		1.9	353	-5	692	-80	274	1,234	14,300
		8:30	5.0		4:30	2.2							
11	9:30		3.6	6:00		2.1	411	-1	513	-45	253	1,131	13,100
		9:30	4.4		5:00	1.6							
12	10:30		2.7	7:00		1.3	422	-1	387	-82	178	904	10,500
		10:00	4.2		5:30	1.2							
13	11:30		2.7	7:30		1.4	381	-17	383	-4	181	924	10,700
		11:00	3.8		6:00	1.5							
14		12:30	2.1	9:00		0.9	530		366	-39	75	932	10,800
		11:30	3.3		7:00	1.2							
15		1:30	2.2	9:00		0.8	612	-18	295			889	10,300
					8:00	1.4							
16	12:30		3.5	10:30		0.8	614	-65	362	-79		832	9,630
		2:30	3.1		9:00	1.8							

¹ Measured at Morrison Bridge and referred to local datum that is 1.55 ft lower than mean sea level.

² Negative sign indicates flow in the upstream direction.

