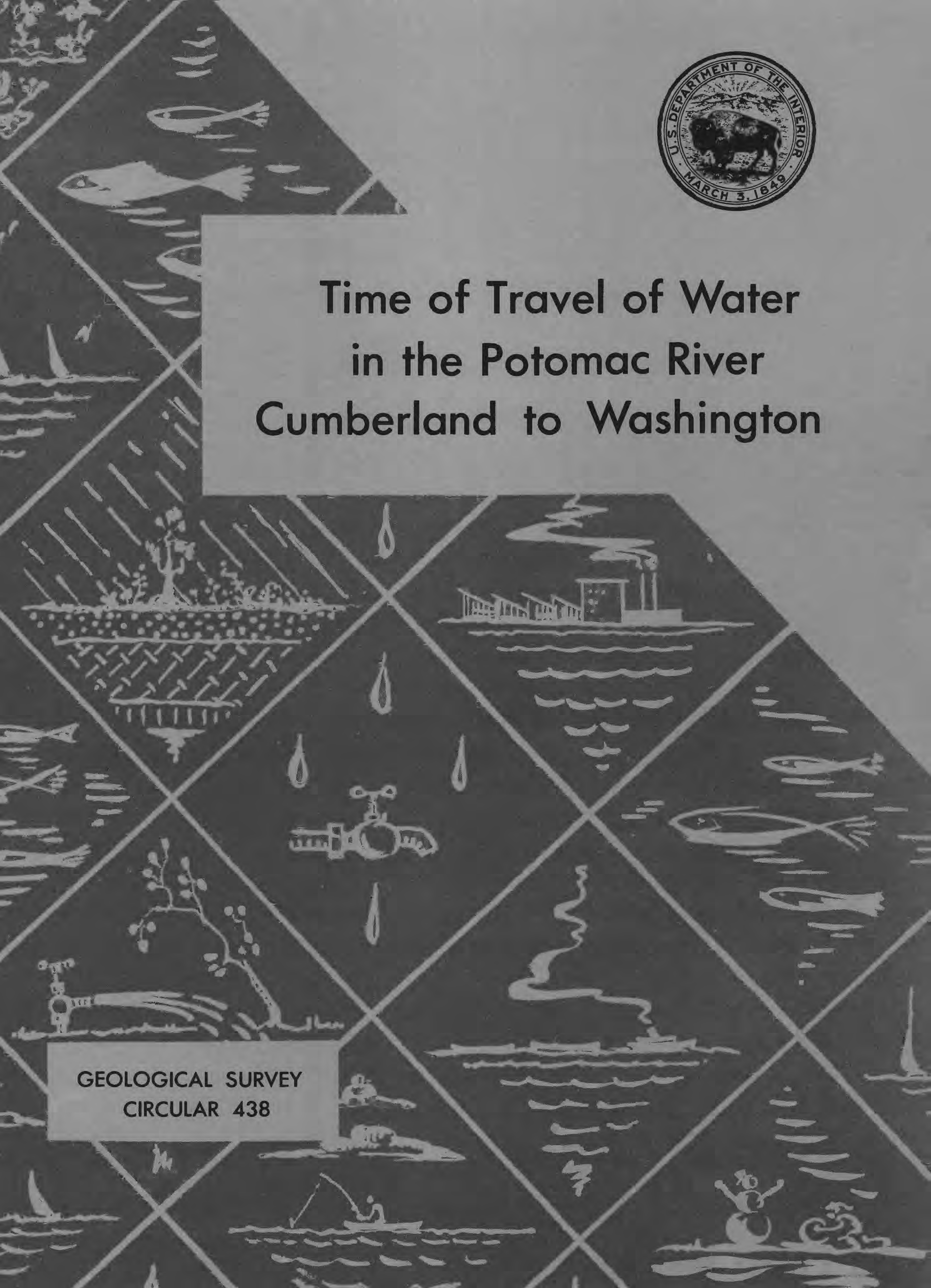

Time of Travel of Water in the Potomac River Cumberland to Washington

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By James K. Searcy and Luther C. Davis, Jr.

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ABSTRACT

This report introduces a graphical procedure for estimating the time required for water to travel down the Potomac River in the reach extending from Cumberland, Md., to Washington, D.C. The time of travel varies with the flow of the river; so the stage of the river at the lower end of the reach—the gaging station on the Potomac River near Washington, D.C.—is used as an index of flow. To develop the procedure, the reach between Cumberland and Washington was divided into five subreaches, delineated by six gaging stations. The average of the mean velocities of the river at adjacent gaging stations was used as the mean velocity in the intervening subreach, and a unit mass of water was assumed to travel at a rate equal to the mean velocity of the river.

A statistical analysis of possible variations in travel time between Cumberland and Washington indicated that the shortest travel time corresponding to a given stage near Washington would be about 80 percent of the most probable travel time.

The report includes a flow-duration curve and a flow-frequency chart for use in estimating discharge at the gaging station near Washington and subsequently the travel time of Potomac River water without knowledge of stage. The flow-duration curve shows the percentage of time during which specified discharges were equaled or exceeded in the past, and it can be used to predict future flow in connection with long-range planning. The flow-frequency chart shows the time distribution of flow by months and can be used to make a more nearly accurate estimate of discharge in any given month than could be made from the flow-duration curve.

The method used to develop the time-of-travel charts is described in sufficient detail to make it usable as a guide for similar studies on other rivers, where the velocity of flow is relatively unaffected by dams and pools in the reach being studied.

INTRODUCTION

This report introduces graphical procedures by which the time of travel of water between any two points on the Potomac River in the reach between Cumberland, Md., and Washington, D.C., can be estimated, provided the river stage near Washington is known. If the stage near Washington is not known, a special flow-frequency chart can be used to estimate the probable discharge near Washington at any time of year. The corresponding stage to use in the time-of-travel chart can be obtained from the stage-discharge relation curve. A flow-duration curve is presented for use in predicting the percent of time during which various flows will occur in the future. This curve would be useful for long-range planning.

The time-of-travel procedures in this report can be used to estimate the arrival time of possible contamination from an upstream source, because dissolved contamination can be assumed to travel at the same speed as a unit mass of water. An estimate of the time for contamination to travel down the river helps water users downstream plan any necessary action. Furthermore, the length of time organic pollution is in transit affects the oxygen requirements and thus is important in quality-of-water studies. Contamination that moves as suspended material is outside the scope of this report, because it travels more slowly than the water and dissolved contamination.

The Potomac River (fig. 1) is formed by the confluence of its North and South Branches, 21 miles downstream from Cumberland, Md. It flows east and southeast for 287 miles to Chesapeake Bay, passing Washington, D.C., 186 miles downstream from Cumberland. The drainage area at the mouth is 14,500 square miles, of which about 11,600 is drained by the nontidal section of the river upstream from Washington. The reach of the river between Cumberland and Washington, which includes a 21-mile section of the North Branch from Cumberland to the confluence with the South Branch, is relatively free of dams. Thus the method used to develop the time-of-travel charts is applicable to other rivers where the velocity of flow is only slightly affected by dams and pools in the reach being studied.

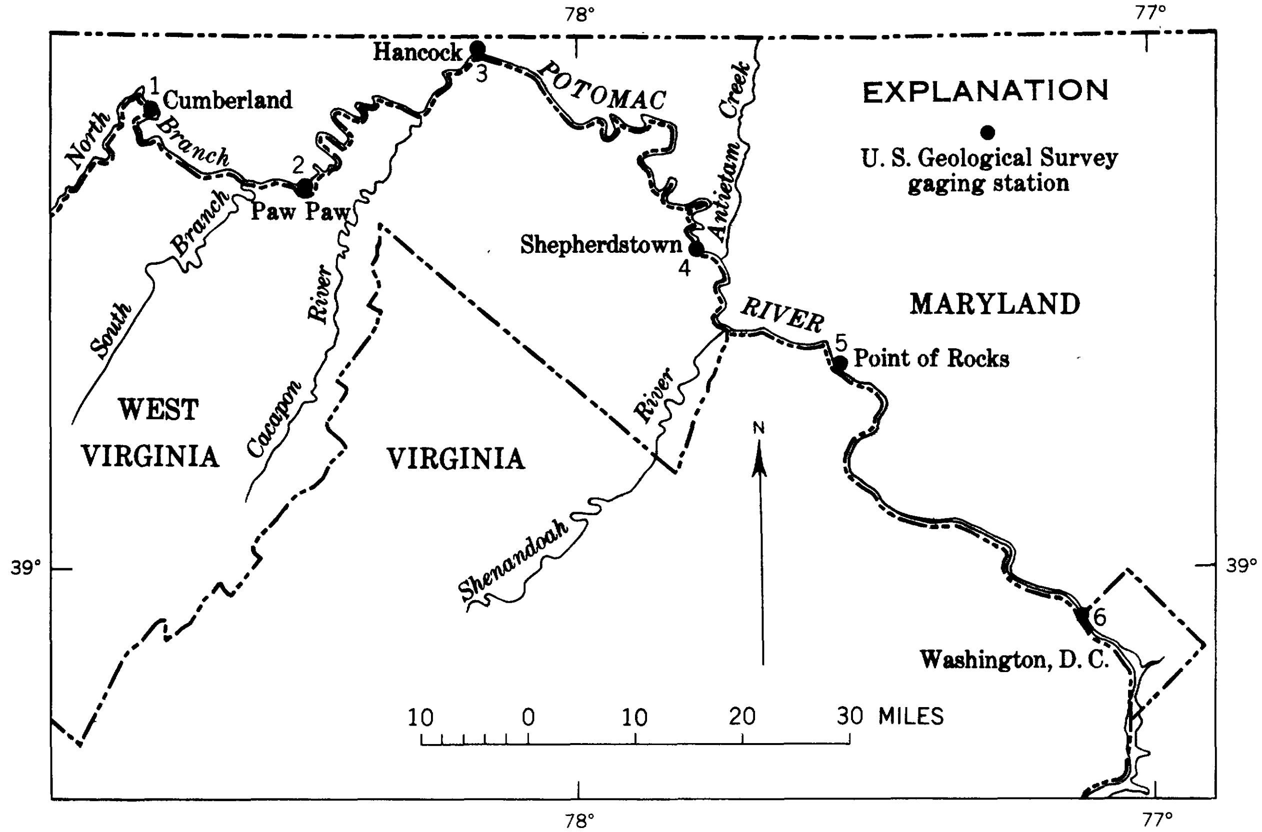

Figure 1.—Location of stream-gaging stations on the Potomac River upstream from Washington, D. C.

COMPUTATIONS

CONTROL POINTS

The reach of the river used in this study was divided into five subreaches, delineated by six stream-gaging stations. Data gathered at the gaging stations are available, from which discharges and velocities at the station sites can be computed. The gaging-station sites, therefore, are ideal control points for computing the time of travel of water in intervening subreaches. Table 1 lists the six stream-gaging stations in the study reach.

Table 1.—*Stream-gaging stations on the Potomac River in downstream order*

Number on figure 1	Location	Miles downstream from Cumberland	Drainage area (sq mi)	Average discharge	
				Period of record	Cubic feet per second
1	Near Cumberland, Md.[1]	0	875	1929–56	1,219
2	At Paw Paw, W. Va	28.1	3,109	1938–56	3,152
3	At Hancock, Md	66.0	4,073	1932–56	4,083
4	At Shepherdstown, W. Va	121.0	5,936	1928-53	5,804
5	At Point of Rocks, Md	145.1	9,651	1896–1956	9,378
6	Near Washington, D.C	186.1	11,560	1930–56	11,260

[1]North Branch Potomac River.

Note.—River mileages from Water-Supply Paper 800. Drainage areas and average discharges from Water-Supply Paper 1432, except for discontinued station at Shepherdstown, which is from Water-Supply Paper 1272.

The Geological Survey stream-gaging station near Washington is used as the index station in this study. It is located above tidewater on the Virginia side of the river, 2½ miles upstream from Chain Bridge. In addition, the Weather Bureau operates a special recorder for use in predicting river stages. From this recorder, the river stage at any time can be determined automatically by coded message over a telephone.

DISCHARGE

To determine the discharge at the next upstream control point, which most probably corresponds to a given discharge at a given control point, correlations were made between streamflow records at successive control points for the 5 years, 1946–50, as follows:

(6) Washington and (5) Point of Rocks
(5) Point of Rocks and (4) Shepherdstown
(4) Shepherdstown and (3) Hancock
(3) Hancock and (2) Paw Paw
(2) Paw Paw and (1) Cumberland

The correlation curve for Washington and Point of Rocks is shown in figure 2. It was used to find the most probable discharge at Point of Rocks corresponding to a given

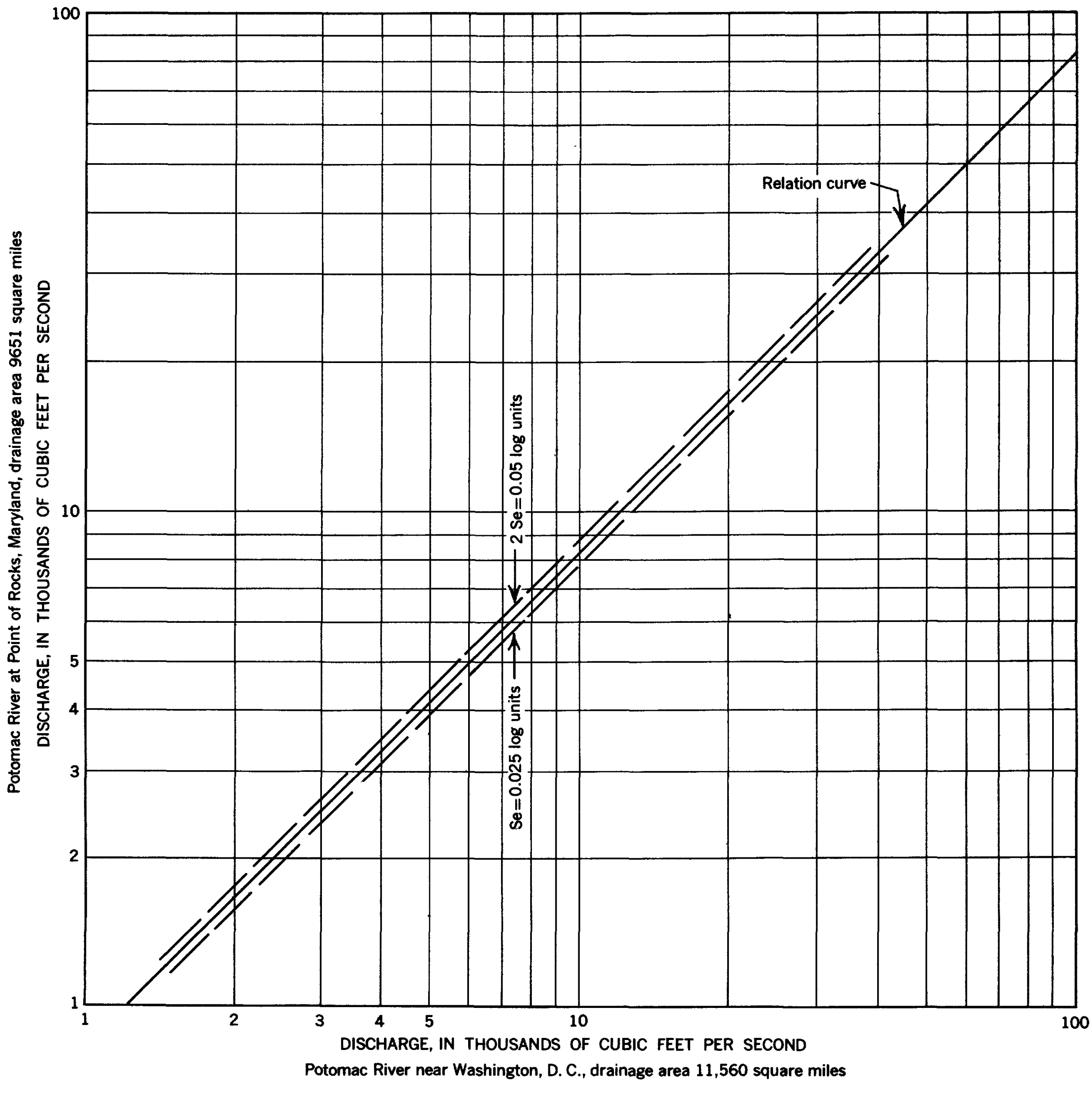

Figure 2.—Correlation of monthly discharge, Potomac River, water years 1946–50.

discharge near Washington. For example, when the discharge near Washington is 3,100 cfs (stage, 2.5 feet) the most probable discharge at Point of Rocks is 2,650 cfs.

The procedure for making correlations between gaging stations and for computing the standard error of estimate (shown as Se in figure 2) has been explained by Searcy (1960).

MEAN VELOCITY

To utilize the relation of mean velocity to discharge, curves of relation were developed for each control point by plotting the discharge against the mean velocity for each of the many discharge measurements that have been made at each gaging station. The relation curve for the control point at Point of Rocks is shown in figure 3.

It is assumed in this study that the average cross section in a subreach is the average of the measured cross sections at the two adjacent control points. Therefore, the mean velocity in a subreach is the average of the mean velocities at the two control points. Thus, with the discharge estimated as described in the preceding section, the mean velocity in each reach can be computed.

TIME OF TRAVEL BETWEEN CONTROL POINTS

The computations for time of travel in the subreaches Point of Rocks (5) to Washington (6) and Shepherdstown (4) to Point of Rocks (5) are shown in table 2. The figures in this table were obtained as follows: Stages (column a) were selected for the critical point (Washington) to provide a suitable spacing of lines on the time-of-travel chart. (See fig. 5.) The corresponding discharges (column b) were taken from the stage-discharge relation curve (fig. 4).

The mean velocities (column c) that correspond to the discharges (column b) were taken from the mean velocity-discharge relation for Washington. This relation is similar to that shown for Point of Rocks. (See fig. 3.)

The most probable discharges at control point 5, Point of Rocks (column d), corresponding to the discharges at the critical point, Washington (column b), were taken from the correlation curve of figure 2. The corresponding mean velocities (column e) were taken from figure 3.

The mean velocities in subreach 5 to 6 (column f) are the average of the corresponding mean velocities at the ends of the subreach (columns c and e). The length of the subreach (column g) is the difference in river miles below Cumberland of the control points at the ends of the subreach. (See table 1.)

The time of travel in hours (column h) was computed by dividing the distance by the mean velocity as follows:

Travel time in hours

$$= \frac{\text{Distance in miles} \times 5{,}280}{\text{Mean velocity (in feet per second)} \times 3{,}600}$$

Table 2.—*Computations of time of travel, Potomac River*

	Washington (6)		Point of Rocks (5)		Subreach (5) to (6)			Shepherdstown (4)		Subreach (4) to (5)		
Stage (feet) (a)	Discharge (cfs) (b)	Mean velocity (fps) (c)	Discharge (cfs) (d)	Mean velocity (fps) (e)	Mean velocity (fps) (f)	Distance (miles) (g)	Time of travel (hours) (h)	Discharge (cfs) (i)	Mean velocity (fps) (j)	Mean velocity (fps) (k)	Distance (miles) (l)	Time of travel (hours) (m)
2.0----	1,810	0.77	1,510	1.13	0.95	41.0	63.3	685	0.34	0.74	24.1	47.8
2.3----	2,470	1.05	2,060	1.24	1.14		52.7	980	.41	.82		43.1
2.5----	3,060	1.32	2,550	1.32	1.32		45.6	1,250	.48	.90		39.3
3.0----	4,940	2.16	4,120	1.55	1.86		32.3	2,200	.72	1.14		31.0
3.5----	7,430	3.10	6,200	1.79	2.44		24.6	3,550	1.05	1.42		24.9
4 -----	10,300	4.15	8,600	2.10	3.12		19.3	5,200	1.38	1.74		20.3
5 -----	17,100	6.35	14,300	2.59	4.47		13.5	9,400	2.05	2.32		15.2
6 -----	26,400	8.70	22,000	3.06	5.88		10.2	14,500	2.69	2.88		12.3
9 -----	63,200	12.40	52,800	4.13	8.26		7.3	34,500	4.29	4.21		8.4
12 ----	108,000	14.50	90,200	4.77	9.64	41.0	6.2	59,500	5.51	5.14	24.1	6.9

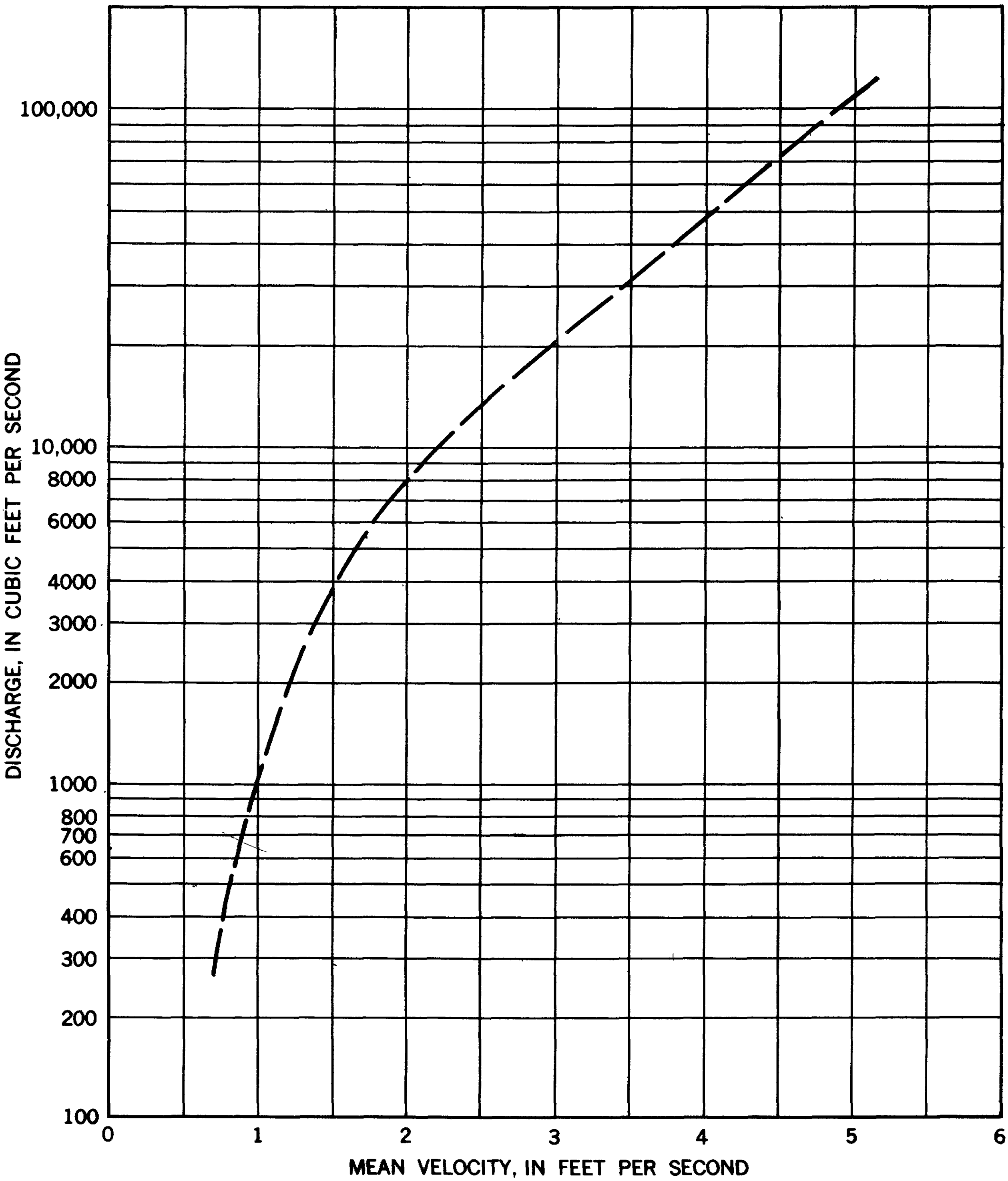

Figure 3.—Relation of mean velocity and discharge, Potomac River at Point of Rocks, Md.

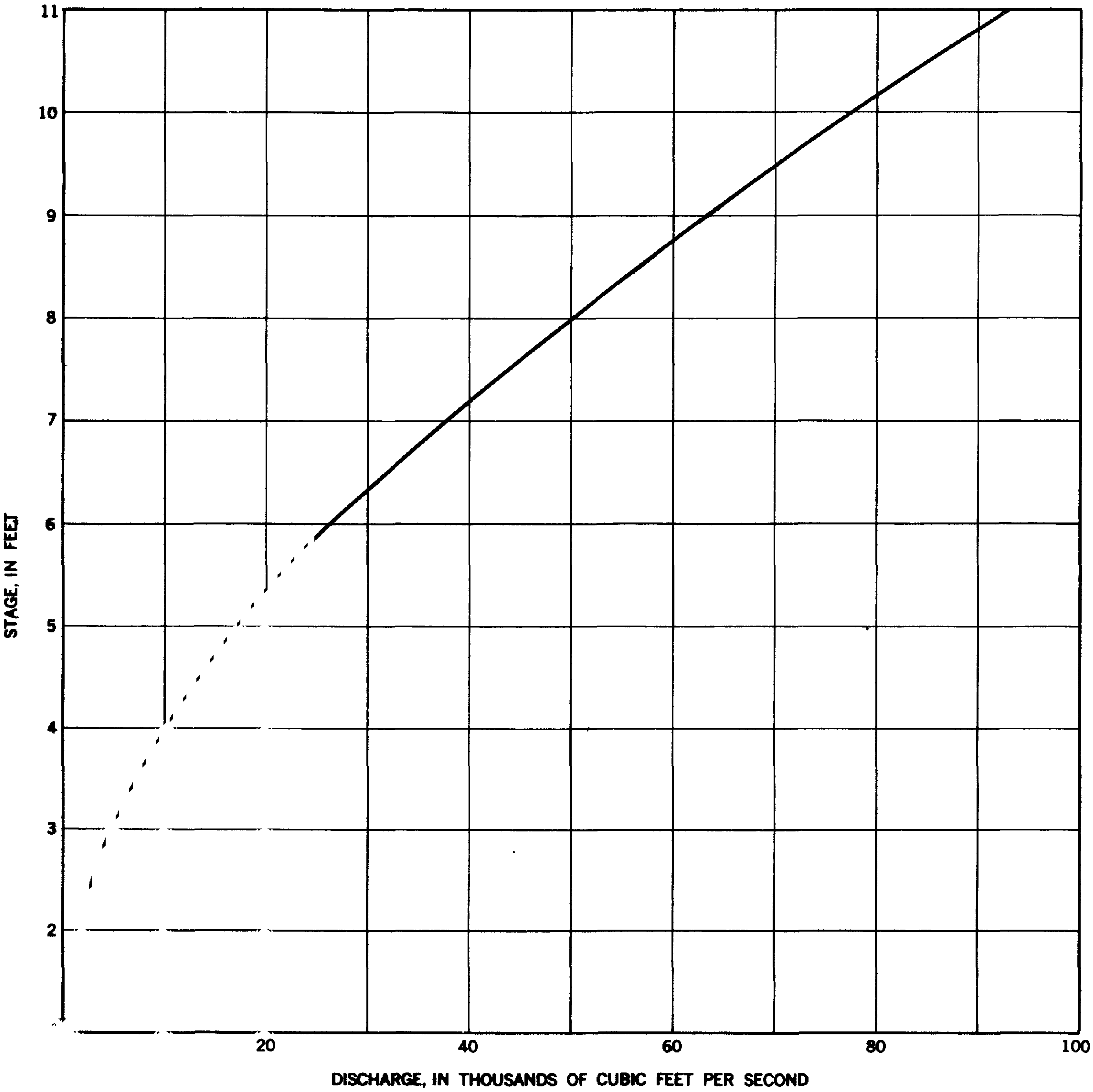

Figure 4.—Stage-discharge relation, Potomac River near Washington, D. C., 1957.

The time of travel in subreach 4 to 5 was determined by using a relation between discharges at Point of Rocks and Shepherdstown to obtain the most probable discharge at Shepherdstown corresponding to the discharge at Point of Rocks listed in column d. The mean velocity (column j) at Shepherdstown (control point 4) was then averaged with the mean velocity (column e) at Point of Rocks (control point 5) to obtain the mean velocity in the subreach. Then, by introducing the length of the subreach (24.1 miles), the time of travel in the subreach was determined. The times of travel in succeeding subreaches were computed in similar manner.

APPLICATION WITH RIVER STAGE KNOWN

TIME OF TRAVEL FROM CUMBERLAND

A time-of-travel chart (fig. 5) for the Potomac River near Washington was plotted by cumulating the computed times of travel. The times of travel for each selected stage near Washington were cumulated for each subreach from Cumberland to Washington and the cumulations were plotted against the river miles downstream from Cumberland. The plotted points for each selected stage were connected by straight lines.

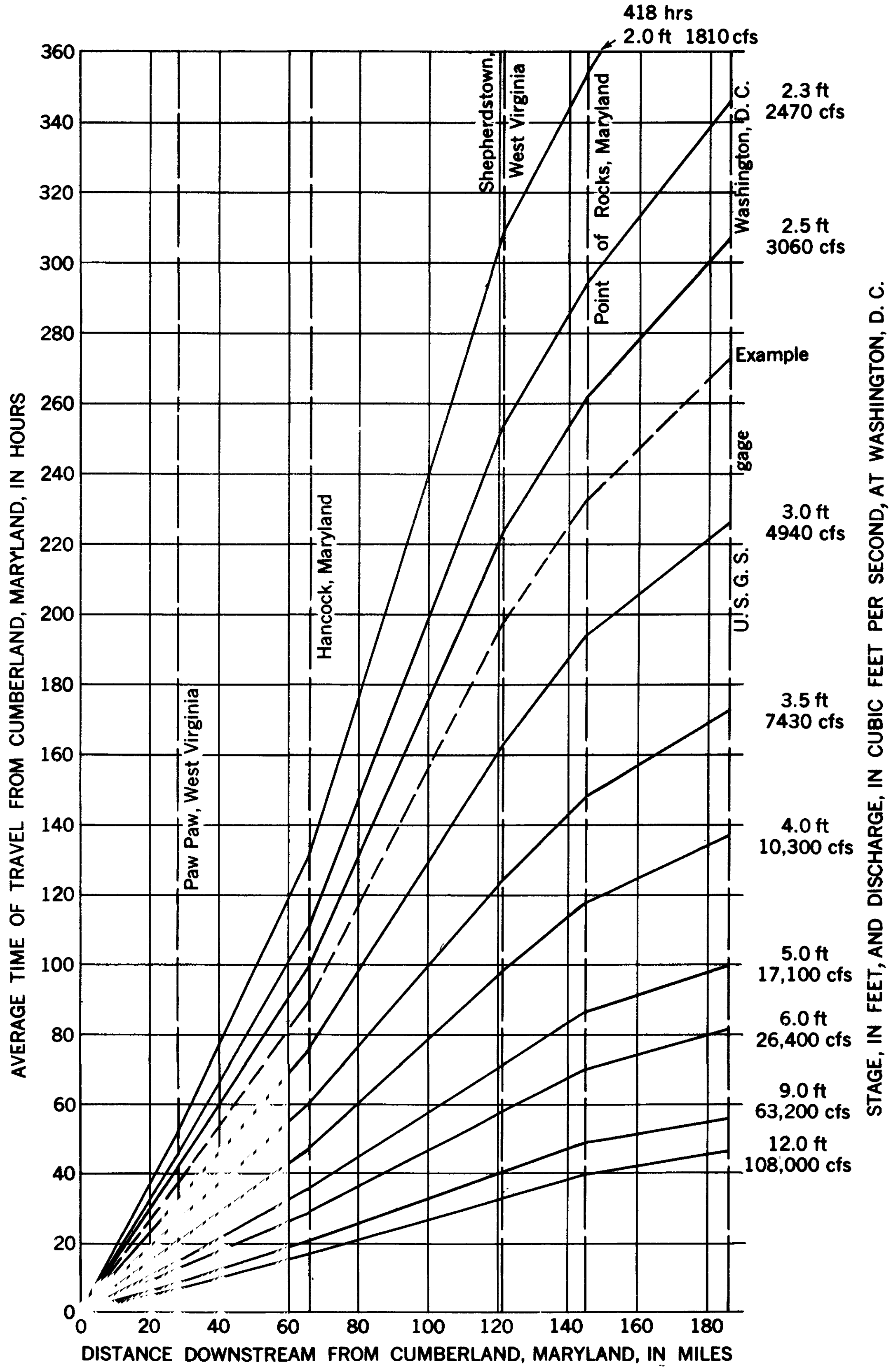

Figure 5.—Time-of-travel chart, Potomac River, Cumberland, Md., to Washington, D. C., for selected stages and discharges near Washington.

The resulting chart (fig. 5) shows the average time, in hours, for water to travel from Cumberland to points along the river at various river stages near Washington. For example, when the stage on the gage near Washington is 3.0 feet, the average time of travel of the water mass from Cumberland to Washington is 226 hours, and from Cumberland to Hancock, 76 hours.

TIME OF TRAVEL BETWEEN OTHER POINTS

The time of travel of water between other points on the Potomac River in the reach between Cumberland and Washington also can be obtained from the time-of-travel chart (fig. 5). For example, the average time of travel of water from Hancock to Point of Rocks when the stage is 3.0 feet near Washington is obtained from the time-of-travel chart as follows:

Time of travel—

		Hours
Cumberland to Point of Rocks	=	194
Cumberland to Hancock	=	76
Hancock to Point of Rocks	=	118

TIME OF TRAVEL TO WASHINGTON

The relation curves shown in figure 6, which are based on the same data as those in figure 5, are presented for convenience in estimating the time of travel from upstream points to Washington. They indicate the average travel time at any given stage at Washington.

The curves in figure 6 can also be used to interpolate between the curves shown in figure 5. For example, the curves in figure 6 show that with a stage of 4.5 feet at Washington, the average travel time from Cumberland to Washington is 116 hours and from Hancock to Washington is 74 hours. The difference of 42 hours, which is the travel time from Cumberland to Hancock, can be plotted on figure 5 between the 4-foot and the 5-foot lines at the Hancock mileage to define the curve for 4.5 feet.

SHORTEST TIME OF TRAVEL

Half the time the water mass will travel faster than it would under average conditions. Statistical analysis using the methods described by Steacy (1961, p. 7) indicate that, except in exceedingly rare cases, the shortest time of travel that could result from unusual conditions within the reach would be about 80 percent of the average time of travel. In this method, discharge corresponding to 3 times the standard error of estimate was added to the most probable discharge to obtain the maximum discharge that would be present in all but the extreme cases. The increased discharge gave faster mean velocities and shorter travel time for the given stage near Washington.

In this report, the maximum concentration of possible contamination is assumed to be at the center of the contaminated mass, as the effect of turbulence within the flowing mass and dilution of the mass with inflow from tributaries is not presently known. It is known, however, that dispersion caused by turbulence and by nonuniform flow tends to spread the contamination so that small amounts arrive in advance of the maximum contamination, and that the dilution effect of uncontaminated inflow tends to reduce the concentration of the contaminant. The behavior of these variables and the behavior of contaminated sediment, which moves more slowly than dissolved pollution, is being studied by the Geological Survey and others.

REFINEMENT BY MONITORING

The most probable time of travel to Washington for a contaminant introduced accidentally into the Potomac River can be read from the time-of-travel chart (fig. 5), and the shortest probable time of travel can be estimated by using 80 percent of that figure. Nevertheless, the progress of the contaminated mass downstream would doubtless be traced by field examination. The observed time of arrival of the contamination front at various points could be used to refine the prediction of the arrival time of contamination at critical points.

For example, if a contaminant is introduced accidentally at Cumberland when the stage near Washington is 3.0 feet, the time of travel from Cumberland to Washington indicated by figure 5 is 226 hours and from Cumberland to Hancock, 76 hours. The actual time of travel to Hancock, however, is found to be 90 hours by field observation. The initial estimate of

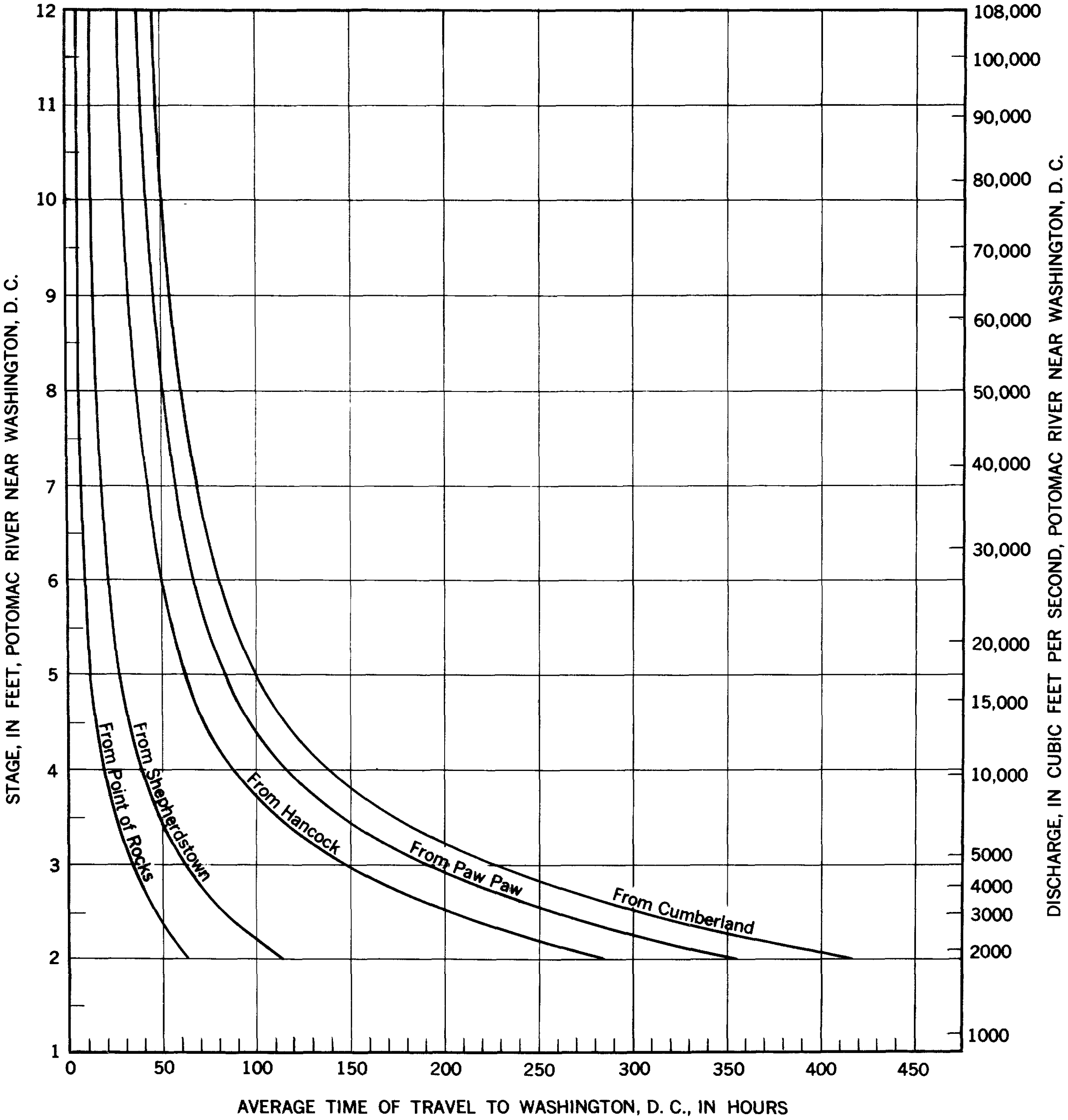

Figure 6.—Relation of stage and discharge near Washington, D. C., to time of travel from selected upstream points.

travel time to Washington can now be improved in the following manner. The observed time to Hancock is plotted on the time-of-travel chart (fig. 5). A revised time-of-travel line is then drawn from Cumberland to Hancock based on the observed time, which is fourteen twenty-fourths of the distance from the 3.0-foot line to the 2.5-foot line. By projecting the revised line downstream at the same ratio, a revised time-of-travel estimate from Cumberland to Washington is then found to be 273 hours.

APPLICATION BASED ON FLOW CHARACTERISTICS

Use of the time-of-travel chart is not restricted to times when the river stage near Washington is known, because flow characteristics of the river at the gaging-station site near Washington provide a means of using the time-of-travel charts (figs. 5 and 6) without knowledge of stage.

The flow-duration curve (fig. 7), which shows the percentage of time specified

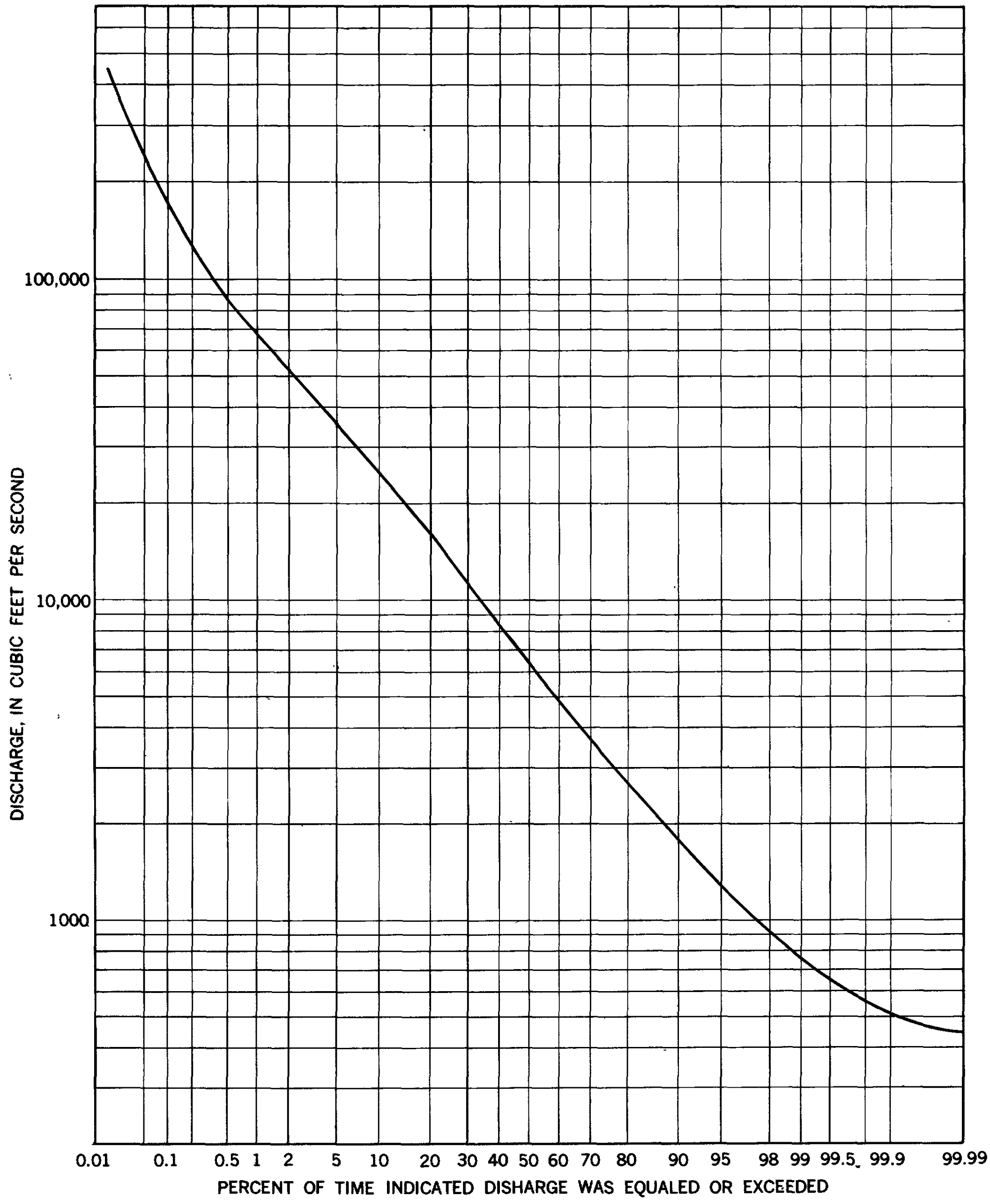

Figure 7.—Duration curve of daily flow, Potomac River near Washington, D. C., 1931—58.

discharges were equaled or exceeded in the period 1931–58, can be used to predict the percentage of time various discharges will exist in the future. This information is useful in long-range planning with regard to stream pollution and alternate water supplies. For example, the flow-duration curve (fig. 7) shows that the discharge near Washington is less than 6,500 cfs during 50 percent of the time, and figure 4 shows that this discharge is equivalent to a stage of 3.3 feet. Then, by entering the time-of-travel chart (fig. 6) with a stage of 3.3 feet, it is found that the time of travel of water from Cumberland to Washington is 190 hours

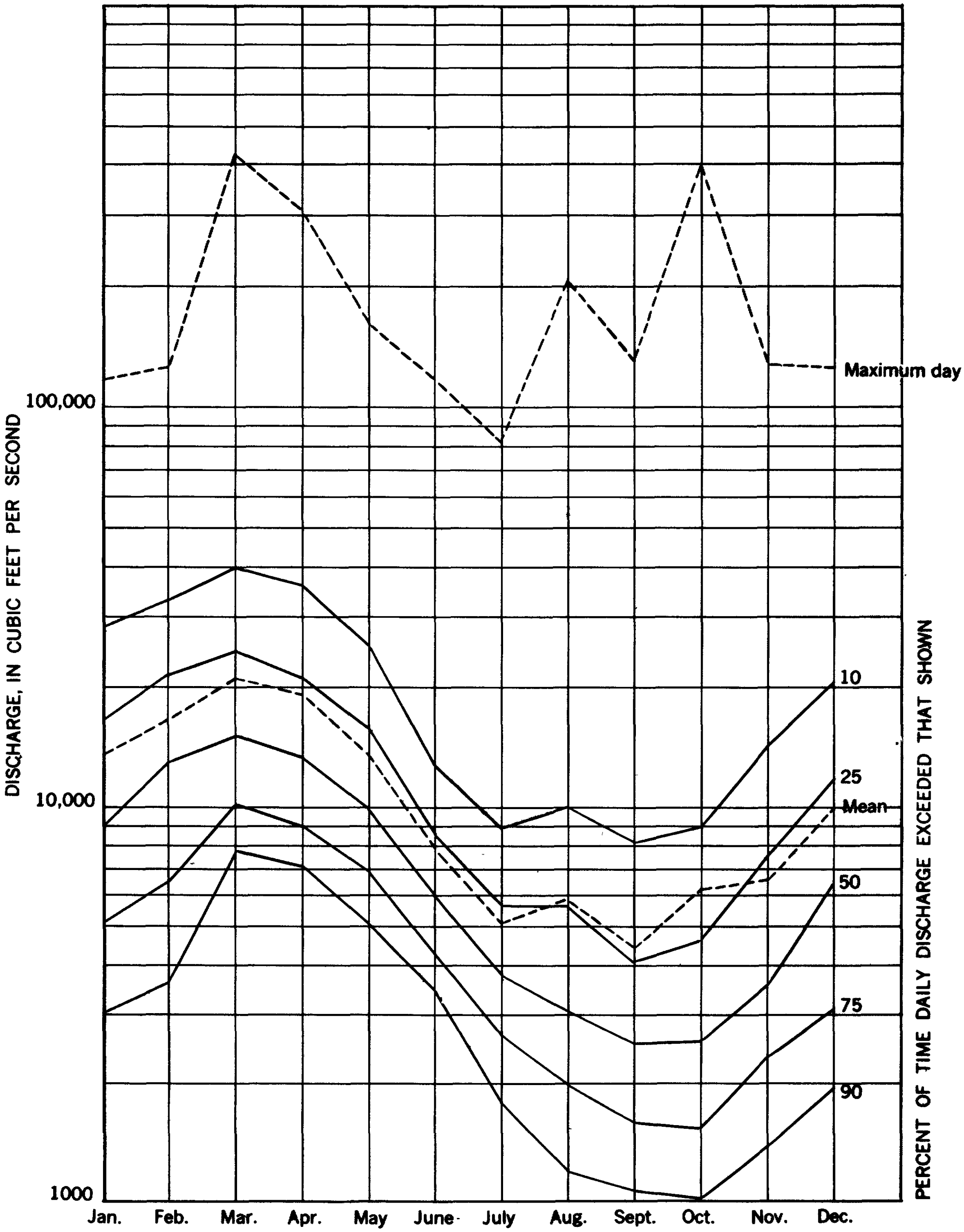

Figure 8.—Frequency of daily flow by months, Potomac River near Washington, D. C., 1931-58.

or more during 50 percent of the time. The discharge at the 50-percent point on the flow-duration curve is the median discharge and the corresponding stage of 3.3 feet is therefore the median stage at the gage near Washington.

The flow-frequency chart (fig. 8), also based on 28 years of record, was developed by cumulating, by months, the days when the discharge was within specified limits. When a reading from the river-stage gage near Washington is not available, the flow-frequency chart (fig. 8) can be used to make a more accurate estimate of discharge in any given month than could be made from the flow-duration curve (fig. 7) and consequently to make a more accurate estimate of the time of travel of Potomac River water. For example, the flow-frequency chart (fig. 8) shows that the median discharge in March is 15,000 cfs and in October, 2,500 cfs, and figure 4 shows the corresponding stages to be 4.7 feet and 2.3 feet. From the time-of-travel chart (fig. 6), the corresponding times of travel are 110 hours and 345 hours, representing the median times of travel from Cumberland to Washington in March and October, respectively.

SUMMARY

For the purpose of this report the reach of the Potomac River from Cumberland to Washington was divided into five subreaches and cross sections at the ends of the subreaches were determined. The cross sections were developed from soundings copied from discharge measurements that are made regularly at gaging stations near the ends of the subreaches. These gaging stations were used as control points for estimating discharge and velocity. The discharges at each gaging station corresponding to various stages and discharges at the gage near Washington were determined from discharge correlation curves. The velocity at each gaging station was obtained from a discharge-velocity relation based on discharge measurements, and the average velocity within each subreach was computed as the average of the velocities at the ends. Based on this information, the times of travel of specific quantities of water in the reach from Cumberland to Washington, corresponding to the various stages near Washington, were computed and used to prepare time-of-travel charts.

When information is available from field observations of change in water quality, a more accurate estimate of travel time can be made by revising the time-of-travel charts.

A duration curve and a frequency chart are provided for use in making estimates of travel time when information about the stage near Washington cannot be obtained or when estimates of future travel times are desired.

REFERENCES

Searcy, J. K., 1960, Graphical Correlation of gaging-station records, Manual of hydrology, pt. 1, General surface water techniques: U. S. Geol. Survey Water-Supply Paper 1541-C, p. 67–100.

Steacy, R. E., 1961, Time of travel of water in the Ohio River, Pittsburgh to Cincinnati: U.S. Geol. Survey Circ. 439.

U. S. Geological Survey, 1937, The floods of March 1936, pt. 3, Potomac, James and Upper Ohio Rivers: U. S. Geol. Survey Water-Supply Paper 800.

______ 1956, Surface water supply of the United States, 1953, pt. 1-B, North Atlantic slope basins, New York to York River: U.S. Geol. Survey Water-Supply Paper 1272.

______ 1959, Surface water supply of the United States, 1956, pt. 1-B, North Atlantic slope basins, New York to York River: U.S. Geol. Survey Water-Supply Paper 1432.

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