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GEOLOGICAL SURVEY PROFESSIONAL PAPER 433-P

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

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By G. A. LUTZ, D. W. HUBBELL, *and* H. H. STEVENS, JR.

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Physical quantity	*Multiply English units*	*By*	*To obtain metric units*
Length	Feet (ft)	0.3048	Metres (m)
		30.48	Centimetres (cm)
	Yards (yd)	.9144	Metres (m)
	Miles (mi)	1.609	Kilometres (km)
Area	Square miles (mi^2)	2.589	Square kilometres (km^2)
Volume	Cubic yards (yd^3)	.7646	Cubic metres (m^3)
Velocity	Feet per second (ft/s)	.3048	Metres per second (m/s)
Water discharge	Cubic feet per second (ft^3/s)	.02832	Cubic metres per second (m^3/s)

TRANSPORT OF RADIONUCLIDES BY STREAMS

DISCHARGE AND FLOW DISTRIBUTION, COLUMBIA RIVER ESTUARY

By G. A. LUTZ, D. W. HUBBELL, and H. H. STEVENS, JR.

ABSTRACT

Low-level radioactive wastes were discharged into the Columbia River at the Hanford Reservation, U.S. Atomic Energy Commission, near Richland, Wash., from 1944 until early 1971. The various radionuclides that made up the waste in the river associated with sediment and biota or remained in solution and were subsequently distributed throughout the estuary and into the Pacific Ocean. To provide information on the amount of radionuclides being transported through the estuary, continuous records of water discharge were obtained near both the upper and the lower ends of the estuary during the period 1968–70.

Complex velocity distributions, mainly due to salinity gradients, made it impossible to use conventional methods of measuring discharge in the lower part of the estuary; however, a new technique, MOVD (measurement of velocity distribution by moving boat), was developed for determining the magnitude and direction of the water velocity throughout the entire depth at a vertical. Repetitive measurements at a series of verticals in cross sections at the Beaver Army Terminal, Oreg., Columbia River mile 53.3, and at Astoria, Oreg., Columbia River mile 14, defined flow hydrographs at these locations during half tidal cycles on a number of occasions.

The defined flow hydrographs, in turn, were used to calibrate mathematical models for computing continuous records of discharge. The models, which were necessary mainly because of the influence of the tide, consisted of partial differential equations that were written to express the conservation of mass and momentum in one-dimensional unsteady homogeneous-density open-channel flow and were solved by the method of characteristics.

At Beaver Army Terminal, which is in the freshwater part of the estuary, application of the mathematical model was fairly straight forward, and discharges computed every 15 minutes for May 1968 through June 1970 are considered to be very accurate.

At Astoria, where salinity gradients are present and channel geometry is complex, it was necessary with the model to vary the flow resistance coefficient throughout each ebb and flood period in order to compute discharge hydrographs having the same shapes as the hydrographs defined by measurements. In addition, in order to compute hydrographs that compared closely in magnitude with defined hydrographs, a factor had to be applied daily to adjust measured water-surface slopes that are used in the model. The factor was determined by trial by comparing model discharges with daily mean discharges from a simple volumetric relation based on the daily mean discharge at Beaver Army Terminal and the net daily storage of water between Astoria and Beaver Army Terminal. Monthly mean discharges determined from model discharges computed every 15 minutes from March 1968 through June 1970 by this technique compare closely with monthly mean discharges determined by the routing technique used by the Northwest Water Resources Data Center. Computations show that daily mean discharges at Astoria follow a cyclic pattern; hence, they cannot be used as indicators of the upland freshwater discharge.

When the daily mean discharge at Beaver Army Terminal is less than about 165,000 ft^3/s (cubic feet per second) or 4,670 m^3/s (cubic metres per second), the south (navigational) channel at Astoria conveys proportionately more flow during the ebb than during the flood, and the remainder of the cross section conveys proportionately more flow during the flood than the ebb. This produces a net clockwise circulation of water between the two channels. For daily mean discharges from about 165,000 to 190,000 ft^3/s (4,670 to 5,380 m^3/s), there is a net counterclockwise circulation, and for those over 190,000 ft^3/s (5,380 m^3/s) the circulation also is clockwise.

In the north channel at Astoria, flow near the bottom is predominantly landward for mean discharges at the measurement cross section less than about 340,000 ft^3/s (9,630 m^3/s), whereas flow in the upper layers is predominantly seaward for all discharges. The pattern in the south (navigational) channel is roughly similar to that in the north channel, but in the middle channel the flow-predominance pattern is more complex.

In the navigational channel on September 14, 1969, when the daily mean discharge at Astoria was 208,000 ft^3/s (5,890 m^3/s), saltwater reached Columbia River mile 22 and the flow was predominantly seaward for all depths upstream from Columbia River mile 17.5. Downstream from that point, flow in the lower half of the depth was predominantly landward, whereas flow in the upper half was predominantly seaward. However, on May 23, 1970, when the daily mean discharge at Astoria was 437,000 ft^3/s (12,400 m^3/s), seawater reached only Columbia River mile 14, and the flow was predominantly seaward throughout the entire study reach, which extended from Columbia River miles 5.6 to 16.2.

INTRODUCTION AND ACKNOWLEDGMENTS

Low-level radioactive wastes were discharged into the Columbia River at the Hanford Reservation, U.S. Atomic Energy Commission, near Richland, Wash. (fig. 1), from the time of the initiation of nuclear-reactor operations in 1944 until early in 1971. The wastes resulted primarily from the neutron activation of chemical constituents in treated Columbia River water that was used to cool the nuclear reactors. Once the radionuclides were released to the river environment, they remained in solution or became associated with

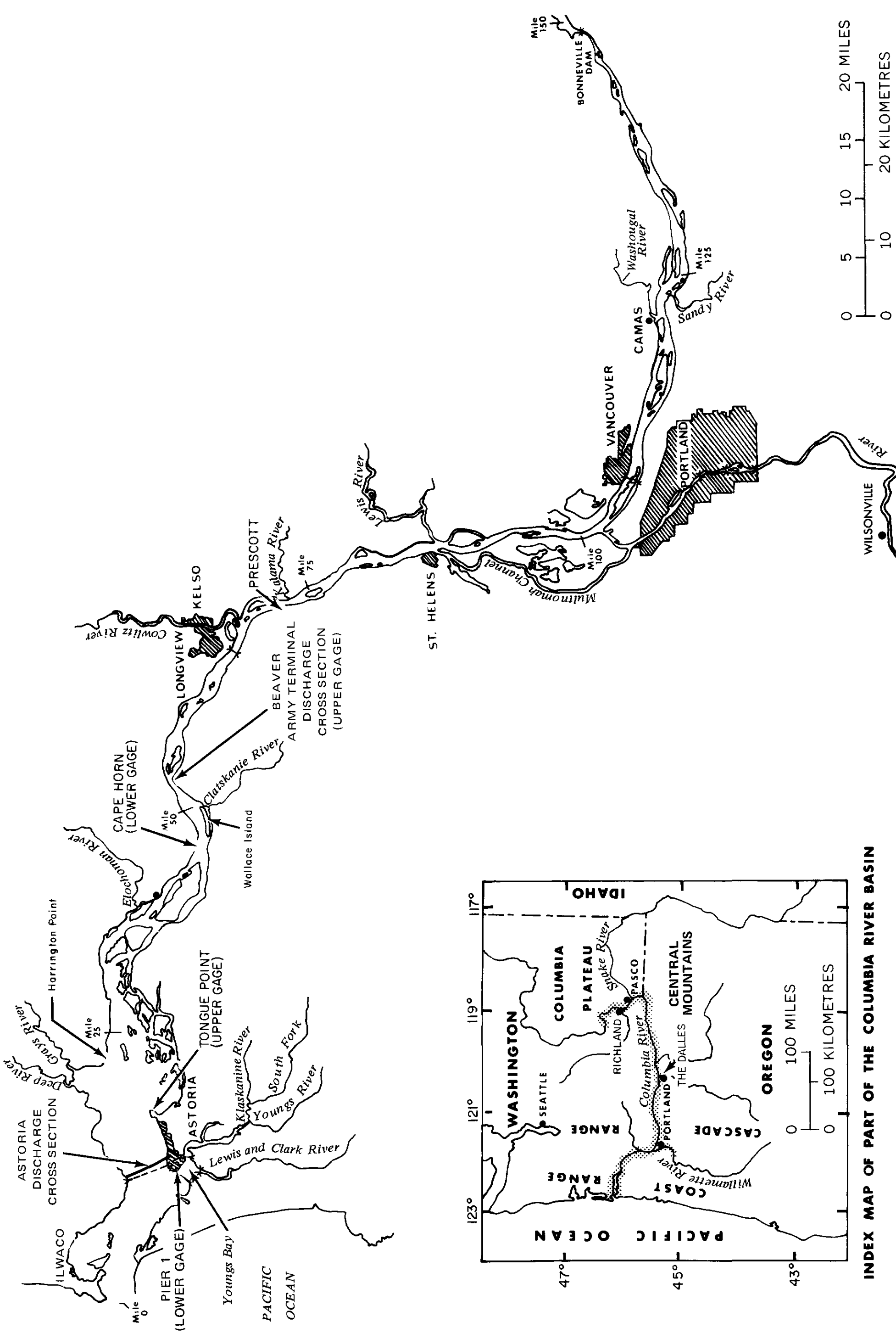

FIGURE 1. — Lower Columbia River and estuary.

sediment or stream biota. Although much of the radioactivity decayed, some radionuclides were transported by the associated media downstream and ultimately reached the Columbia River estuary and, thence, the Pacific Ocean.

In late 1963 the U.S. Geological Survey undertook, in cooperation with the U.S. Atomic Energy Commission, an investigation of the movement of radionuclides in the Columbia River estuary downstream from CRM 65.8 (Columbia River mile) at Longview, Wash. (fig. 1). One of the purposes of the investigation was to define rates of transport of radionuclides at cross sections along the longitudinal axis of the estuary. To accomplish this end, it was necessary to obtain continuous records of total water discharge at the cross sections of interest. This report briefly describes the equipment and techniques used to obtain measurements of the flow, discusses the mathematical models utilized to determine discharges at two different cross sections, presents discharge data, and suggests the nature of circulation patterns in the vicinity of Astoria, Oreg., CRM 14.

In the early phases of the investigation, Chintu Lai aided in the selection of the farthest upstream reach, which is in the vicinity of the former Beaver Army Terminal, Oreg., CRM 53.3 (fig. 1), and prepared a computer program for processing data obtained during discharge measurements in the field. E. A. Prych contributed substantially to the physical installation of water-stage recording equipment utilized throughout the investigation, to the development of the discharge-measuring system, and to some of the early techniques for processing measurement data.

GENERALIZED DESCRIPTION OF THE ESTUARY

The Columbia River estuary receives freshwater flow from throughout a drainage area of 259,000 mi^2 (671,000 km^2). Based on long-term records at The Dalles, Oreg., CRM 189 (U.S. Geological Survey, 1971), the flow at Vancouver, Wash., CRM 107 (fig. 1), averages about 200,000 ft^3/s (5,660 m^3/s). During 1963–70 daily mean discharges at Vancouver ranged from 78,900 to 675,000 ft^3/s (2,230 to 19,100 m^3/s; U.S. Geological Survey, 1971).

Tides of the mixed-type characteristic of the Pacific coast, two high waters and two low waters during a 24.8-hour period, produce landward (upstream) flows in the estuary that have been measured as far upstream as Prescott, Oreg., CRM 72 (U.S. Geological Survey, 1970). At the mouth, CRM 0, the mean tidal range (U.S. Coast and Geodetic Survey, 1969, p. 172–173) is 5.6 feet (1.7 m), and the diurnal range is 7.5 feet (2.3 m). Tide ranges are amplified somewhat within the estuary and are a maximum in the vicinity of Youngs Bay, CRM 12 (fig. 1); the mean and diurnal tide ranges at this location are 6.7 and 8.6 feet (2.0 and 2.6 m), respectively. In the vicinity of the Beaver Army Terminal, Oreg., CRM 53.3, the mean the diurnal tide ranges are approximately 4.3 and 5.2 feet (1.3 and 1.6 m), respectively. During periods of low and moderate runoff, tides influence flow in the Columbia River as far upstream as Bonneville Dam, CRM 145 (fig. 1); at Vancouver, CRM 107, the tidal influence persists for all flows to as much as 500.000 ft^3/s (14,200 m^3/s).

The combination of moderate tide ranges and a large freshwater discharge produces a dynamic environment within the estuary. At low upland flows, cold saline water from the ocean intrudes as far upstream as Harrington Point, Wash., CRM 23 (fig. 1). At times of high upland flow, salinity intrusion is limited to the lower part of the estuary. For instance, on May 23, 1970, when the daily mean discharge through the cross section at CRM 14 was about 437,000 ft^3/s (12,400 m^3/s), measurable salinities extended upstream only to about CRM 14. As a result of the wide variation in the patterns of salinity intrusion, salinity gradients in the three coordinate directions vary significantly throughout the year. According to the classification of Pritchard (1955), the Columbia River estuary is in the general category of a coastal-plain estuary that exhibits characteristics most of the time of a type-B (partly mixed) estuary.

Velocity distributions in both the vertical and lateral directions vary significantly with time as a result of tidal motion, large freshwater discharges, and salinity (density) gradients. Several observed velocity distributions in the vertical direction are shown in figure 2. The lack of uniformity, with time and position, in the distribution of velocity complicates the definition of flow and necessitates detailed velocity measurements in both the vertical and lateral directions.

DISCHARGE-MEASUREMENT EQUIPMENT AND TECHNIQUES

In order to define the temporal variation of discharge through a cross section in the estuary it is necessary to define both the vertical and lateral distributions of velocity by repetitive measurements throughout the tidal cycle. Because of the cycle changes in velocity with time, it is essential that individual velocity measurements be obtained rapidly. A unique measuring system suitable for operation on a continuously moving boat was developed (Prych and others, 1967) to meet this requirement. With the system, the magnitude and direction of water velocities relative to the boat are measured throughout the depth with a modified version of a VADA (velocity-azimuth-depth assembly) unit (Lockett and Kidby, 1961; Barron, 1963) that is fitted with a modified Ott cosine-propeller current meter (fig. 3). Concurrently, the heading, the speed over the bottom, and the drift angle of the boat are determined from a compass and an

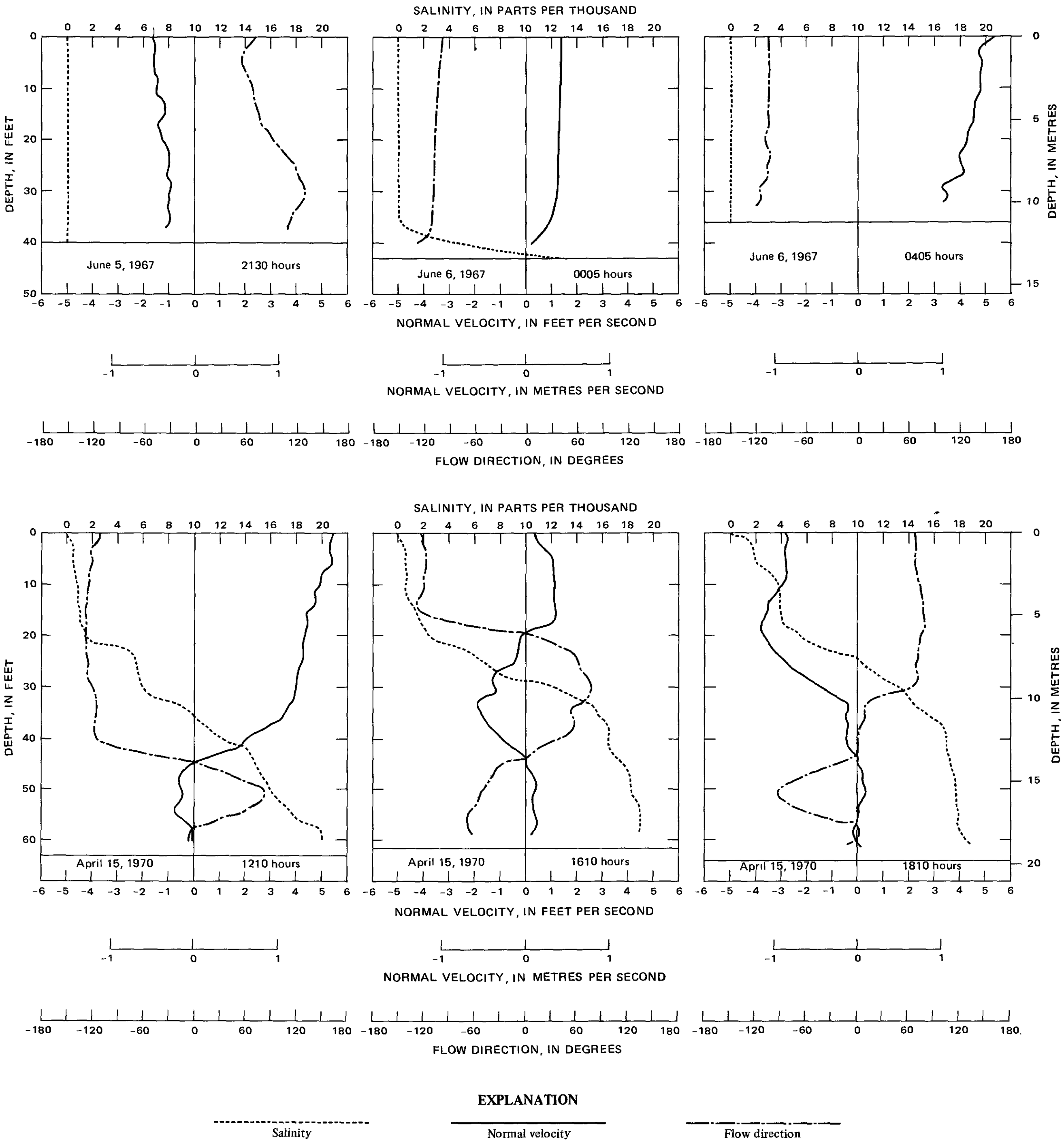

FIGURE 2. — Observed vertical distributions of salinity, normal velocity, and flow direction at CRM 14 at various times in tidal cycles during periods of high (June 1967) and moderate (April 1970) upland flows. Indicated normal velocities are components normal to the measurement cross section of absolute velocity vectors; negative values designate upstream flow. Flow directions give the angle of approach of the flow to the cross section; positive and negative values pertain to angles measured clockwise and counterclockwise, respectively, from the southward heading of the cross section; hence, an angle of −90° indicates downstream flow normal to the cross section. Tide height during each set of distributions can be deduced by considering the bottom (solid horizontal line) to be at a fixed elevation.

on-board sonic navigation unit. Outputs from all sensors, including the velocity meter, are analog signals that either are or can be displayed visually on strip-chart recorders (fig. 4), and all signals are sampled on command, virtually instantaneously, by a moderately high speed scanning digital voltmeter. Voltages, in turn, are recorded (fig. 4) on magnetic tape (except the signal from the depth transducer that indicates the height of the VADA unit above the bed; this signal is recorded only as an analog signal on strip chart).

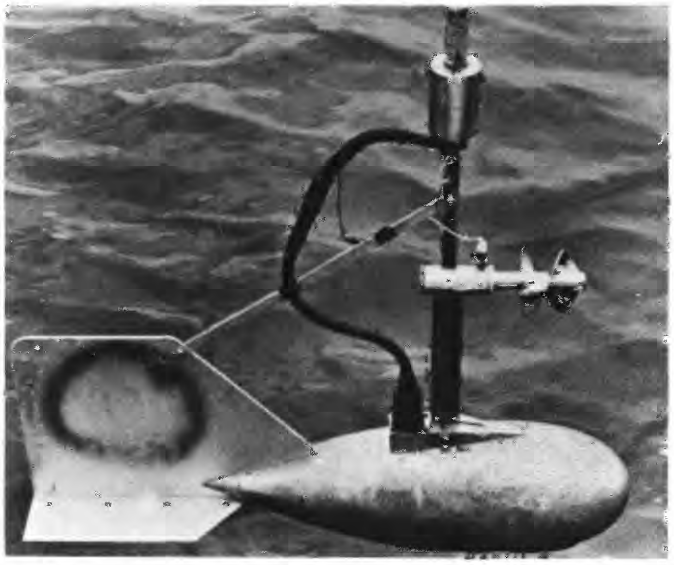

FIGURE 3. — Velocity-azimuth-depth assembly (from Prych and others, 1967).

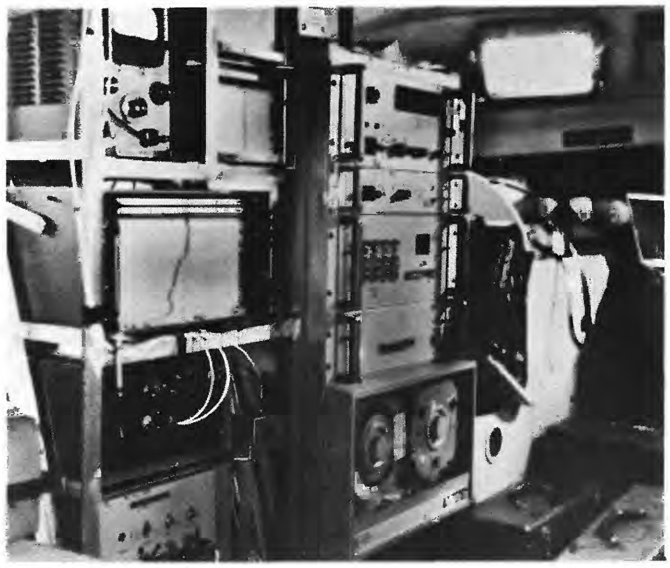

FIGURE 4. — Data-acquisition system. The strip-chart recorders provide continuous real-time displays of sensor signals, and the magnetic-tape unit digitizes data for computer processing.

For the definition of the velocity distribution at a vertical, the boat is positioned and kept as stationary as possible by heading into the current and using power. Ordinarily, an attempt is made to maintain slight headway during the measurement. The VADA unit is lowered to within 2 to 3 feet (0.6 to 0.9 m) of the streambed, allowed to stabilize, and then raised slowly to the surface. The vertical velocity of the unit is regulated so that the angle of attack of the water relative to the meter is less than 20°. During the upward traverse, the analog signals are sampled and recorded every 3 seconds. Later, the recorded data (relative speed and direction of the current, absolute speed and drift angle of the boat, and boat heading) are combined by vector addition, using a digital computer, to yield the absolute velocity (speed and direction) of the current at each data point throughout the depth.

Discharge is measured by observing the entire velocity profile at a series of verticals along a cross section. Ordinarily, measurements are made at about 20 verticals during each traverse of the cross section. As soon as a traverse is completed, the boat is moved to the opposite side of the estuary, and the measurement sequence is repeated. The exact location of each measurement vertical is determined by triangulation with hydrographic sextant; hence, measurement sequences can only be made during daylight hours.

For the computation of discharge, the velocity component normal to the cross section at each data point in a vertical is used to calculate a discharge per unit width for the increment of depth represented by the point. The incremental discharges are summed over the depth to give a discharge per unit width for the entire vertical. The discharge for the section represented by the vertical is determined by multiplying the section width, which is computed according to the standard midsection method, by the discharge per unit width for the vertical. Because discharge changes rapidly with time, section discharges are not summed to give a total discharge; rather, the cross section is divided into several parts and the discharge through each part is determined by summing the section discharges within the part. Hydrographs are then obtained by plotting the discharge for each part against the corresponding mean times when the verticals were measured. The total discharge hydrograph is defined by summing the hydrographs for the individual parts.

In addition to this "standard" method, which hereinafter will be called the MOVD (measurement of velocity distribution by moving boat) method, discharge measurements sometimes were made at the Beaver Army Terminal cross section by a modification of the moving-boat technique developed by Smoot and Novak (1969). With the Smoot-Novak method, a boat is traversed across the width of the measuring section by "crabbing" along a range line that is normal to the flow direction. During the traverse, a current-meter-vane unit, which is mounted to the boat 3 to 4 feet (0.9 to 1.2 m) below the water surface by a rod and angle-indicator assembly, freely and continuously alines in a direction parallel to the vector sum of the lateral velocity of the boat and the velocity of flow. Periodically noting the current-meter velocity and the vane direction permits the velocity of flow normal to the cross section at the current-meter depth, V, to be determined at a series of data points across the width from

$$V = V_V \sin\alpha,$$

where

V_V is the instantaneous flow velocity relative to the boat as measured by the current meter;

and

α is the complementary angle between the cross-section line and the current-meter direction.

The lateral positions of the data points, where depth as well as velocity and current-meter direction are observed, are established each time the filament of water passing the current meter reaches a preselected length, L_V. That is, observations are made whenever the current meter has turned a preselected number of revolutions. (Because the relationship between velocity and rate of rotation of the current meter is linear, a given number of revolutions is equivalent to a particular filament length.) If the flow is normal to the cross section, the width between data points, L_B, equals $L_V \cos \alpha$. Section discharges are computed by the standard midsection method from values of V, L_B, and the depth, d. Total discharge is obtained by correcting (multiplying) the sum of the section discharges by (1) a width-correction factor, which is the ratio of the measured width to the sum of the computed section widths (this factor adjusts for variations in boat course and for variations in the flow direction relative to cross section), and by (2) a velocity-correction factor, which is the ratio of the mean velocity in a vertical to velocity at the current-meter depth (this ratio is determined from detailed velocity-distribution data at several verticals).

The modified technique used at the Beaver Army Terminal is essentially the same as the Smoot-Novak method; however, it was designed to permit use of the VADA and the navigation units. During the lateral traverse, the VADA unit was suspended 15 feet (4.6 m) below the water surface and lateral data points were established at 10-yard (9.1-m) intervals as indicated by the navigation unit. All variables were measured in the same way as in the MOVD method, and the velocity of flow normal to the cross section at the 15 foot (4.6-m) level was determined by vector addition in the same way as in the MOVD method. The widths between data points, except the sections adjacent to the shores, were assumed to be constant and were determined by dividing the measured width between the first and last stations by one less than the total number of data points. Section discharges were computed by the midsection method and summed to give a total discharge. This total was altered by a velocity-correction factor that, in effect, adjusted the velocity at the 15-foot (4.6-m) level to represent the mean velocity in the vertical. The factor, c, was determined as

$$c=0.82(d/y)^{0.2},$$

where

y is the height of the velocity meter above the bed,

by assuming (1) the parabolic velocity-distribution law

$$V_y=C(y)^{1/n},$$

where

V_y is the velocity at a height, y;

C is a constant for given conditions (C cancels in the derivation of c); and

n is a constant assumed to be equal to 5.0 for a rough boundary (Savini and Bodhaine, 1971, p. 12),

and (2) the condition that the mean velocity, $\overline{V}$, in the vertical occurs at $y=0.368\ d$. The correction factor, c, was applied as a constant for all verticals by taking d equal to the mean depth in the cross section and y equal to the mean depth minus 15 feet (4.6 m).

MATHEMATICAL-MODEL THEORY

Whenever unsteady flow conditions exist, such as in an estuary, a unique relation between water-surface elevation (stage) and discharge does not exist, and continuous records of discharge cannot be obtained by conventional methods of discharge computation. In 1961, Baltzer and Shen developed a mathematical model for computing discharge for unsteady flow conditions. Two other methods for computing discharges for unsteady flow conditions have been developed by Lai (1965a; 1965b). All three mathematical models are based on the equations of continuity and motion expressed in one spatial dimension and simplified by approximations to represent open-channel flow.

The equation of continuity, or conservation-of-mass equation, states that the net change in discharge in a reach is equal to the change in storage in the reach — that is (fig. 5, definition sketch),

mass in − mass out + side inflow = increase of mass within the reach,

or

$$\rho Au-\left[\rho Au+\frac{\partial(\rho Au)}{\partial x}\Delta x\right]+\rho q\Delta x=\rho B\frac{\partial Z}{\partial t}\Delta x,$$

where

ρ is the density of water;

A is the channel cross-section area;

u is the flow velocity in the longitudinal direction;

Z is the elevation of water surface;

t is time;

q is the lateral inflow per unit length;

x is a distance measured along the x axis; and

B is the top width of the cross section.

The equation of motion, or conservation-of-momentum equation, 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. Applying Newton's Law

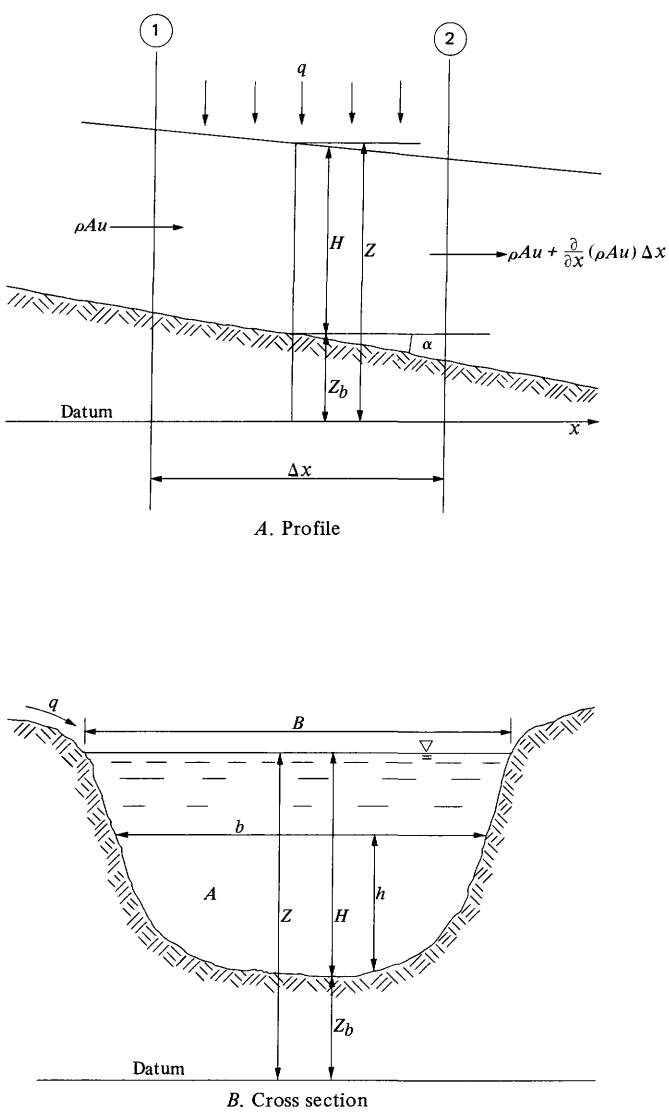

FIGURE 5. — Definition sketch of an element of channel (from Lai, 1965a). See text for description of symbols.

of momentum, the equation of motion can be obtained as

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+g\frac{\partial Z}{\partial x}+g\frac{k}{R^{4/3}}u\,|\,u\,|+\frac{qu}{A}=0,$$

where

- g is acceleration due to gravity;
- R is the hydraulic radius; and
- k is a parameter depending on the flow-resistance coefficient, η which is similar to Manning's n.

The assumptions made in the derivation of the above two basic partial differential equations for describing unsteady flow are (1) the flow is moderately unsteady, (2) the fluid is of homogeneous density, (3) the channel is prismatic and has a very mild bottom slope, (4) the velocity of flow is uniform over the cross section, (5) the variables in the equations and their derivatives are continuous functions with respect to distance and time, and (6) the flow-resistance coefficient is the same as that for steady flow and, hence, can be approximated from the Chézy or Manning formulas.

Because an explicit analytical solution for the set of partial differential equations is not possible, Baltzer and Shen (1961) developed a power-series method of solution. The method is based on a Maclaurin-series expansion of the two equations about a reference point along the waterway at a given instant in time. The expansion is made in terms of the stage at the reference point and the associated stage at a nearby point, and then it is rewritten in finite-difference form with respect to time in order to obtain the change in discharge during a finite increment of time; discharge is computed from appropriate boundary conditions in a stepwise manner throughout time. Lai (1965a) developed another means of solution by applying the method of characteristics which transforms the basic partial differential equations into four ordinary differential equations. These four equations are treated as finite-difference equations for which unique solutions of the flow at successive times are readily possible with the known boundary conditions. He also (Lai, 1965b) utilized the implicit method in which the two basic partial differential equations are directly transformed into corresponding finite-difference equations; by setting up as many equations as there are unknown dependent variables, the equations are solved simultaneously for all unknowns at the advanced (or forward) time level, using the appropriate boundary conditions, to obtain flow at subsequent times.

The three methods of computing discharges for unsteady flow conditions are designed for use on high-speed digital computers. All three methods have produced accurate results in the freshwater parts of tide-affected streams or in well-mixed tidal estuaries (Baltzer and Lai, 1968); however, depending on the physical properties of the site, one method may be more appropriate than the others.

Recently, two-dimensional flow models have been developed to account for variations in either the lateral or vertical directions, as well as in the longitudinal direction. These models usually must be solved with extensive quantities of input data and by using computers having extremely large core memory. Also, like the one-dimensional models, they represent flow in well-mixed estuaries and are not adequate to describe complicated saltwater circulation.

DEVELOPMENT OF MATHEMATICAL MODELS

To meet the need for radionuclide and suspended-sediment transport rates through the upper and lower parts of the estuary, measurement cross sections where discharges would be defined were established at Beaver Army Terminal and at Astoria (fig. 1). At both these locations tides produce unsteady flow; hence, the most feasible means for obtaining records of water discharge was to apply transient-flow models. When data collection for discharge determinations began in 1966, only one-dimensional models, as previously described, were available, and computer memory systems were relatively limited. As a result, the field program was designed to provide essential data for only the one-dimensional approach.

Physical conditions at the Beaver Army Terminal can be represented moderately well by a one-dimensional model; however, at Astoria, significant salinity gradients and complex flow patterns introduce serious deviations from one dimensionality. Because of the differences, the development and application of the model for each location was substantially different.

In order to adapt and use on a continuous basis any of the three mathematical models previously described, certain boundary values and other data are required. Boundary values include (1) frequent periodic simultaneous stages at the extremities of a reach that is sufficiently long to permit the accurage determination of the fall (water-surface slope), yet is not so long as to violate limitations implicit in the mathematical solutions; and (2) for all stages, values of the channel width, depth, and area that are representative of the reach. In addition, reach length and inflow or outflow within the reach must be known, and actual hydrographs of discharge at a cross section in the reach (preferably at oner end) must be abailable to define parameters of the model.

BEAVER ARMY TERMINAL REACH

The Beaver Army Terminal (hereinafter referred to as "Beaver") is a deactivated military reservation located on the Oregon side of the Columbia River at CRM 53.3 (fig. 1). The cross section at Beaver is at one of the narrowest parts of the estuary (about 2,300 ft, or 700 m, wide), is devoid of any islands or extensive flats, is reasonably uniform in depth, and has a fairly uniform lateral velocity distribution. As such, it is an excellent measurement and sampling section. To develop a mathematical model of discharge at Beaver, two sites had to be selected for the collection of water-stage data. The upstream gage was installed on the main wharf at Beaver and the downstream gage was installed at Cape Horn, Wash., CRM 47.6 (fig. 1). Both stations were equipped with digital and graphic water-stage recorders. A-C synchronous motor-driven timers actuated the digital recorders essentially simultaneously (within 30 seconds of each other) every 15 minutes. A float and stilling-well system was used to operate the gage at Beaver and a "bubble gage" (Barron, 1963) was used at Cape Horn. Because at times the water level within the reach is lower than mean sea level and the digital recorders used require the stage data to be always positive, "MSL 1929" −10 feet (3.048 m) was selected as the gage datum for the reach. The reach between the two gages (fig. 6) includes Wallace Island and surficial areas that are regularly inundated by the tide. However, the reach is relatively straight, and most of the flow is conveyed in the navigational channel.

The geometry of the reach was defined from lateral profile data obtained at 11 cross sections (fig. 6) that were spaced roughly equidistant apart. The configuration of the wetted perimeter of each cross section was determined by sounding depths with a recording fathometer and measuring horizontal distances with the navigation unit in the deep parts of the channel and with a Tellurometer in the shallow parts where only a small skiff could go. The profile above the waterline was defined by using a hand level, level rod, and survey chain. Data from all defined cross sections were combined according to the procedures outlined by Davidian (1964) to provide relations between the water-surface elevation, cross-sectional area, and width for average cross sections representative of the entire reach or of several subreaches. Lengths between sections of the reach were measured along the centerline of the main channel on a U.S. Coast and Geodetic Survey navigation chart of the Columbia River.

Discharge hydrographs were defined just downstream from the upper gage at Beaver by applying the MOVD method and the modified Smoot-Novak method to measure the flow. In order to obtain optimum information, measurements were scheduled so that both a complete ebb and a complete flood period would be defined during the measurement sequence.

Discharge measurements at Beaver began on March 24, 1966, and were concluded on April 1, 1970. During this period, 17 hydrographs of discharge, or a total of 119 individual lateral traverses, were made during varying flow conditions. A summary is given in table 1. Examination of table 1 shows that most of the hydrographs were well defined over a time span of about 10 hours. Those of less than about 8 hours resulted because of equipment malfunction or bad weather conditions. Both occurrences could cause a late start or an early termination of the measurement sequence.

CALIBRATION PROCEDURE

The term "calibration" in this report refers to the process of determining values for the parameters in a mathematical model that provide the best possible fit between measured discharge hydrographs (hydrographs defined from discharge measurements) and hydrographs computed with the model. To calibrate the

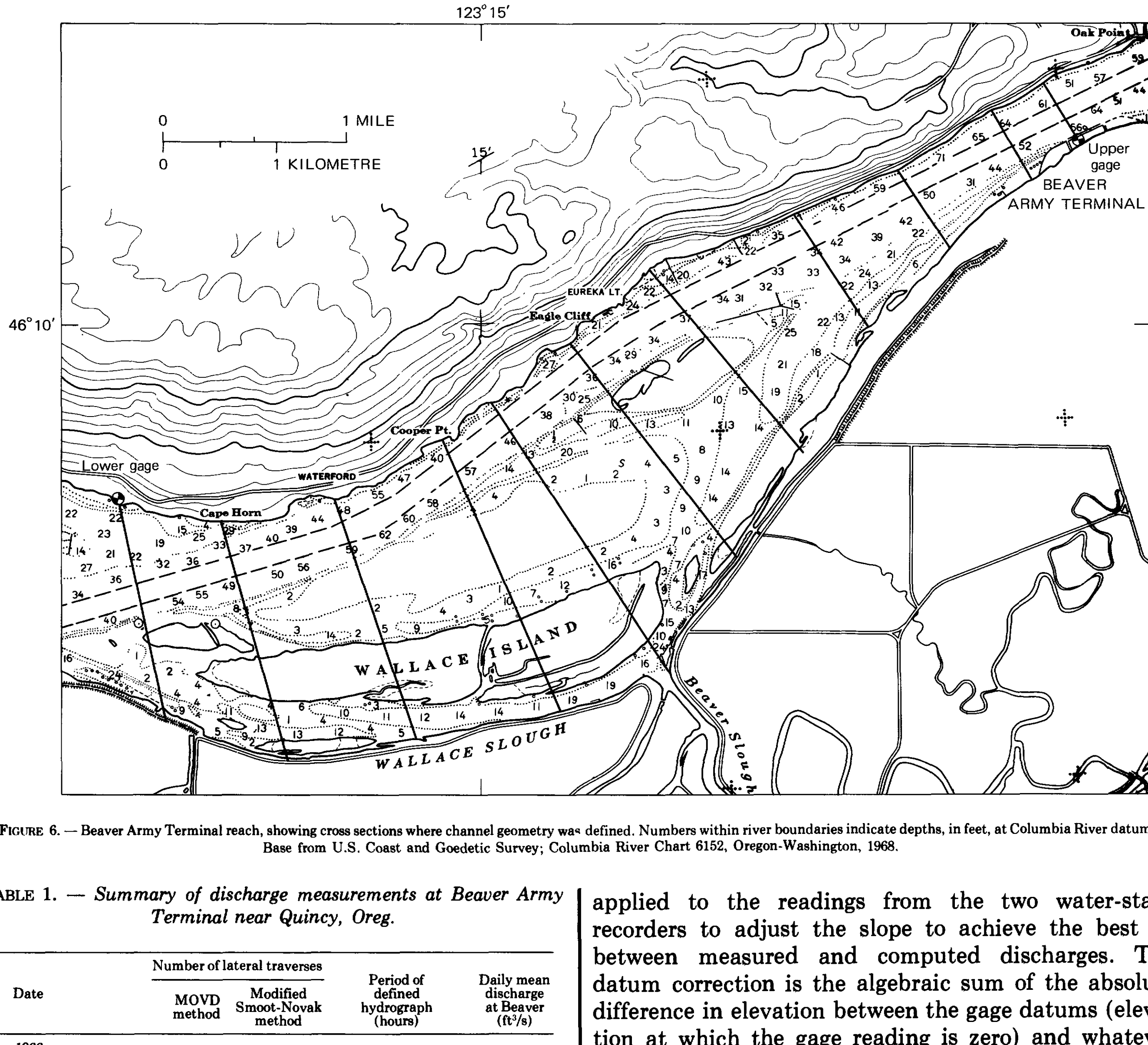

FIGURE 6. — Beaver Army Terminal reach, showing cross sections where channel geometry was defined. Numbers within river boundaries indicate depths, in feet, at Columbia River datum. Base from U.S. Coast and Geodetic Survey; Columbia River Chart 6152, Oregon-Washington, 1968.

TABLE 1. — *Summary of discharge measurements at Beaver Army Terminal near Quincy, Oreg.*

Date	Number of lateral traverses: MOVD method	Number of lateral traverses: Modified Smoot-Novak method	Period of defined hydrograph (hours)	Daily mean discharge at Beaver (ft³/s)
1966				
Mar. 24	6	0	9.8	210,000
May 19	7	0	10	304,000
June 30	7	0	10	306,000
Aug. 2	6	0	10	198,000
Oct. 21	3	0	5.3	106,000
1967				
June 26	0	4	2	637,000
July 25	6	1	11	250,000
Aug. 20	5	1	9.5	130,000
Sept. 12	4	5	8.3	81,000
1968				
Feb. 15	2	5	4.5	163,000
May 7	6	3	10.5	148,000
July 4	5	7	11.5	297,000
Oct. 22	5	7	7.3	152,000
1969				
Apr. 11	0	7	5	404,000
June 12	5	0	10.3	450,000
July 23	4	3	10.5	181,000
1970				
Apr. 1	5	0	8	172,000

mathematical models adopted for the Beaver reach values for two parameters had to be determined. The first was the datum correction, which is the factor that is applied to the readings from the two water-stage recorders to adjust the slope to achieve the best fit between measured and computed discharges. The datum correction is the algebraic sum of the absolute difference in elevation between the gage datums (elevation at which the gage reading is zero) and whatever other correction is necessary to obtain accurate discharges with the model. Ordinarily, levels are run between the two gages to evaluate or eliminate any difference between the gage datums; however, because the gages for the Beaver reach were located on opposite banks of the estuary, this was not practicable. Instead, each gage datum was referenced only to the U.S. Coast and Geodetic Survey bench mark located nearest to the gage site, and the required datum correction was determined by trial and error from the model without reference to the magnitudes of the separate elements in the correction. The other parameter that was evaluated is the flow-resistance coefficient, η. Although the value of η is dependent mainly on the flow resistance, it is affected like the datum correction by discrepancies between the mathmatical formulations and actual physical conditions. Manning's n can be used as an initial estimate of η for a given hydrograph; however, a trial-and-error method of calibration must be used to obtain the final value of η.

The first attempt at developing a suitable model was made by using the power-series method. However, because the magnitude of the flood and ebb discharges and the general shape of the computed hydrographs did not correspond sufficiently closely to the measured hydrographs, it was concluded that the complex channel geometry precluded treating the Beaver reach as a single entity.

The second method tried was the characteristic method. The advantage of the characteristic method is that discrepancies caused by complex channel geometry can be minimized by dividing the total reach into several subreaches (Lai, 1967). For the Beaver model, the reach was divided into two subreaches. The upper subreach extends from the gage at Beaver downstream to the upstream tip of Wallace Island (fig. 6). This reach is virtually a single channel, although a midchannel bar is periodically exposed at the downstream end. The lower subreach extends from the upstream tip of Wallace Island downstream to the Cape Horn gage. This reach consists of the main river channel and a smaller channel formed by Wallace Island (fig. 6). Extensive flats on the north side of Wallace Island are exposed during periods of low tide. Table 2 lists for various elevations the areas and top widths of cross sections that are representative of the two subreaches and which were computed from data obtained at the 11 cross sections in figure 6.

Calibration of the model was done by the trial-and-error method. First, by repeated trials with various η values, it was found that measured and computed hydrographs compared most consistently when the datum correction was taken as 0.10 foot (3.0 cm). To correct this condition, 0.10 foot (3.0 cm) was added to Cape Horn stages. Then, values of η that provided the closest comparisons between measured and computed hydrographs were extablished. Figure 7 shows the relationship for the upper subreach between final η values and daily mean discharge. For daily mean discharges less than 225,000 ft^3/s (6,370 m^3/s), η equals 0.0297. As the daily mean discharge increases from 225,000 to 430,000 ft^3/s (6,370 to 12,200 m^3/s), η decreases from 0.0297 to 0.0248. When the daily mean discharge is greater than 430,000 ft^3/s (12,200 m^3/s), η equals 0.0248. For lower subreach, η is equal to the η value of the upper subreach plus 0.0004. The causes for the variation in η with daily mean discharge were not investigated; however, it seems reasonable that important contributing factors were the variation in the Reynolds number of the flow and the apparent change in the heights and lengths of the bed forms in the channel with discharge.

TABLE 2. —*Areas and top widths of average cross sections representative of the two subreaches in the Beaver reach*

Upper Subreach			Lower Subreach		
Depth[1] (ft)	Top width (ft)	Cross-sectional area (sq ft)	Depth[1] (ft)	Top width (ft)	Cross-sectional area (sq ft)
0	2,560	78,200	0	2,350	73,800
2.0	2,650	83,600	2.0	2,400	78,500
4.0	2,730	88,800	4.0	2,470	83,400
6.0	2,780	94,300	6.0	2,600	88,500
8.0	2,860	99,800	10.0	2,760	99,200
10.0	2,950	105,700	12.0	2,840	104,800
13.0	3,090	114,800	13.0	2,890	107,700
14.0	3,110	117,800	14.0	2,920	110,600
16.8	3,200	126,800	16.0	2,980	116,500
22.0	3,320	143,600	24.0	3,180	141,100
24.0	3,360	150,300	---	---	----

[1]Depth of water above gage datum ("MSL 1929" —10.0 ft).

MATHEMATICAL-MODEL DISCHARGE RESULTS

Values of the parameters defined by the calibration, together with appropriate stage data, were used in the model to generate a record of instantaneous discharge every 15 minutes for the period May 1, 1968, through June 30, 1970. Daily mean discharges obtained from this record by algebraically averaging the 96 instantaneous values for each 24-hour day have been published by the U.S. Geological Survey (1971, p. 275-277). To check the accuracy of the computed discharges, monthly mean discharges determined from the model discharges were compared with monthly mean discharges computed by the Northwest Water Resources Data Center. The method used by the Data Center to obtain a monthly mean discharge was developed by Orem (1968) and is believed to be accurate within 2 or 3 percent. Throughout the period of record, monthly mean discharges from the model consistently compared within ±5 percent of the Data Center values. Presumably, the computed daily mean discharges are in this same general accuracy range. Inasmuch as the agreement between measured and computed hydrographs obtained during the calibration is good and the average relation for the variation of η (fig. 7) is moderately well defined, it also seems reasonable to conclude that the computed instantaneous discharges are fairly accurate.

Continuous-flow hydrographs for the period of discharge record at Beaver exhibit the following characteristics:

1. For daily mean discharges of less than about 125,000 ft^3/s (3,540 m^3/s), flow reverses (flow upstream) during at least one of the flood periods during the day, and reversals are very common for both flood periods.
2. For daily mean discharges of about 125,000 to 185,000 ft^3/s (3,540 to 5,240 m^3/s), flow almost always reverses during the strongest flood.
3. For daily mean discharges of about 185,000 to 225,000 ft^3/s (5,240 to 6,370 m^3/s), the flow reverses occasionally during the strongest flood.

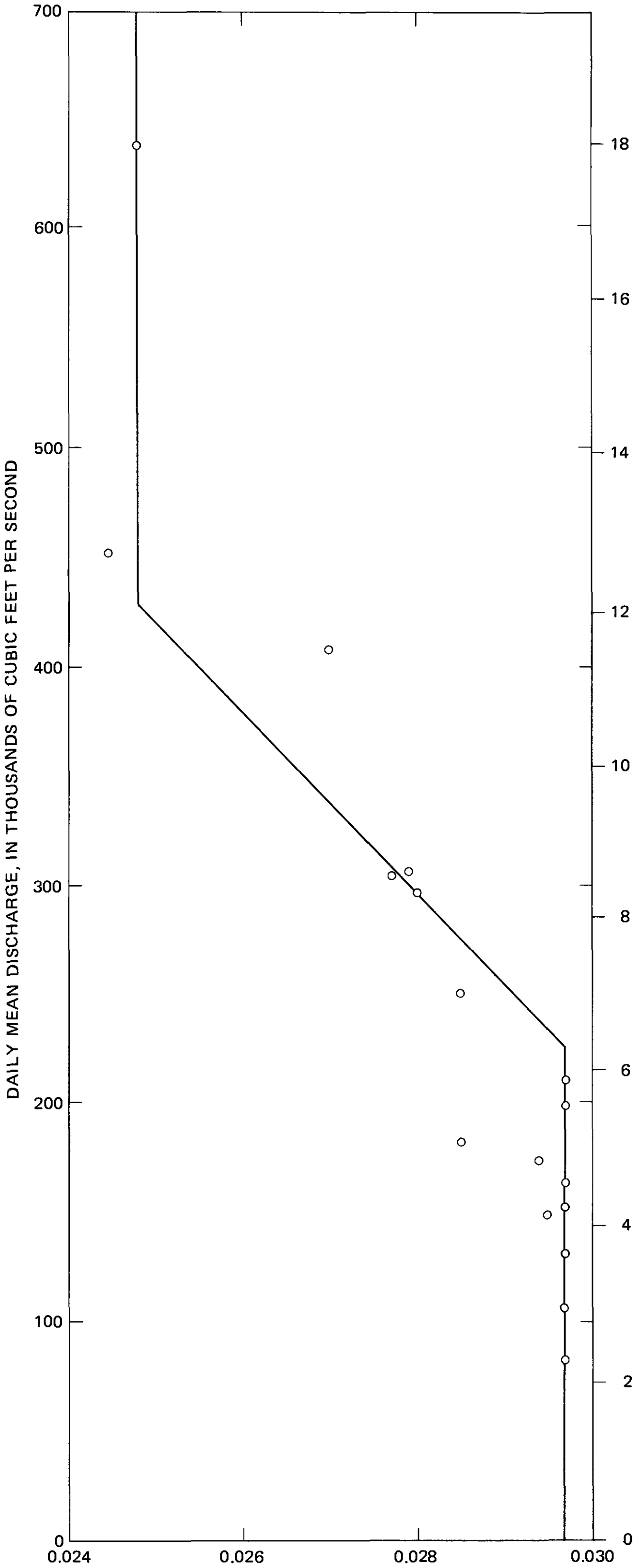

FIGURE 7. — Variation of the flow-resistance, coefficient, η, with daily mean discharge, Columbia River at Beaver Army Terminal near Quincy, Oreg.

4. For daily mean discharges greater than about 225,000 ft^3/s (6,370 m^3/s), the flow rarely reverses.

A review of the daily mean discharges shows that, on the average, flow reversals occur during about 10 months of the year and at all times except during the period of high upland flow during the spring.

During the calibration, it was found that a gage correction of 0.01 foot (0.3 cm) would change the daily mean discharge by about 5,000 ft^3/s (142 m^3/s) or about 2 percent of the average daily mean discharge of 225,000 ft^3/s (6,370 m^3/s) for the period of discharge record at Beaver. Although the stage records from both the float-stilling well system and the bubble gage are accurate at best to only ±0.01 foot, (0.3 cm), it is reasonable to assume that, on the average throughout a tidal cycle, the difference between gage readings would be in error no more than about 0.01 foot (0.3 cm).

ASTORIA REACH

The reach at Astoria extends from Tongue Point (CRM 17.5) downstream to the west side of Astoria (CRM 13.1), as shown in figure 1. The flow characteristics of the Astoria reach are complicated by both longitudinal and lateral salinity gradients that result from saltwater intrusion into the reach. Generally, salinity is present during at least one of the floodtides each day, and usually during both, except when runoff is high in the late spring. Also the geometry of the reach is complex (fig. 8); the navigational channel is along the south shore, the center part is laced diagonally with shallow minor channels and with flats that are exposed at low tide, and a deep channel along the north shore at the lower end of the reach divides and becomes shallow toward the upstream end of the reach. The width-to-length ratio of the reach is close to 1.0.

The upstream gage was located at the U.S. Coast Guard Tongue Point Station and consisted of a digital recorder coupled to a permanent tide-station gage recorder that is operated by the U.S. Coast and Geodetic Survey. The gage is float-stilling-well type and is maintained daily by Coast Guard personnel. The lower gage was installed on Pier 1 of the Port of Astoria Docks. This gage also was a float-stilling-well type with digital and graphic water-stage recorders. A–C synchronous motor-driven timers were used to obtain virtually simultaneous stage readings at both gages every 15 minutes. The datum to which the gages were set was the same as for the Beaver reach; that is, "MSL 1929" −10 feet (3.048 m). Channel cross-sectional geometry was defined from eight cross sections (fig. 8) equally spaced along the reach. The shape and dimensions of each section were determined from Coast and Geodetic Survey navigational charts rather than from field-survey measurements. Data from the eight sections were com-

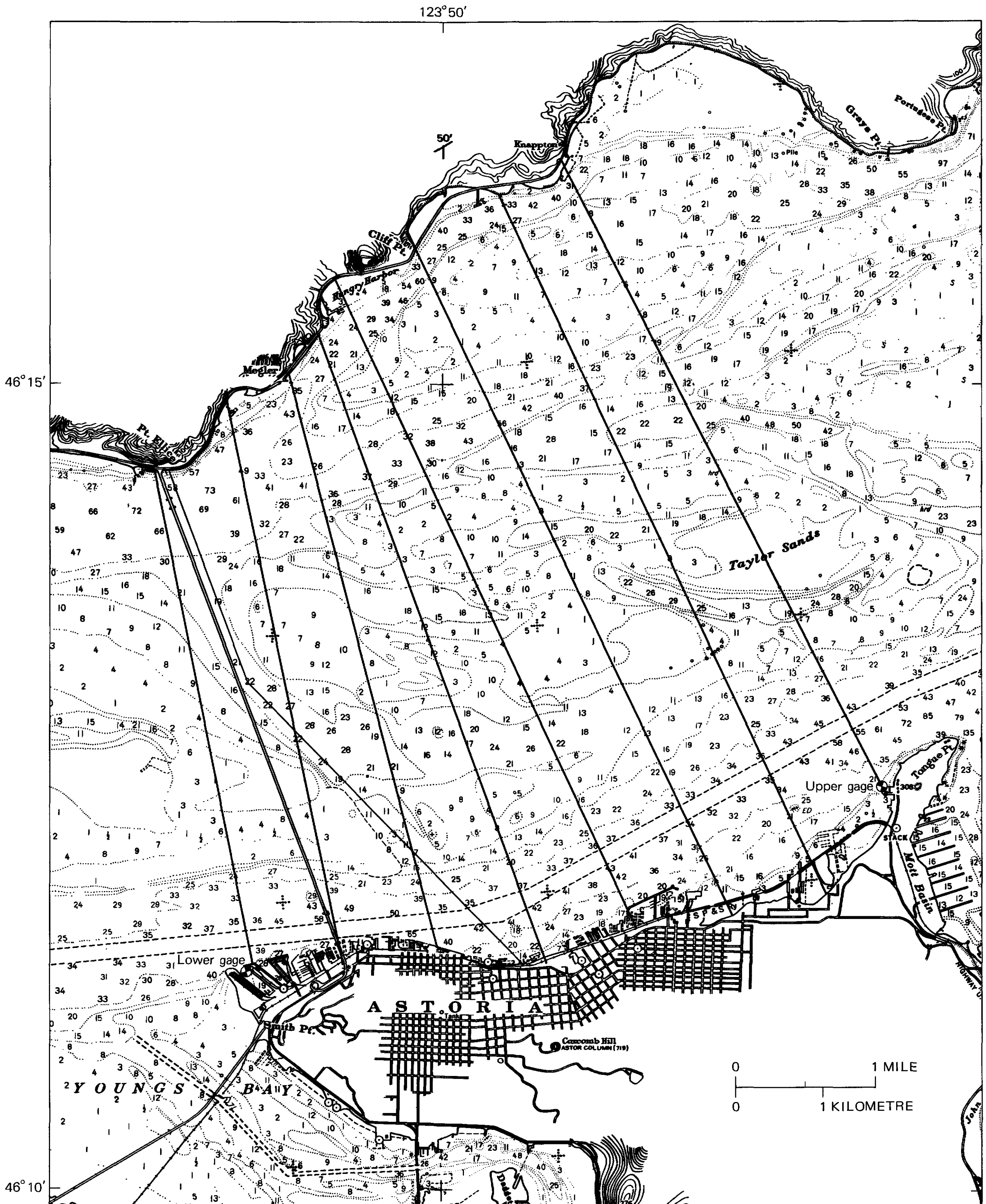

FIGURE 8 — Astoria reach showing cross sections where channel geometry was defined. Numbers within estuary boundaries indicate depths, in feet, at mean lower low water. Base from U.S. Coast and Geodetic Survey; Columbia River Chart 6151, Oregon-Washington, 1968.

bined to define the geometric characteristics of cross sections that are representative of upper and lower subreaches which roughly divide the total reach in half (table 3). The length of the reach was obtained by measuring the distance between the two gages along the centerline of the navigational channel.

Discharge hydrographs for calibration of the mathematical model were obtained at the measuring cross section at Astoria (fig. 8) exclusively by the MOVD method. With this method, the complex velocity profiles produced by salinity gradients are defined throughout the entire depth; thus, regardless of conditions, accurate section discharges can be measured. As at Beaver, measurements were scheduled so that both ebb and flood discharges would be defined during the measurement sequence.

Discharge measurements at Astoria began on April 13, 1966, and were concluded on May 19, 1970. During this period, 20 discharge hydrographs, or a total of 82 lateral traverses, were made during varying flow conditions. A summary of the discharge measurements is given in table 4. At Astoria, it was considered a successful day if four or more complete traverses could be made. On the average, it would take about 2 hours for a complete round-trip lateral traverse. Of the 2 hours, about 1½ hours were spent obtaining the measurements, and the other one-half hour was spent traveling back across the 4-mile-wide (6-km-wide) cross section. Lateral traverses were always started on the north side of the estuary so time differences between corresponding verticals of the different traverses would be the same.

Weather conditions played a very important part in how successful a measurement sequence would be. Heavy morning fogs caused delays in starting, and winds caused cancellations or delays in the starting time and early terminations of the measurements. Equipment malfunctions also caused late starts, early terminations, or delays during the discharge measurements.

TABLE 3. — *Areas and top widths of average cross sections representative of the two subreaches in the Astoria reach*

Upper Subreach			Lower Subreach		
Depth[1] (ft)	Top width (ft)	Cross-sectional area (sq ft)	Depth[1] (ft)	Top width (ft)	Cross-sectional area (sq ft)
0	17,500	226,000	0	16,900	286,000
2.0	19,700	263,000	2.0	17,500	321,000
4.0	23,100	306,000	4.0	19,700	358,000
6.0	24,300	353,000	6.0	20,400	398,000
7.0	25,600	378,000	8.0	21,900	440,000
8.0	27,200	405,000	24.0	21,900	791,000
24.0	27,200	840,000	---	----	----

[1]Depth of water above gage datum ("MSL 1929" −10 ft).

TABLE 4. — *Summary of discharge measurements at Astoria, Oreg.*

Date	Number of lateral traverses	Period of defined hydrograph (hours)	Daily mean discharge at Astoria (ft^3/s)
1966			
Apr. 13	4	9.8	223,000
May 25	2	5	331,000
July 6	4	9.5	287,000
July 28	4	10.3	203,000
Nov. 4	3	8.3	105,000
1967			
July 28	3	7	276,000
Aug. 17	4	8.8	-----
Sept. 15	4	9.5	85,000
1968			
Feb. 13	4	9.5	202,000
Apr. 3	3	6.5	236.000
May 10	5	11.5	112,000
June 16	6	11.8	462,000
July 26	5	11.3	278,000
Sept. 12	5	10.8	168,000
Oct. 17	4	8.8	98,000
Dec. 18	3	7.3	350,000
1969			
Apr. 24	5	10	442,000
1970			
Mar. 7	5	8.3	268,000
Apr. 13	5	10.3	188,000
May 19	4	9.5	292,000

CALIBRATION PROCEDURE

From the beginning of the study, there was speculation as to whether any one-demensional model could be adapted to provide reasonably accurate discharges throughout the tidal cycle at Astoria because of the complex geometry of the reach, the existence of salinity gradients, and the presence — at particular times in each tidal cycle — of diametrically opposed flow both within a vertical and laterally within the cross section. In order to provide the most flexibility, the model based on solution of the flow equations by the method of characteristics (Lai, 1967) was adopted and computations were made within the framework of a two-subreach system. The initial calibration procedure for the Astoria reach was the same as that used for the Beaver reach; that is, an attempt was made to determine values for the datum correction and flow resistance, η, by the trial-and-error procedure. After evaluating many trials with various combinations of datum corrections and η's, it was concluded that (1) a constant datum correction could not be determined, and (2) use of η=0.025 produced flow hydrographs with maximum and minimum discharges that corresponded closely to comparable measured data, but whose shapes deviated consistently from measured hydrographs.

Baltzer and Lai (1968) showed, with data from Threemile Slough near Rio Vista, Calif., that η increases sharply as the Reynolds number approaches zero. Because the Reynolds number is a function of and varies mainly with water velocity, in effect, they showed that as the velocity (or discharge) approaches zero, η increases. Because the tidal pattern at Astoria is such that the discharge passes through zero four times each day, the variation of η is a significant consideration. To ascertain how η varies with time at Astoria, the model was solved for η by using measured discharges and an arbitrary datum correction. Computed η values, normalized by dividing by the minimum computed η value, are plotted in figure 9 against the corresponding relative times, $T/\Delta T$, in the period between zero discharges. The graph in figure 9 for ebb periods shows that for relative times

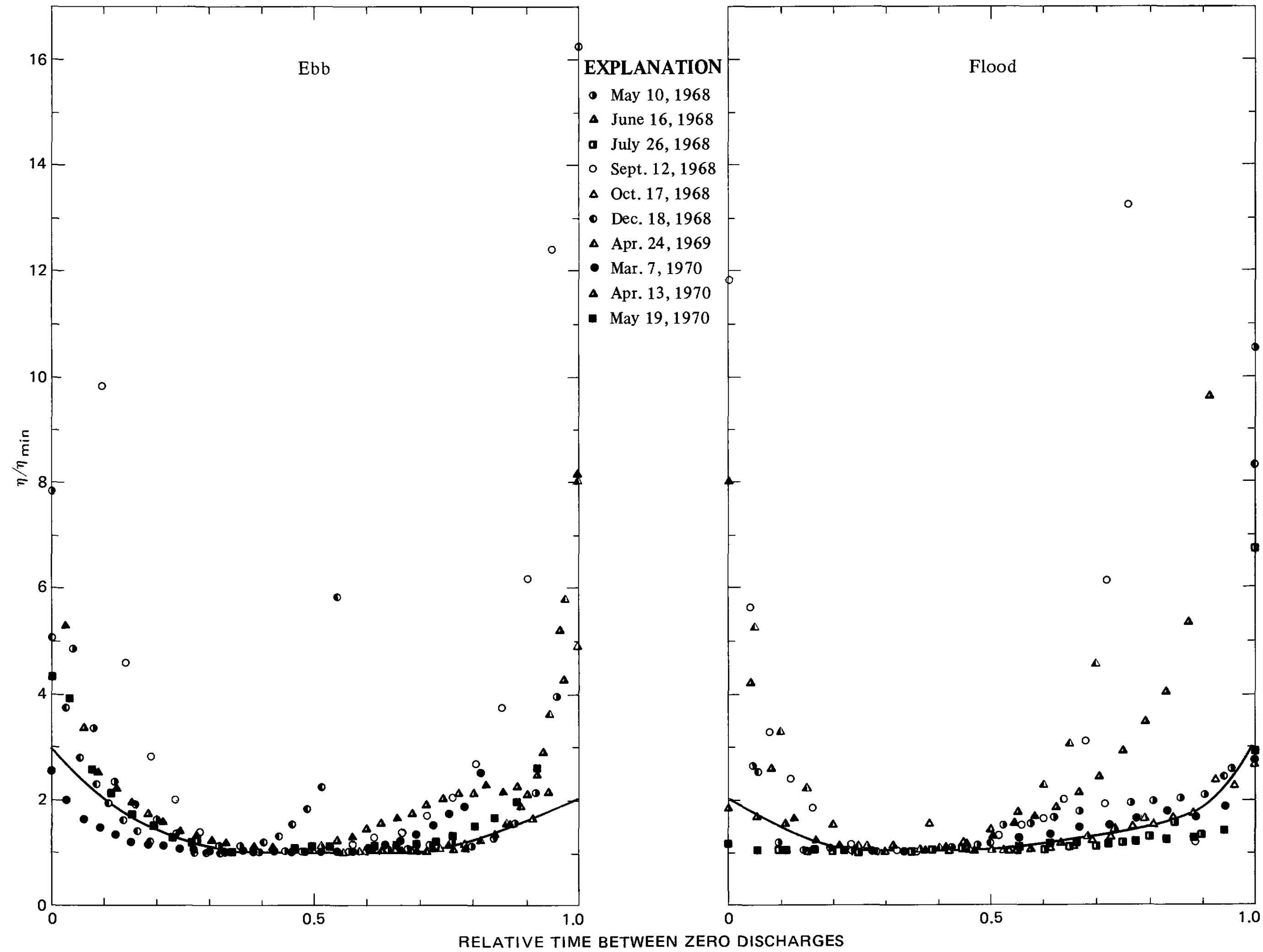

FIGURE 9. — Change in η/η_{min} with relative time at Astoria, Oreg.

between 0.35 and 0.70, the value of η is constant. For the remaining 65 percent of the time, η increases as $T/\Delta T$ approaches zero and 1.0. For flood periods (fig. 9), η is constant and a minimum for $T/\Delta T$ values between 0.23 and 0.47 or for 24 percent of the time. As with ebb periods, whenever η is not at the minimum value it progressively increases as $T/\Delta T$ approaches zero and 1.0. It should be noted that the data in figure 9 cannot be taken as absolute because (1) the best datum correction for each hydrograph may not have been used in the computations; and (2) no deliberate provisions were taken to correct the model for salinity gradients, Coriolis effects, wind, and other factors that could have an effect on the discharge. However, the general trends in the figure can be assumed to be representative.

In order to incorporate the variation of η, the mathematical model was programmed to accept the curves shown in figure 9. With this change, close comparisons between measured and computed hydrographs (figs. 10, 11) could be obtained by using $\eta_{min}=0.025$, provided a different datum correction was used for each hydrograph. Apparently, the necessity for a variable datum correction is mainly a reflection of the fact that a variable water-surface slope (fall) correction is necessary to adjust the model to compensate for the influence of salinity gradients, complex geometry, and other factors not expressed in the fundamental equations.

Because a direct independent means for determining the required datum correction was not available, an indirect approach was adopted. First, a simple volumetric model to compute daily mean discharges at Astoria was developed. This model equated the daily mean discharge at Astoria with the algebraic sum of the daily mean discharge at Beaver and the daily rate of net change in the volume of storage within the reach between Beaver and Astoria. That is,

$$\bar{Q}_A=\bar{Q}_B+\frac{\Delta V}{T}, \quad (1)$$

DAY	HR	MEAS. DIS. *	COMP. DIS. 0
13	24		556829
			438462
			278471
			182861
			99295
			2299
			-134412
			-218175
	2		-335387
			-457130
			-506153
			-577286
			-663828
			-703338
			-733659
			-750409
	4		-735952
			-739267
			-621799
			-523383
			-417185
			-261650
			-133428
			7509
	6		154200
			301355
		179000	404663
		305000	488902
		448000	616866
		570000	720657
		690000	806696
		805000	909945
	8	913000	989180
		1010000	1044859
		1103000	1099886
		1180000	1162210
		1249000	1202435
		1295000	1231921
		1337000	1269943
		1355000	1274068
	10	1365000	1287141
		1360000	1302615
		1347000	1280580
		1315000	1255371
		1275000	1220291
		1230000	1153285
		1173000	1052246
		1110000	998539
	12	1043000	901165
		955000	813420
		870000	761613
		775000	637859
		680000	500071
		570000	429658
		460000	275874
		345000	186642
	14	233000	146649
		90000	10034
		-45000	-68416
		-175000	-144307
		-301000	-245249
		-440000	-319458
		-555000	-412435
		-650000	-506770
	16	-737000	-573938
		-795000	-655641
		-839000	-721867
		-860000	-751742
		-868000	-821645
		-860000	-839523
		-840000	-838890
		-805000	-831189
	18	-763000	-816991
		-715000	-770267
		-655000	-704374
		-580000	-610851
		-500000	-501836
		-410000	-422176
		-315000	-344327
		-210000	-199044
	20	-90000	-91182
		40000	32325
		182000	201434
			314332
			384961
			456311
			525820
			610517
	22		684361
			753165
			824044
			886637
			921284
			949646

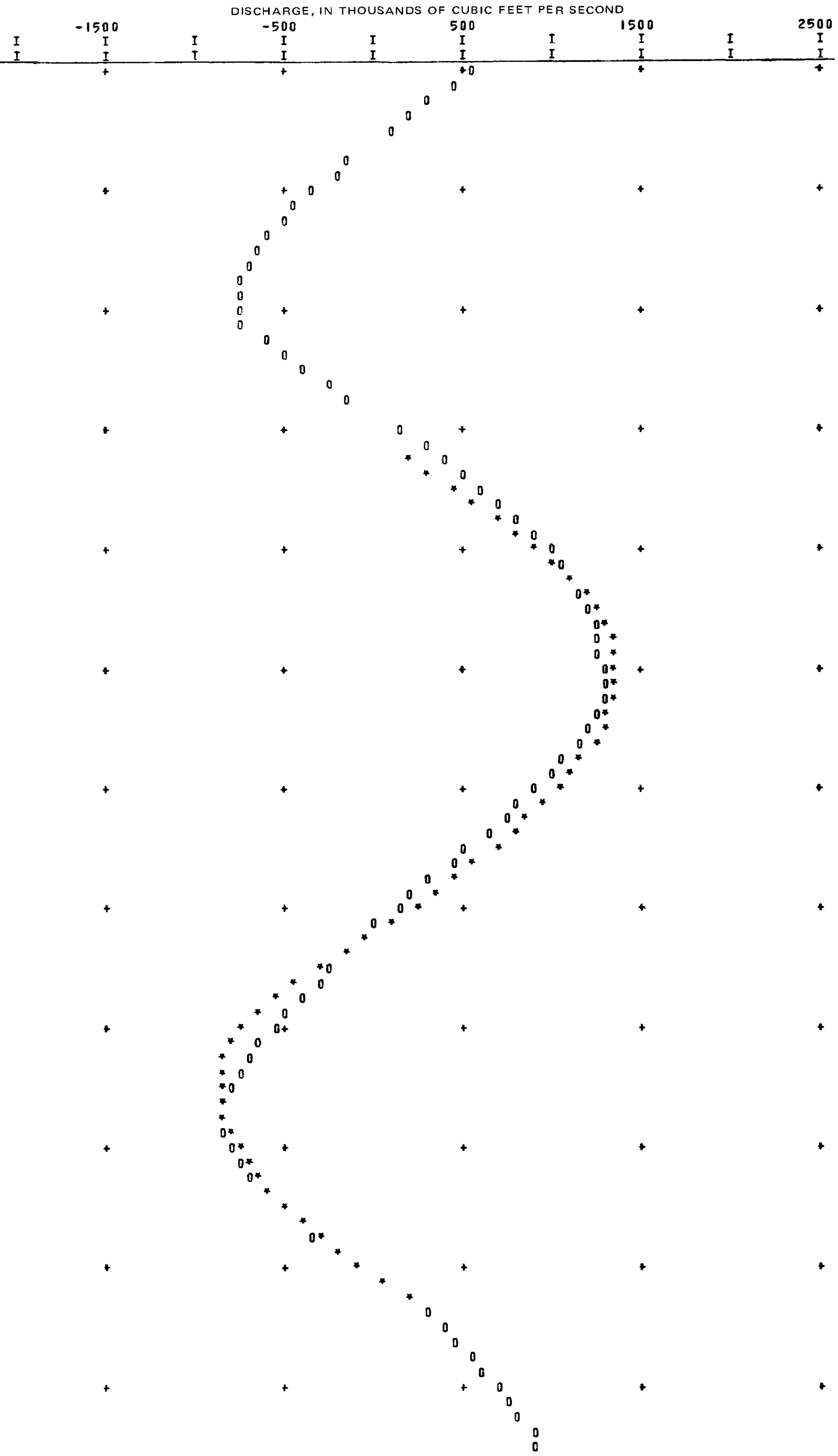

FIGURE 10. — Comparison between measured (*) and computed (0) discharges for low instantaneous discharges at Astoria, Oreg., on April 13, 1970.

DAY HR	MEAS. DIS. *	COMP. DIS. 0
7 24		-1185588
		-953949
		-768868
		-464894
		-176359
		180063
		500169
		738587
2		891382
		1120879
		1249572
		1492655
		1586183
		1868247
		1964267
		2168716
4		2205072
		2322740
		2288833
		2299599
		2233739
		2158475
		2052043
		1974391
6		1801991
		1651460
		1489169
		1270409
		1048300
		791882
		505053
		269412
8	40000	70310
	-210000	-178766
	-470000	-462114
	-730000	-717537
	-993000	-1007673
	-1180000	-1224767
	-1349000	-1439672
	-1490000	-1651563
10	-1611000	-1755139
	-1700000	-1815276
	-1779000	-1818778
	-1820000	-1723970
	-1795000	-1646916
	-1740000	-1553112
	-1643000	-1368756
	-1500000	-1180525
12	-1315000	-909130
	-1110000	-713555
	-875000	-456511
	-620000	-223061
	-328000	83779
	-15000	477243
	325000	687112
	660000	828326
14	982000	1002154
	1270000	1268686
	1541000	1326055
	1775000	1600907
	1965000	1582740
	2075000	1825455
	2171000	1839822
	2230000	2044441
16	2240000	1996823
	2230000	2142791
	2194000	2102134
	2160000	2105568
	2093000	2075647
	2025000	2090655
	1940000	2057344
	1875000	2003301
18	1746000	1910726
	1625000	1814926
	1495000	1691705
	1355000	1549529
	1204000	1377837
	1030000	1163504
	860000	963597
	680000	731929
20	513000	491153
	320000	286546
	124000	102735
	-50000	-178015
		-405121
		-702258
		-945981
		-1122605
22		-1367663
		-1577942
		-1732265
		-1881617

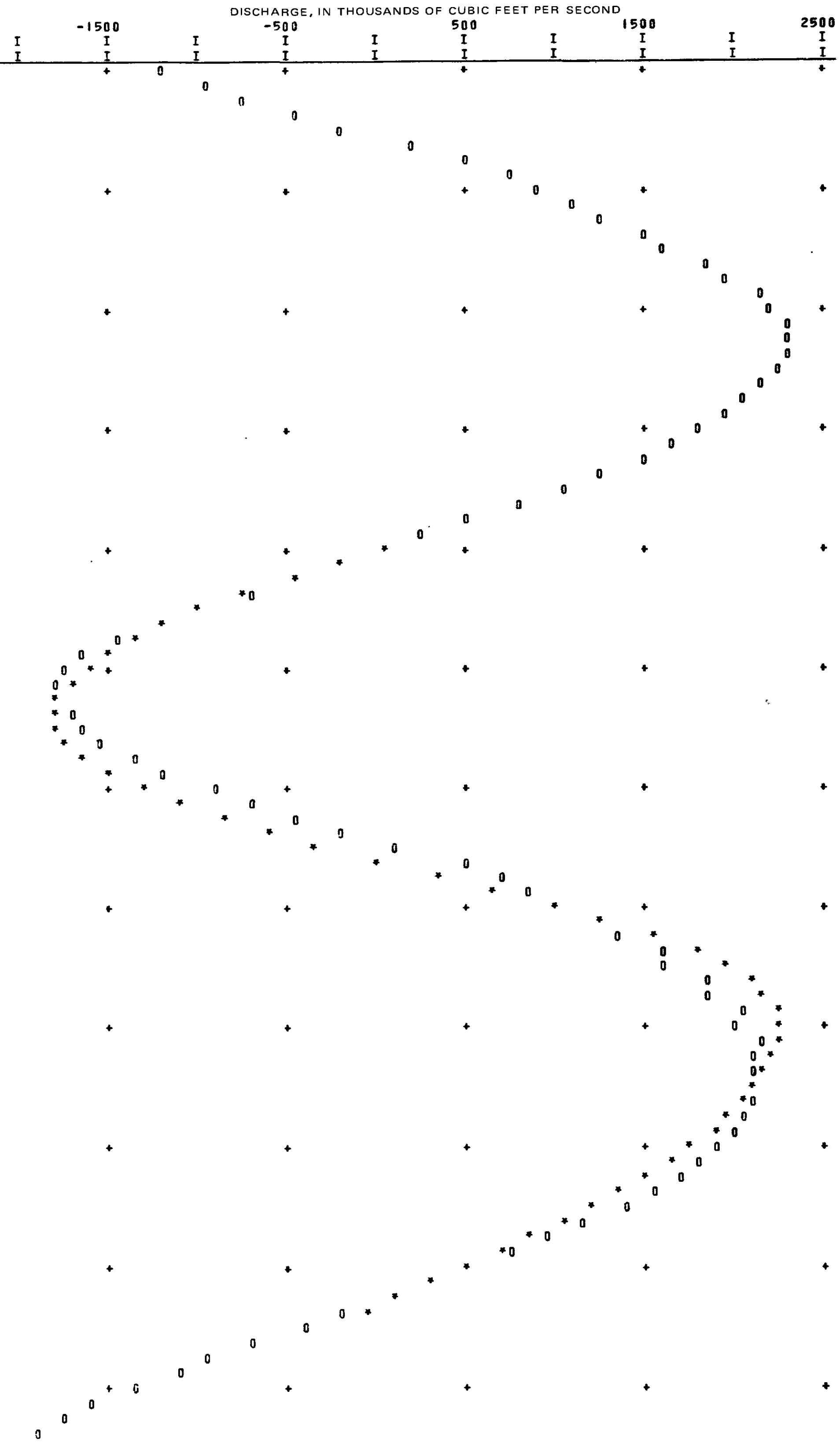

FIGURE 11. — Comparison between measured (*) and computed (0) discharges for high instantaneous discharges at Astoria, Oreg., on March 7, 1970.

where

$\bar{Q}_A$ and $\bar{Q}_B$ are the daily mean discharges, in cubic feet per second, at Astoria and Beaver, respectively;

ΔV is the difference in the volume of water within the reach, in cubic feet, at the beginning and at the end of each day; and

T is 86,400 seconds (equivalent to 24 hours).

ΔV is the product of the surface area of the reach, K', and the weighted average depth of the net change in storage, $\Delta S'$, which may be either positive or negative. K' was determined from a correlation with the stage at Tongue Point, S_{TP}, at the beginning of the day; the correlation was established with K' values obtained by solving equation 1 with values of Q_A for days when discharge hydrographs were defined at Astoria, comparable values of Q_B computed from the Beaver model, and values of $\Delta S'$ determined from

$$\Delta S' = (2/3)\Delta S_{TP} + (1/2)\Delta S_B, \quad (2)$$

where

ΔS_{TP} and ΔS_B are the differences in stage between the beginning and end of each day at Tongue Point and at Beaver, respectively.

Equation 2 was determined to give $\Delta S'$ values that, in turn, yielded K' values which gave the best correlation with the Tongue Point stages. The equation also roughly reflects the fact that approximately two-thirds of the surface area is located in the lower one-third of the reach.

Daily mean discharges at Astoria computed from equation 1 were used to calculate monthly mean discharges. These values were compared with monthly mean values computed by the Northwest Water Resources Data Center by a routing technique (Orem, 1968). Because the agreement between the monthly mean discharges was consistently within ±5 percent, the individual daily mean discharges were assumed to be reasonably accurate. Then, for each day, trial discharges were computed every 15 minutes with the mathematical model, using different daily datum corrections, until the resultant daily mean discharge corresponded within ±5 percent of the "known" daily mean discharge for each day determined from the volumetric model (eq 1).

MATHEMATICAL-MODEL DISCHARGE RESULTS

A continuous record of the discharge at Astoria every 15 minutes was computed by the trial procedure throughout the period from March 1, 1968, to June 30, 1970, except during periods of missing gage records. A summary of this record (app. 1) shows that daily mean discharges ranged from 630,000 to −7,400 ft³/s (17,800 to −210 m³/s; minus sign indicates upstream flow). Instantaneous discharges frequently exceeded 2 million ft³/s (0.06 million m³/s) downstream and 1.5 million ft³/s (0.04 million m³/s) upstream (fig. 11). Near-surface velocities observed during the discharge measurements ranged up to 8 ft/s (2.4 m/s) during the ebb and were as high as 6 ft/s (1.8 m/s) during the flood. However, the time-average velocity in the cross section is about 3 ft/s (0.9 m/s) during an ebb and about 2 ft/s (0.6 m/s) during a flood.

Daily mean discharges determined from instantaneous discharges computed with the mathematical model (solution by the method of characteristics) are considered to be reasonably accurate because they were adjusted by trial to be within ±5 percent of the results obtained with the volumetric model. However, because the datum (slope) correction had to be applied as a daily factor and could not be varied throughout the tidal cycle, the computed instantaneous discharges are generally less accurate than the daily mean discharges. A statistical analysis of the percentage differences between discharges computed with the model and comparable discharges from the measured hydrographs is presented in appendix 2. The analysis indicates that the probability is 0.90 that 90 percent of all computed instantaneous discharges greater than 1,250,000 ft³/s (35,400 m³/s; both ebb or flood discharges) will be within about ±25 percent of the actual discharge; the error decreases as the discharge increases. (See fig. 18 and table 7.) For discharges less than 1,250,000 ft³/s (35,400 m³/s), the percentage error increases rapidly as discharge decreases. Flows less than 1,250,000 ft³/s (35,400 m³/s) generally occur only during those periods in the tidal cycle when discharge either is increasing or decreasing rapidly after having been zero. Hence, even though the proportion of time such flows occur may be fairly large, their contribution to the total volume of flow passing the cross section during an entire ebb or flood is generally small. For this reason, the large errors, as such, are not significant when the volume of flow during a partial tidal cycle is a prime concern.

During calibration of the Astoria reach, it was determined that the model was very sensitive to datum corrections. On the average, a correction of 0.01 foot (0.3 cm) would change the daily mean discharge by about 25,000 ft³/s (710 m³/s). This extreme sensitivity is believed to have resulted primarily because the reach was not long enough and the cross-sectional area was very large. Although the reach length was 4.4 miles (7.1 km), the maximum water-surface fall was only slightly over 1.0 foot (30 cm), and the average fall was only about 0.65 foot (20 cm). Hence, a datum correction of 0.01 foot (0.3 cm) caused an appreciable change in the fall, and this caused a significant change in computed velocity that, in turn, was magnified into a large change in discharge because of the extensive size of the cross section.

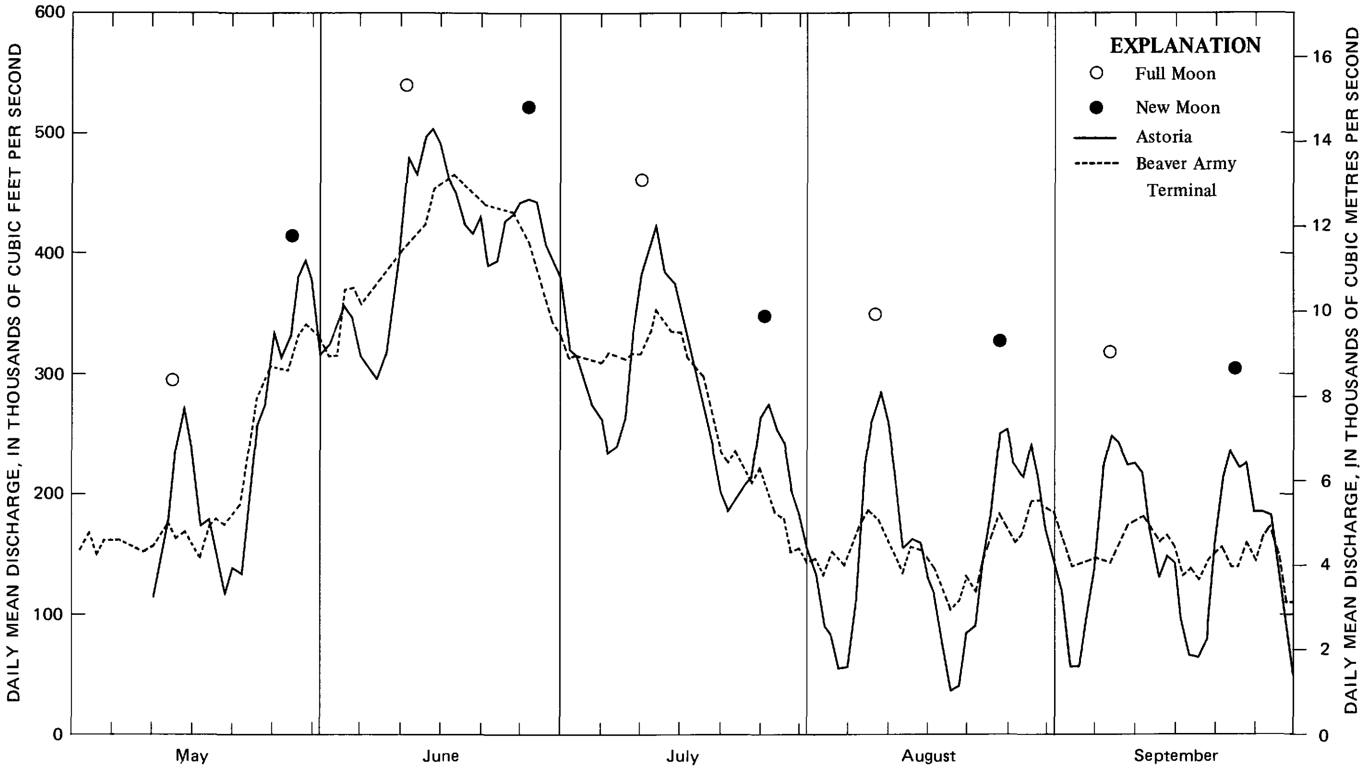

FIGURE 12. — Daily mean discharges at Beaver Army Terminal and Astoria, Oreg., May–September 1968.

In tidal flow, the daily mean discharge is not necessarily indicative of the magnitude of upland flow as it is in nontidal flow. According to the volumetric model, and daily mean discharge at the station may be either less or greater than the upland discharge; the difference is caused by the net change in storage within the reach upstream from the station. The effect of changes in storage is shown in figure 12 by the hydrographs of the daily mean discharges at Beaver and Astoria. Although there is little inflow into the Columbia River between Beaver and Astoria, daily mean discharges fluctuate cyclically through a much greater range at Astoria than they do at Beaver because of the greater change in the amount of storage per unit change in stage at Astoria. The character of the cyclic pattern of the hydrograph for Astoria is affected significantly by the combined effects of (1) the daily 50-minute shift in the position of the tide curve relative to absolute clock time due to the difference in the length of lunar (24.8 hours) and solar (24 hours) days, and (2) the cyclic variation in maximum and minimum tide heights that occur with a frequency of about 14.3 days (spring tides occur a day or two after a full moon or a new moon, and neap tides occur about 7 days later). Essentially, the daily mean discharge increases from one day to the next, so long as ΔV (eq 1) increases or becomes less negative — that is, it increases so long as $\Delta S'$ continues to increase algebraically. Daily mean discharges progressively decrease when the opposite trend in $\Delta S'$ occurs. Because the moon is the major force-producing body that influences the timing and magnitude of the tides, moon phases correlate well with the cyclic variations in daily mean discharges. (See fig. 12.)

As stated earlier, the net change in storage during the day due to tide effects can be severe enough to produce daily mean discharges that are in the upstream direction at Astoria. For instance, on September 21–22, 1969, when the daily mean discharge at Beaver was about 100,000 ft^3/s (2,830 m^3/s), the tides were such that the daily mean discharges at Astoria for these 2 days were 3,200 and 7,400 ft^3/s (91 and 210 m^3/s) upstream, respectively. At Beaver, similar cycling (but not net upstream daily flow) occurs; however, it appears that for daily mean discharges greater than about 450,000 ft^3/s (12,700 m^3/s), the cycling effect is essentially eliminated.

The cyclic variations in daily mean discharges significantly affect the degree to which the discharge during any short period of time (days) can be used to represent a longer term discharge. However, because the average period for the cyclic pattern is about 14 days, a monthly mean discharge will cover approximately 2 cycles and, therefore, should largely eliminate the effects of the ocean tides.

FLOW CHARACTERISTICS IN THE LOWER ESTUARY

The adaptation and application of the one-dimensional mathematical model for determining instantaneous discharges at Astoria was made possible by using, both implicitly and explicitly, information on flow and salinity distributions at the measuring cross section and elsewhere in the lower estuary. This same information also has been utilized to examine gross circulation and mixing patterns in the estuary.

LATERAL CIRCULATION AT THE DISCHARGE-MEASURING CROSS SECTION, ASTORIA REACH

To better understand the general pattern of flow in the estuary, the net circulation that results from differences in the lateral flow distribution of flood and ebb discharges was investigated at the measuring cross section at Astoria. Flow volumes from the discharge-measurement sequences were used for this purpose.

For measured hydrographs in which both an ebb and flood period are defined, the quantities of water flowing upstream and downstream in the north and south channels[1] were determined from the individual hydrographs for each part of the cross section (p. P5) that had been used to obtain the total flow hydrograph. The percentage of the total ebb volume that passed through each channel was then determined; a similar computation was made for the flood volumes. The various percentages are presented in table 5.

The results in table 5 reveal some interesting facts about the flow characteristics and lateral circulation patterns at the measuring cross section. On the average, the north channel conveys 76 percent of the floodflow and 69 percent of the ebbflow, or 73 percent of the total flow. More importantly, however, comparison of the differences in the percentages of flow through each channel during the ebbs and floods indicates the net lateral circulation during the half tidal cycle defined by the hydrograph. For instance, on September 15, 1967 (table 5), the proportion of the ebbflow which passed through the north channel was 9 percent less than the proportion which passed through during the floodflow (9 percent loss). Conversely, the proportion in the south chanel was 9 percent greater. This indicates a net clockwise circulation wherein some of the floodwater that flowed into the estuary via the north channel returned to the ocean via the south channel. On October 17, 1968, the data indicated a net counterclockwise circulation. Examination of table 5 shows that the lateral circulation of water correlates with the discharge at Beaver. For discharges at Beaver of less than about 165,000 ft^3/s (4,670 m^3/s), the south channel conveys a proportionately higher flow during the ebb than the flood (gains water from the north channel during the ebbflow). For discharges from about 165,000 to 190,000 ft^3/s (4,670 to 5,380 m^3/s), the north channel gains water from the south channel during the ebbflow, and for discharges at Beaver greater than about 190,000 ft ^{3}/s (5,380 m^3/s), the south channel gains water from the north channel during the ebbflow.

[1]In this analysis, the part of the estuary that includes the shallow midestuary area and the northernmost channel (fig. 8) is referred to as the north channel, and the navigational channel is called the south channel.

TABLE 5. — *Lateral distribution of ebb and flood discharge in the measuring cross section at Astoria, CRM 14*

[Flow period: E, ebb; F, flood]

Date	Daily mean discharge at Beaver (ft^3/s)	Flow period	Percent of flow		Difference in percentage of flow conveyed during ebb and flood	
			North channel	South channel	North channel	South channel
9-15-67	[1]129,000	F E	79 70	21 30	−9	+9
5-10-68	157,000	F E	79 72	21 28	−7	+7
9- -59[2]	[3]162,000	F E	[2]73 [2]68	[2]27 [2]32	−5	+5
10-17-68	166,000	F E	68 80	32 20	+12	−12
9-12-68	171,000	E F	79 70	21 30	+ 9	− 9
8-17-67	[1]175,000	F E	71 71	29 29	0	0
3- 7-70	186,000	F E	73 75	27 25	+2	−2
4-13-70	197,000	E F	58 73	42 27	−15	+15
12-18-68	282,000	F E	80 74	20 26	−6	+6
5-19-70	325,000	F E	79 66	21 34	−13	+13
4-24-69	415,000	E F	58 88	42 12	−30	+30
6-16-68	462,000	E F	65 81	35 19	−16	+16
6- -59[2]	[3]551,000	F E	[2]77 [2]61	[2]23 [2]39	−16	+16

[1]Daily mean discharge at Prescott, Oreg.
[2]From data presented by Hansen (1965).
[3]Daily mean discharge at the mouth as computed by the U.S. Army Corps of Engineers (1960).

Also shown in table 5 are percentages computed from Hansen's (1965, fig. 3, p. 954) interpretation of U.S. Army Corps of Engineers data collected at CRM 5.5 in June and September of 1959. The results from Hansen's work consistently agree with data from the measured hydrographs at the Astoria measuring cross section.

FLOW-PREDOMINANCE PATTERNS AT THE DISCHARGE-MEASURING CROSS SECTION, ASTORIA REACH

One especially useful way to characterize in simple terms the distribution of tidal flow in an estuary is by the method of flow predominance (Simmons, 1955). Application of this method to the analysis of velocity profile data from the measurement cross section at Astoria has provided an insight into the variation of the net vertical distribution of flow at various lateral locations across the section.

TABLE 6. — *Variation of flow predominance with depth at selected locations in the measuring cross section at Astoria, CRM 14*

[Fraction of tidal cycle: A, half tidal cycle consisting of one flood and one ebb; B, full tidal cycle]

Date	Fraction of tidal cycle	Mean discharge 1/ (ft³/s)	Flow predominance at height above the bed equal to the indicated percentage of the total depth														
			"North" Channel					Middle Channel					South Channel				
			5	25	50	75	95	5	25	50	75	95	5	25	50	75	95
1966																	
Apr. 13	A	294,000	36	48	65	74	78	22	44	49	58	61	42	60	78	82	76
July 6	A	220,000	41	51	65	80	68	34	61	59	71	70	26	80	76	78	62
July 28	A	93,000	43	48	54	82	89	71	19	34	82	53	3	10	45	88	80
1967																	
June 6	B	453,000	----	----	----	----	----	----	----	----	----	----	77	82	85	83	80
June 20-21	B	616,000	----	----	----	----	----	----	----	----	----	----	93	90	92	93	92
July 28	A	150,000	81	82	65	64	65	35	62	60	71	56	----	----	----	----	----
Aug. 18-19	B	194,000	----	----	----	----	----	----	----	----	----	----	60	53	61	68	68
Sept. 15	A	-24,000	57	65	53	43	56	19	23	38	70	74	44	44	55	45	48
1968																	
Feb. 13	A	538,000	81	86	79	72	73	----	----	----	----	----	----	----	----	----	----
May 10	A	84,000	48	55	55	61	65	6	37	52	56	62	45	48	53	61	58
June 16	A	425,000	68	72	76	78	81	46	84	99	79	72	81	81	82	78	77
July 26	A	57,000	24	46	71	79	79	60	36	61	61	78	52	62	64	74	75
Sept. 12	A	34,000	49	62	68	60	65	55	46	54	63	75	39	33	42	57	62
Dec. 18	A	468,000	69	66	57	56	60	----	----	----	----	----	48	47	61	62	68
1969																	
Apr. 25	A	368,000	----	----	----	----	----	----	----	----	----	----	60	75	75	84	82
1970																	
Mar. 7	A	280,000	51	54	47	51	57	----	----	----	----	----	68	45	41	50	60
Apr. 13	A	264,000	46	32	53	62	68	----	----	----	----	----	57	64	73	78	84
Apr. 14	A	226,000	----	----	----	----	----	----	----	----	----	----	51	49	81	88	90
Apr. 15	A	131,000	71	58	80	64	74	----	----	----	----	----	----	----	----	----	----
May 19	A	133,000	2	27	45	57	59	----	----	----	----	----	69	51	63	56	65

1/ Algebraic mean during the indicated fraction of tidal cycle.

Flow predominance at a point is determined by the following procedure: (1) A conventional plot of the velocity normal to the cross section versus time is made over a complete tidal cycle; (2) the areas, F, subtended by the flood curves, and the areas, E, subtended by the ebb curves of the plot are planimetered; and (3) the flow predominance is calculated from

$$\text{flow predominance} = \frac{\Sigma E}{\Sigma E + \Sigma F} \times 100.$$

Thus, flow predominance is the percentage of the total flow at a point that is downstream or toward the ocean. By having velocity data for several points in a vertical, a plot to define the distribution of flow predominance from surface to bottom at the vertical can be made. It is emphasized that this plot does not represent the distribution of discharge from surface to bottom, but only defines the direction and degree of predominance of flow throughout the vertical. For example, although a vertical may have a flow predominance of 50 percent at points near both the top and bottom, this does not mean that the same volume of water flowed past both points, because the top would probably have higher velocities than the bottom.

At the measurement cross section at Astoria, flow is conveyed through three broad parts termed "channels."[2] Flow in the "north" and south channels parallels the banks, but flow in the middle channel is in a diagonal direction. In each of these channels, a specific vertical was selected to characterize the flow of the entire channel. For each discharge-measurement sequence (table 4) that had sufficient velocity data, flow predominance was calculated at heights above the bed of 5, 25, 50, 75, and 95 percent of the total depth at the selected vertical in each of the three channels. These data are given in table 6. Inasmuch as the discharge measurement sequences were usually about 10 hours long, most of the flow-predominance values in table 6 are based on velocity data from only one-half of a tidal cycle instead of a complete tidal cycle. However, unless there were extreme differences between the high-high and the low-high, or the low-low and the high-low tides, flow-predominance values calculated using data for only one-half of a tidal cycle should be reasonably representative of the flow-predominance values for the complete tidal cycle. Also, the "mean discharge" given for each date in table 6 is the algebraic mean for exactly the same part of the tidal cy-

[2]In this analysis, the northernmost channel, the midestuary area, and the navigational channel are called the "north," middle, and south channels, respectively.

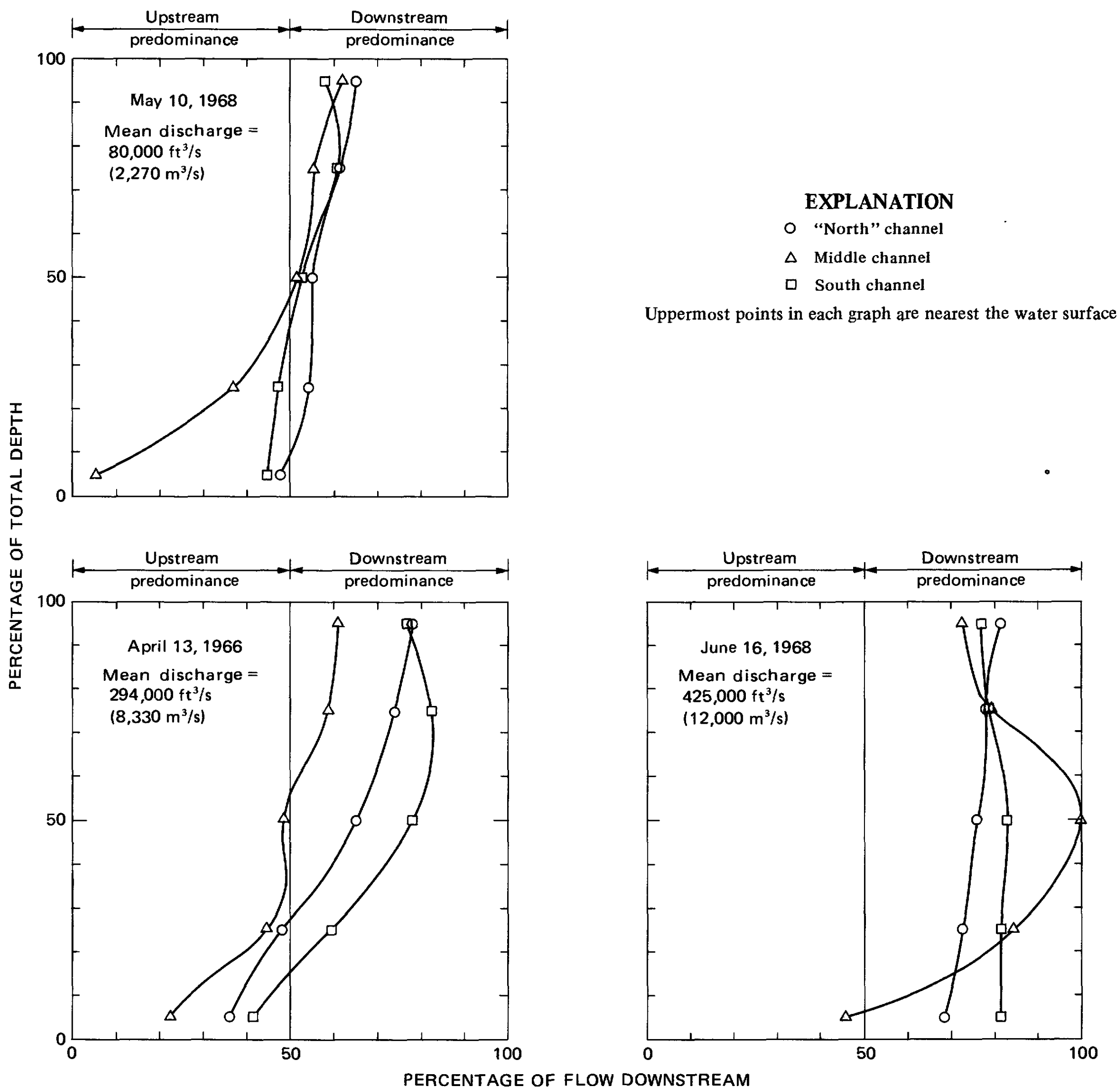

FIGURE 13. — Vertical distribution of flow predominance in the "north," middle, and south channels at the measuring cross section at Astoria, CRM 14, for various mean discharges.

cle as was used to calculate the flow predominance. Therefore, the correlation between the two variables should be roughly the same as would be obtained from using data for a full tidal cycle.

Flow-predominance curves for three different times are plotted in figure 13 to indicate how the flow distribution varies with the mean discharge at these verticals and within each channel. For zero upland discharge, normally the flow predominance at all depths would be close to 50 percent because there would be no possibility of stratification. The figure demonstrates that for some mean discharges the flow is predominantly upstream near the bottom and predominantly downstream near the surface.

The variation of flow predominance with mean discharge is shown more clearly in figure 14. In the "north" channel, at the bottom, flow is predominantly landward for all mean discharges of less than about 340,000 ft^3/s (9,630 m^3/s) and is most predominantly landward (37 percent seaward) at a mean discharge of 200,000 ft^3/s (5,660 m^3/s); as mean discharge increases, flow predominance gradually changes from landward to seaward and at 550,000 ft^3/s (15,600 m^3/s) it reaches a value of 75 percent seaward. At the 25 percent depth, flow predominance remains at 50 percent for mean discharges of less than about 370,000 ft^3/s (10,500 m^3/s) and increases gradually as mean discharge increases up to a value of 77 percent seaward at about 550,000 ft^3/s (15,600 m^3/s). In the upper half of the vertical, seaward flow predominance increases rapidly to a value of 70 percent as the flow increases to a mean discharge of 100,000 ft^3/s (2,830 m^3/s). It then levels off and gradually increases to 78 percent at 550,000 ft^3/s (15,600 m^3/s). For all depths within the vertical, flow predominance approached the

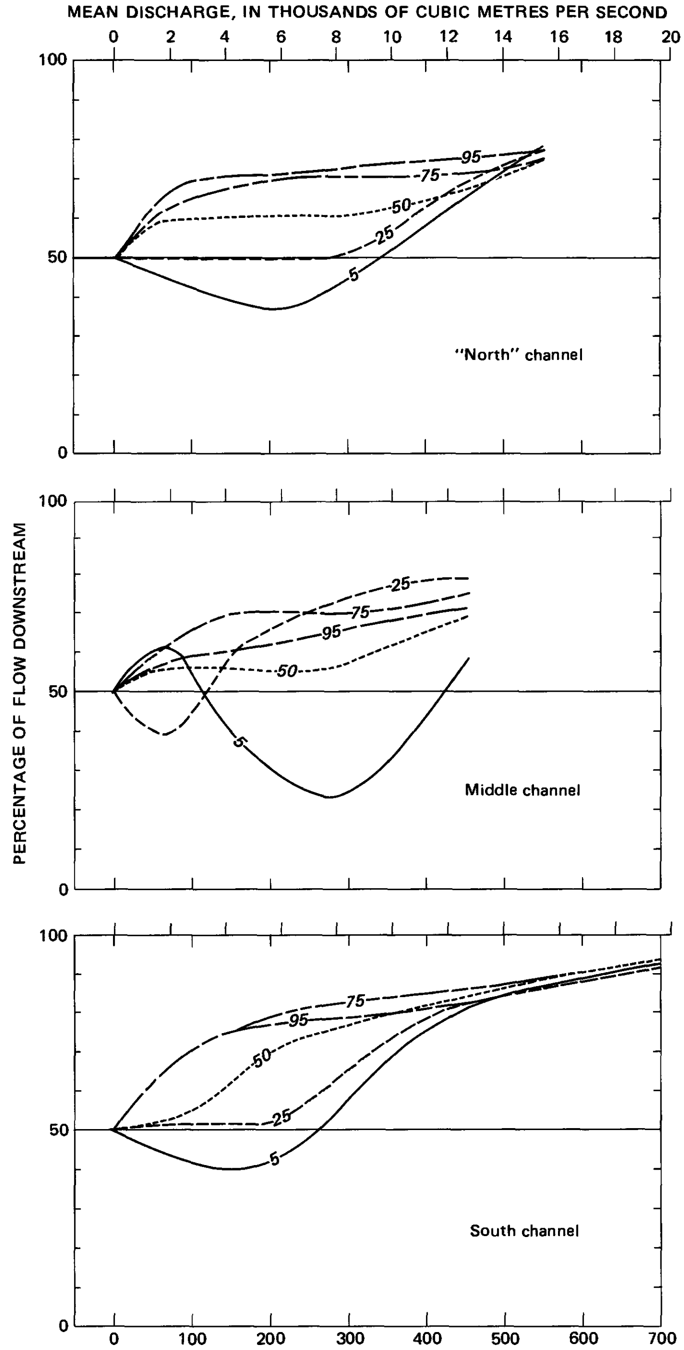

FIGURE 14. — Variation of flow predominance with mean discharge at the measuring cross section at Astoria, CRM 14. Numbers indicate height above bed expressed as a percentage of the total depth.

same level of about 77 percent at 550,000 ft^3/s (15,600 m^3/s), but at no time during the measurement did the flow ever reach 100 percent seaward.

The flow-predominance pattern for the south channel is very similar to that for the "north" channel. Near the bottom it is less than 50 percent for low mean discharges and decreases to a minimum of 40 percent at a mean discharge of 150,000 ft^3/s (4,250 m^3/s). With mean discharges greater than 150,000 ft^3/s (4,250 m^3/s), it progressively increases to 50 percent at a mean discharge of 260,000 ft^3/s (7,360 m^3/s) and is as high as 93 percent at a mean discharge of 700,000 ft^3/s (19,800 m^3/s). At the 25 percent depth, flow predominance is close to 50 percent for mean discharges under 200,000 ft^3/s (5,660 m^3/s), and increases as mean discharge increases to 92 percent at 700,000 ft^3/s (19,800 m^3/s). In the upper half of the vertical, flow predominance increases rapidly with increases in mean discharge up to about 200,000 ft^3/s (5,660 m^3/s) and then it gradually increases to 93 percent at 700,000 ft^3/s (19,800 m^3/s). Although flow predominance in the south channel was not defined at mean discharges greater than about 700,000 ft^3/s (19,800 m^3/s), by extrapolation it appears that for a mean discharge of about 1 million ft^3/s (0.03 million m^3/s) the flow at CRM 14 would be 100 percent seaward. This agrees with the mean discharge predicted for 100 percent seaward flow for the "north" channel.

Flow-predominance patterns for the middle channel are different from those in the "north" and south channels. At the bottom, flow predominance is seaward with mean discharges of less than 115,000 ft^3/s (3,260 m^3/s); however, it is landward with mean discharges from 115,000 to 425,000 ft^3/s (3,260 to 12,000 m^3/s). At 25 percent of depth, flow predominance is landward with mean discharges of less than 120,000 ft^3/s (3,400 m^3/s), but it is seaward at higher mean discharges. The upper half of the vertical follows the same pattern as was observed in the "north" and south channels except the magnitude of the seaward predominance is not as large. The main reason for the difference in flow patterns between the middle channel and the "north" and south channels is that the flow in the "north" and south channels is generally perpendicular to the cross section, whereas the flow in the middle channel is not and at times parallels the cross section.

FLOW-PREDOMINANCE PATTERNS IN THE SOUTH CHANNEL, CRM 5.6-22.5

For a more complete understanding of flow patterns in the estuary, data were collected at two different flow conditions to define sediment transport and flow characteristics along the longitudinal axis of the south channel. During a 3-day period when the tidal patterns and upland discharges were relatively constant, data were collected at seven stations that were located about 2 miles (3.2 km) apart. On each day, measurements were made at three adjacent stations from a single vessel that repetitively occupied each station about every 2 hours during the daylight hours. On the second day the occupied stations were located in the middle part of the study reach and the upstream and downstream stations corresponded, respectively, to the downstream station on the first day and the upstream station on the last day. Measurement data were combined according to the

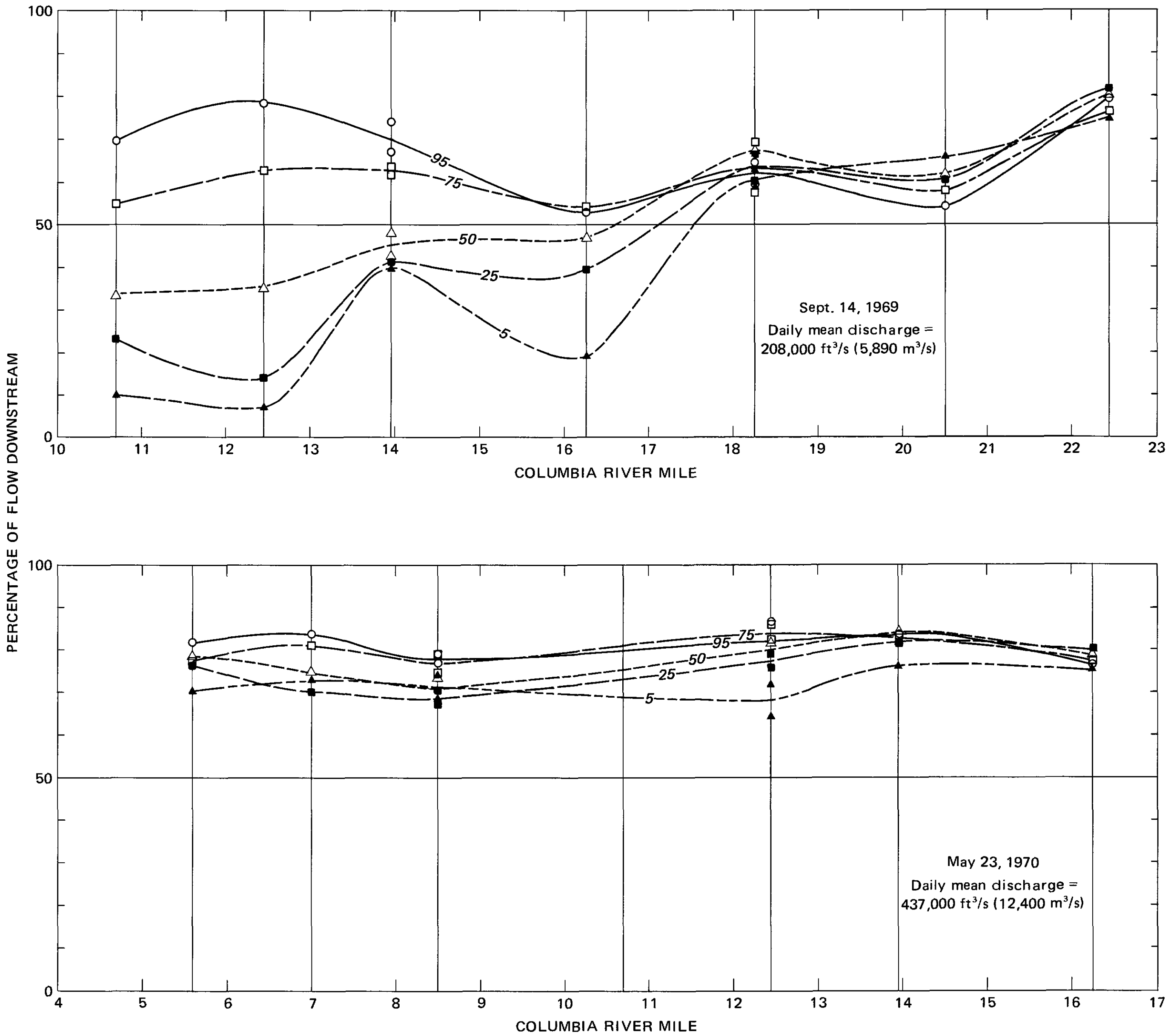

FIGURE 15. — Flow predominance along the longitudinal axis of the south channel during a half tidal cycle. Numbers indicate height above the bed expressed as a percentage of the total depth.

relative time of collection in the tidal cycle to give distribution curves that show the time variations of variables at all stations on the second (middle) day.

For the first flow condition (September 14, 1969) the daily mean discharge at the Astoria cross section was 208,000 ft^3/s (5,890 m^3/s) and the study reach extended from CRM 10.7 to CRM 22.5. From velocity profile data, flow-predominance values were calculated for the seven stations at heights above the bed of 5, 25, 50, 75, and 95 percent of the total depth. A plot of these data (fig. 15) shows that upstream from CRM 17.5, the flow was predominantly downstream at all depths. Near the bottom, net flow was zero at CRM 17.5 and was predominantly upstream in the lower half of the study reach. At middepth, the net flow was zero at CRM 16.6 and downstream from that point it was predominantly landward. Flow in the upper layers remained predominantly downstream throughout the entire study reach.

For the second flow condition (May 23, 1970) the daily mean discharge at the Astoria cross section was 437,000 ft^3/s (12,400 m^3/s), and the study reach extended from CRM 5.6 to CRM 16.2. Velocity profiles collected at each of the 7 stations during this study also were used to compute flow predominance at heights above the bed of 5, 25, 50, 75, and 95 percent of the total depth. Figure 15 also shows these data. Near the bottom, the flow predominance ranged from 76 percent at the upstream

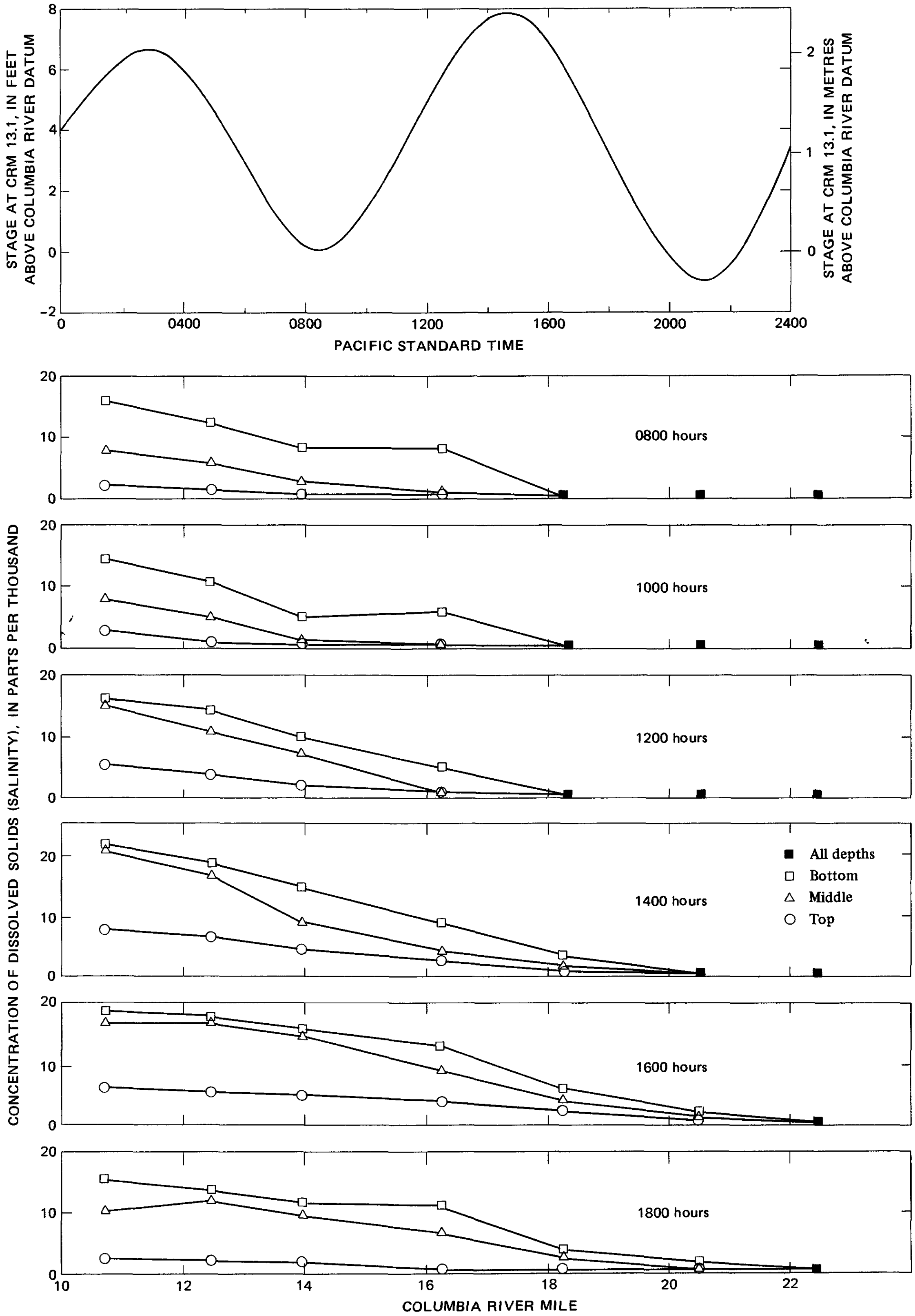

FIGURE 16. — Salinity distribution along the longitudinal axis of the south channel at various times in the tidal cycle on September 14, 1969.

end of the reach to 70 percent at the downstream end. At the top, the flow predominance remained approximately a constant 80 percent over the entire reach.

In both studies, the flow predominance was determined with velocity data for only half of the tidal cycle—the early morning ebb and the following flood. Tide ranges during these periods (figs. 16, 17) were such that the computed values of flow predominance on September 14 probably are lower than full-tidal-cycle values, and those computed for May 23 are higher. Despite this discrepancy, the data show that the point on the bed where the flow predominance is 50 percent (where the net flow is zero) varies longitudinally in response to the upland flow.

According to Simmons (1955), heaviest shoaling in partly mixed estuaries is between the high-tide and the low-tide positions of the upstream limit of saltwater intrusion, and flow predominance near the bottom in this zone is close to 50 percent. Shoaling occurs because the net downstream transport of sediment along the bottom is effectively stopped where there is a predominance of upstream currents and because suspended sediment tends to accumulate in the zone where net flow is near zero. This latter effect results from the tendency for sediment particles in the upper layers, where the flow is predominantly seaward, to settle during slack water into the lower layers where they are transported back upstream by the predominantly landward currents (fig. 13); this action over many tidal cycles causes an accumulation of sediment at and near the bed in the zone where neither upstream or downstream flow predominates. In the Columbia River estuary, much of the accumulated sediment is resuspended during the high-velocity period of each flood and ebb, thereby creating locally a "turbidity maximum" wherein the concentration of suspended sediment is considerably higher than it is either upstream or downstream (Hubbell and others, 1971).

Salinity data from the two longitudinal studies (figs. 16, 17) show that on September 14, during the time for which flow predominance was computed, saltwater intrusion ranged between about CRM 18 and CRM 21; on May 23 it varied between about CRM 5 and CRM 14. On the basis of these data, shoaling would be expected in the reach between CRM 5 and 21. In confirmation, Lockett (1967) pointed out that in the 11-mile (17.7-km) reach from Tongue Point (CRM 17.5) to Sand Island (CRM 6.5) there has been 77 million cubic yards (59 million m^3) of material dredged from the navigational channel during 1868 to 1958.

SUMMARY

Unsteady flow, caused mainly by tides, and complex velocity distributions, due mainly to salinity gradients, precluded use of conventional methods of measuring discharge and of computed discharge records in the Columbia River estuary. However, discharge data were obtained by employing a moving-boat technique (MOVD) in which both the direction and magnitude of the water velocity are measured throughout the entire depth at a series of laterally spaced verticals in a cross section. Data from repetitive measurements at Astoria and the Beaver Army Terminal during half tidal cycles (about 10 hours) were used to define flow hydrographs at these locations, and the hydrographs, in turn, were used to adapt and calibrate one-dimensional mathematical models for calculating continuous records of discharge. The discharge models for both Beaver Army Terminal and Astoria were based on solution of partial differential equations that express the conservation of mass and momentum in one-dimensional unsteady homogeneous-density open-channel flow according to the method of characteristics (Lai, 1965a) using measured water-surface slopes and channel geometry as boundary conditions.

The mathematical model for the Beaver Army Terminal, which is in the freshwater part of the estuary at CRM 53.3, was used to compute instantaneous discharges every 15 minutes; daily mean discharges, in turn, were determined from these values. The flow-resistance coefficient, η, in the model varied with discharge and was lowest at high flows. Discharges computed for the period May 1968 through June 1970 show that flow reversals at Beaver commonly occur during at least one of the twice-daily flood periods whenever the daily mean discharge is less than 185,000 ft^3/s (5,240 m^3/s). For daily mean discharges of 185,000 to 225,000 ft^3/s (5,240 to 6,370 m^3/s), the flow reverses occasionally during the strongest flood period, and for daily mean discharges greater than 225,000 ft^3/s (6,370 m^3/s) the flow rarely reverses.

At Astoria (CRM 14), application of the basic one-dimensional model was complicated because of the complex geometry of the reach and the presence of both longitudinal and lateral salinity gradients. To obtain, with the model, hydrographs having an overall shape that corresponded to measured hydrographs, it was necessary to vary η throughout each flood and ebb period. In addition, in order to compute hydrographs that compared closely with measured hydrographs, a factor had to be applied daily to adjust the measured water-surface slopes. The required factor for each day of record was established by adjusting the slopes by trial until the daily mean discharge calculated from the instantaneous discharges computed every 15 minutes by the mathematical model agreed within a few percent of the daily mean discharges determined from a simple volumetric model. Because monthly mean discharges determined with daily mean discharges from the

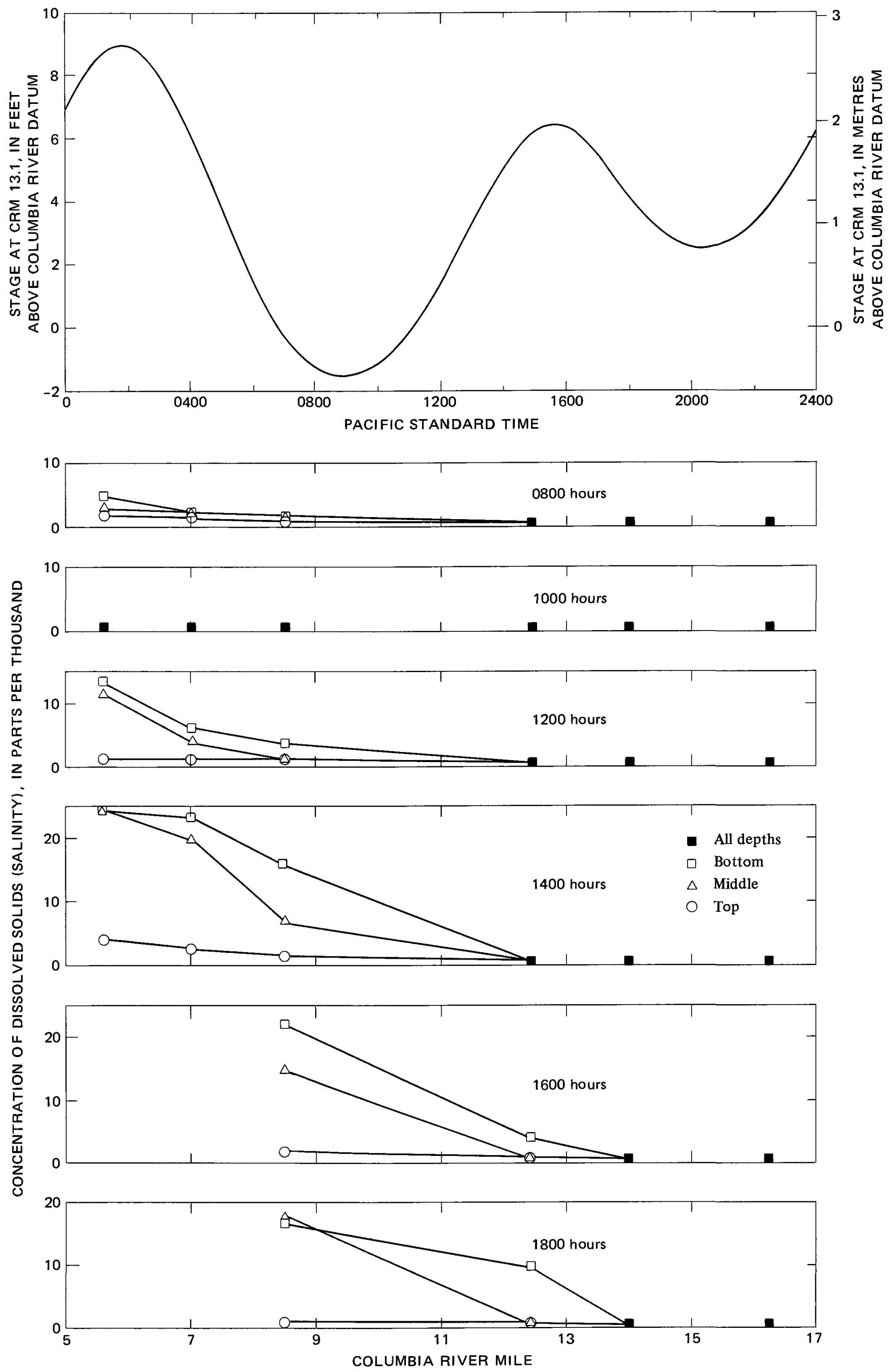

FIGURE 17. — Salinity distribution along the longitudinal axis of the south channel at various times in the tidal cycle on May 23, 1970.

volumetric model compared within 5 percent of monthly mean discharges computed by the routing technique used by the Northwest Resorces Data Center (Orem, 1968), instantaneous discharge computed every 15 minutes with the mathematical model for the period March 1968 through June 1970 are considered to be fairly accurate.

Observations at Astoria indicate that near the surface, ebb velocities are as much as 8 ft/s (2.4 m/s) and flood velocities are as much as 6 ft/s (1.8 m/s). Time-averaged velocities in the cross section during each ebb and flood period, however, are about 3 and 2 ft/s (0.9 and 0.6 m/s), respectively. Because of the relatively large upland flow and moderate tide range, instantaneous ebb discharges frequently are greater than 2 million ft^3/s (0.06 million m^3/s) and instantaneous flood discharges often are over 1.5 million ft^3/s (0.04 million m^3/s).

Daily mean discharges at Astoria fluctuate cyclically because of (1) the daily 50-minute shift in the position of the tide curve relative to absolute clock time, due to the difference in the length of lunar (24.8 hours) and solar (24.0 hours) days; and (2) the periodic variations in the maximum and minimum tide heights that occur with a frequency of about 14.3 days. Because of this cyclic pattern, daily mean discharges at Astoria are not a measure of the upland freshwater discharge. For instance, on September 22, 1969, the daily mean discharge at Beaver was about 100,000 ft^3/s (2,830 m^3/s) downstream, but at Astoria it was 7,400 ft^3/s (210 m^3/s) upstream.

Based on the change in the proportion of flow through the north (northernmost channel and shallow midestuary area combined) and south channels at CRM 14 during ebbs and floods, for daily mean discharges at Beaver of less than about 165,000 ft^3/s (4,670 m^3/s) there is a net clockwise circulation in the lower estuary. That is, the proportion of the total quantity of water flowing upstream in the north channel during the flood is greater than the proportion of the total quantity of water flowing downstream during the ebb, whereas the reverse occurs in the south channel. For daily mean discharges from 165,000 to about 190,000 ft^3/s (4,670 to about 5,380 m^3/s) the net circulation is counterclockwise, and for discharges greater than 190,000 ft^3/s (5,380 m^3/s) it is also clockwise. On the average, the north channel conveys 76 percent of the flood flow and 69 percent of the ebb flow.

At the measuring cross section at Astoria, flow near the bottom in the "north" (northernmost) channel is predominantly landward for mean discharges (algebraic mean throughout a tidal cycle) less than about 340,000 ft^3/s (9,630 m^3/s), whereas from middepth to the surface it is predominantly seaward with the highest predominance being near the surface. At a mean discharge of 550,000 ft^3/s (15,600 m^3/s), the flow predominance at all depths is about 77 percent. In the south channel, the flow-predominance pattern is very similar to that of the "north" channel. Near the bottom the flow is predominantly landward for mean discharges less than 260,000 ft^3/s (7,360 m^3/s), and in the upper half of the depth the flow is predominantly seaward, with the highest predominance near the surface. At a mean discharge of 700,000 ft^3/s (19,800 m^3/s), the flow predominance at all depths is about 92 percent. It is estimated that the flow predominance in the "north" and south channels would reach 100 percent seaward at a discharge of about 1 million ft^3/s (0.03 million m^3/s). The direction of flow in the "north" and south channels is parallel to the riverbank, but the direction of flow in the middle channel trends in a diagonal direction, and the channel is not well defined. As a result, in the middle channel, at the bottom, flow predominance is seaward for mean discharges less than 115,000 ft^3/s (3,260 m^3/s) and landward for discharges from 115,000 to 425,000 ft^3/s (3,260 to 12,000 m^3/s). At 25 percent of the depth, flow predominance is landward for discharges less than 120,000 ft^3/s (3,400 m^3/s) but is seaward for higher flows. In the upper half of the depth, the flow predominance is seaward and increases as the discharge increases. At a mean discharge of about 450,000 ft^3/s (12,700 m^3/s), the flow predominance at all depths is about 70 percent.

Longitudinal flow characteristics in the south channel determined when the daily mean discharge at Astoria was 208,000 ft^3/s (5,890 m^3/s; Sept. 14, 1969), indicated that flow at all depths was predominantly seaward upstream of CRM 17.5. At CRM 17.5, flow predominance near the bottom became landward while the flow in the upper layers remained seaward. Salinity data showed that during the day the upstream extent of saltwater instrusion ranged between about CRM 18 and CRM 21. For a daily mean discharge at Astoria of 437,000 ft^3/s (12,400 m^3/s; May 23, 1970), the flow was predominantly seaward at all depths throughout the entire study reach, which extended from CRM 5.6 to 16.2. During the day saltwater intrusion extended upstream to CRM 14 and receded to about CRM 5. On the basis of these data, heavy shoaling should occur in the reach between CRM 5 and 21; dredging records of the U.S. Army Corps of Engineers confirm that this is the case.

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APPENDIX 1. — *Daily mean discharge of the Columbia River at Astoria, Oreg.*

[Discharge in thousands of cubic feet per second]

1968

Day	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	---	222	---	324	320	135	118	64.9	161	234
2	---	260	---	340	312	90.7	58.0	66.3	172	236
3	---	236	---	357	292	85.0	58.7	108	227	244
4	---	206	---	346	273	53.8	105	205	246	276
5	---	249	---	316	261	56.6	150	193	250	340
6	---	195	---	305	235	113	222	250	244	379
7	---	182	---	297	242	210	250	239	232	318
8	---	159	---	315	265	262	242	205	195	362
9	224	151	---	353	337	285	223	165	262	288
10	207	150	112	419	380	257	226	164	275	276
11	195	190	149	480	402	216	217	143	272	313
12	214	224	187	467	428	157	168	189	332	343
13	242	204	246	498	384	162	131	182	316	278
14	274	198	272	504	378	160	149	138	262	260
15	269	235	234	490	359	133	142	199	255	225
16	273	224	173	462	330	114	90.2	151	227	286
17	273	177	179	449	299	75.9	67.2	98.0	239	272
18	264	85.7	153	422	270	37.7	65.6	104	267	350
19	252	96.7	119	417	246	40.6	82.1	122	302	366
20	231	96.2	139	432	202	84.3	160	204	332	322
21	212	92.2	134	390	188	91.3	211	229	278	312
22	146	47.1	195	395	198	135	238	279	332	262
23	132	127	257	425	208	185	221	269	333	214
24	146	150	276	431	216	251	226	248	313	199
25	165	166	338	442	266	254	1/186	270	302	215
26	238	---	312	446	278	225	1/186	220	221	203
27	257	---	330	443	254	215	1/181	154	248	224
28	292	---	379	411	243	243	147	69.2	202	259
29	326	---	397	394	204	214	74.9	60.4	164	274
30	276	---	377	374	187	168	41.5	144	151	324
31	215	---	318	---	151	149	-----	130	---	1/314
Mean:	---	---	---	405	278	157	155	170	254	283
Max:	326	260	397	504	428	285	250	279	333	379
Min:	132	47.1	112	297	151	37.7	41.5	60.4	151	199

1969

Day	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	1/292	1/245	193	293	416	499	457	216	150	114	137	143
2	1/283	1/255	177	359	439	510	460	187	116	126	116	106
3	1/258	1/253	190	369	444	493	421	136	112	164	70.9	71.5
4	1/266	1/260	220	422	449	485	390	117	95.8	124	23.0	164
5	1/296	1/285	229	504	421	479	352	137	91.8	68.5	82.9	130
6	1/336	304	278	424	386	444	323	99.7	70.2	29.8	183	136
7	1/414	258	262	309	351	408	316	101	56.3	1/91.0	186	156
8	422	228	284	337	318	402	311	70.3	57.1	1/154	286	177
9	398	275	293	374	349	400	281	99.1	121	201	284	197
10	387	220	268	383	396	390	263	105	156	273	259	178
11	451	228	211	352	410	415	308	137	182	238	219	159
12	378	261	197	345	445	440	325	152	180	236	234	244
13	326	323	168	437	471	448	300	234	223	186	210	243
14	287	357	175	441	528	474	308	232	208	164	161	262
15	330	342	173	460	534	501	322	230	154	135	164	226
16	356	346	146	432	579	470	1/309	223	125	157	170	194
17	413	232	247	450	549	472	1/286	186	82.5	139	168	174
18	369	211	280	473	558	437	1/263	181	67.5	118	114	170
19	325	222	260	426	555	391	1/240	167	68.3	126	78.5	160
20	322	268	277	437	558	391	1/260	144	59.7	66.2	99.8	194
21	311	278	332	456	540	339	1/237	109	-3.2	1/39.0	200	256
22	322	203	292	380	522	260	1/194	50.4	-7.4	1/115	230	309
23	278	183	362	408	516	233	1/167	23.3	95.9	1/163	220	374
24	268	189	309	442	516	220	1/160	47.5	158	1/237	231	375
25	229	170	261	417	466	220	1/149	93.3	220	1/214	217	381
26	226	183	230	400	463	220	82.0	165	228	1/186	202	397
27	172	149	242	388	479	254	124	228	212	163	194	319
28	205	149	221	395	446	310	184	263	171	211	172	294
29	183	---	212	399	450	386	258	224	150	167	151	281
30	1/236	---	228	401	491	440	290	190	142	169	169	251
31	1/220	---	273	---	483	---	255	164	-----	165	-----	207
Mean:	308	246	242	404	469	394	277	152	125	153	175	224
Max:	451	357	362	504	579	510	460	263	228	273	286	397
Min:	172	149	146	293	318	220	82.0	23.3	-7.4	29.8	23.0	71.5

1970

Day	Jan.	Feb.	Mar.	Apr.	May	June
1	190	388	168	114	172	381
2	160	302	132	105	172	408
3	147	327	185	161	152	513
4	206	329	1/185	226	217	518
5	217	330	1/211	95.4	1/265	455
6	246	310	168	193	1/266	480
7	228	346	268	224	248	445
8	205	288	250	251	276	446
9	223	252	210	254	257	446
10	234	228	191	269	270	458
11	205	221	217	286	234	417
12	169	202	209	238	236	387
13	140	222	1/208	188	219	353
14	276	160	1/178	177	199	314
15	279	92.9	1/127	114	153	284
16	286	1/186	1/181	159	216	232
17	259	1/297	1/198	196	216	256
18	298	1/364	1/241	174	228	319
19	331	355	238	213	292	381
20	361	349	242	188	326	416
21	430	353	254	216	360	444
22	431	333	238	243	422	429
23	506	252	248	253	437	419
24	601	204	278	238	428	383
25	630	240	226	245	435	317
26	569	188	241	249	418	279
27	608	157	208	252	430	264
28	621	182	214	221	393	247
29	508	-----	188	176	404	235
30	491	-----	168	158	401	247
31	398	-----	129	-----	377	---
Mean:	337	266	206	203	294	372
Max:	630	388	278	286	435	518
Min:	140	92.9	129	95.4	153	232

1/ Estimated.

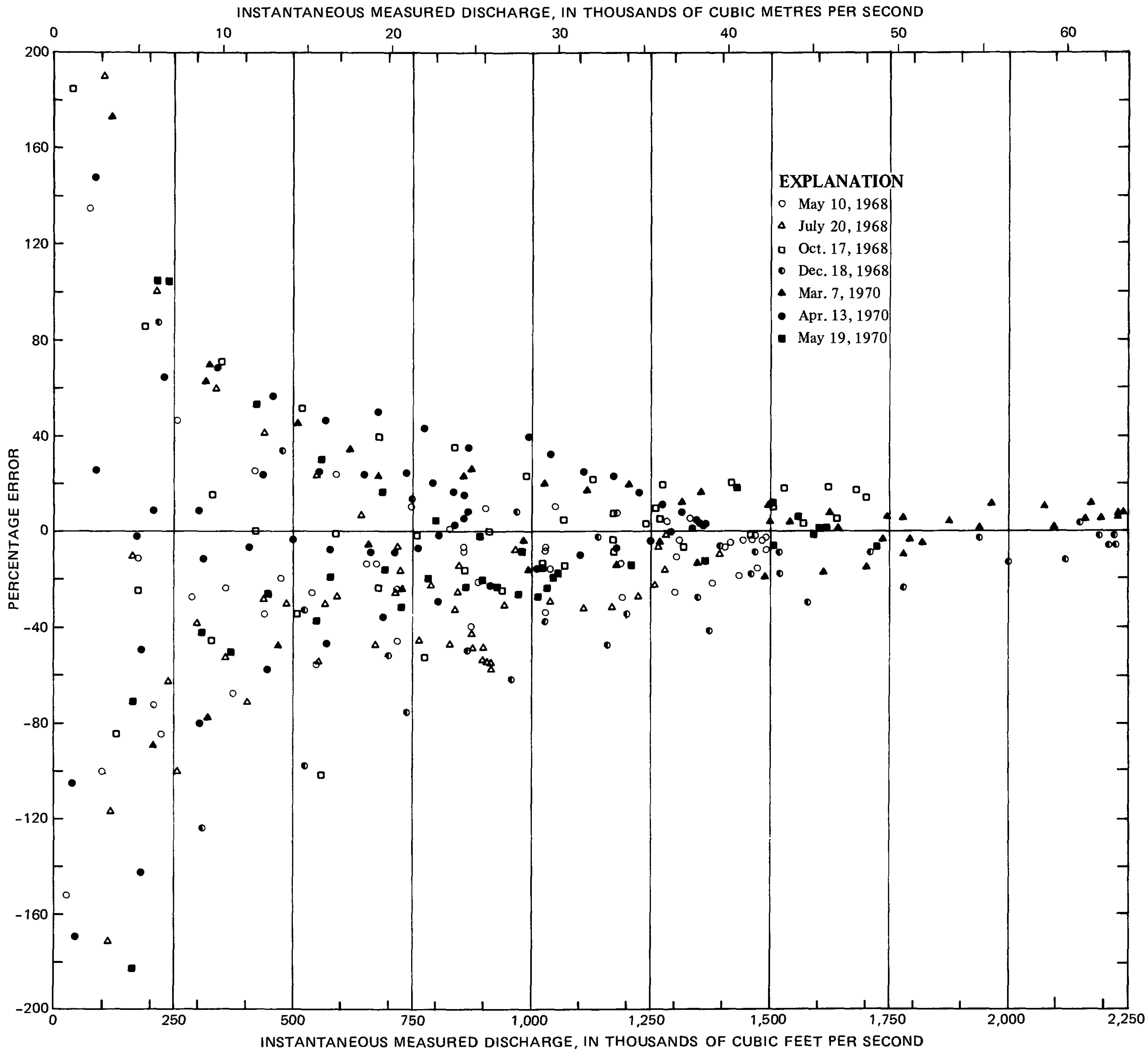

FIGURE 18. — Percentage error in computed instantaneous discharge at Astoria, Oreg., plotted against comparable measured discharge.

APPENDIX 2. — DETERMINATION OF PERCENTAGE ERROR BETWEEN MEASURED AND COMPUTED DISCHARGES AT ASTORIA

In order to evaluate the accuracy of the mathematical model for computing instantaneous discharges at Astoria, differences between discharges determined every 15 minutes and comparable discharges from the measured hydrographs have been analyzed statistically to define the "tolerance interval" (Dixon and Massey, 1957, p. 130), which indicates with a specified confidence the proportion of a population of computed discharges that have an error (difference) equal to or less than a specified value. The tolerance interval is expressed as

$$\bar{y} \pm Ks,$$

where

$\bar{y}$ is the mean error of a sample from the population;

K is the tolerance factor for a normal distribution and depends on the specified proportion of the population, sample size, and confidence coefficient; and

s is the standard deviation of the sample errors.

Figure 18 shows the percent error in computed discharges plotted against the corresponding measured discharges for all hydrographs used in the calibration of the mathematical model. This graph demonstrates that the distribution of plus and minus errors is roughly symmetrical about the zero-error line and that the scatter decreases as the discharge increases. In order to eliminate the influence of discharge from the statistical analysis, the errors were divided into 10 ranges according to discharge, and values within each range were treated as an independent set of data. In addition, several sets of data were examined to confirm that the distribution of errors within any set approximately follows the normal error curve—a requirement for the use of K.

Results from the analysis are presented in table 7. The tolerance limits define the end points of the tolerance interval and indicate, with 90 percent confidence, the percentage error that will not be equaled or exceeded by more than 10 percent of all computed discharges in a discharge range. Although errors are large when discharges are low, table 7 shows that for discharges greater than 1,250,000 ft^3/s (35,400 m^3/s), which occur about 30 percent of the time, 90 percent of all instantaneous discharges might be expected to be in error less than about 25 percent.

TABLE 7. — *Error analysis of computed discharges at Astoria, Oreg.*

[Values are based on percentage errors].

Discharge range[1] (ft^3/s)	Number of observations	Mean percentage error ($\bar{y}$)	K[2]	Standard deviation (s)	Tolerance limits: Lower limit	Tolerance limits: Upper limit
0- 225,000	38	102.1	1.971	408.5	−703.1	907.2
226,000- 500,000	43	−0.6	1.945	62.5	−122.2	121.0
501,000- 750,000	51	−7.6	1.913	39.3	−82.8	67.6
751,000-1,000,000	57	−10.9	1.895	29.8	−67.4	45.6
1,001,000-1,250,000	45	−5.4	1.935	21.5	−47.0	36.2
1,251,000-1,500,000	51	−2.2	1.913	13.4	−27.8	23.4
1,501,000-1,750,000	24	1.6	2.089	12.3	−24.1	27.3
1,751,000-2,000,000	11	−3.3	2.463	9.7	−27.2	20.6
2,001,000-2,250,000	12	1.7	2.404	6.8	−14.6	18.0
2,251,000-2,500,000	3	7.7	5.847	1.5	−1.1	16.5

[1]Pertains to both ebb and flood discharges.

[2]Tolerance factor for normal distribution which defines with 90-percent confidence an interval about the sample mean that includes 90 percent of the population. (From Dixon and Massey, 1957, table A-16.)

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