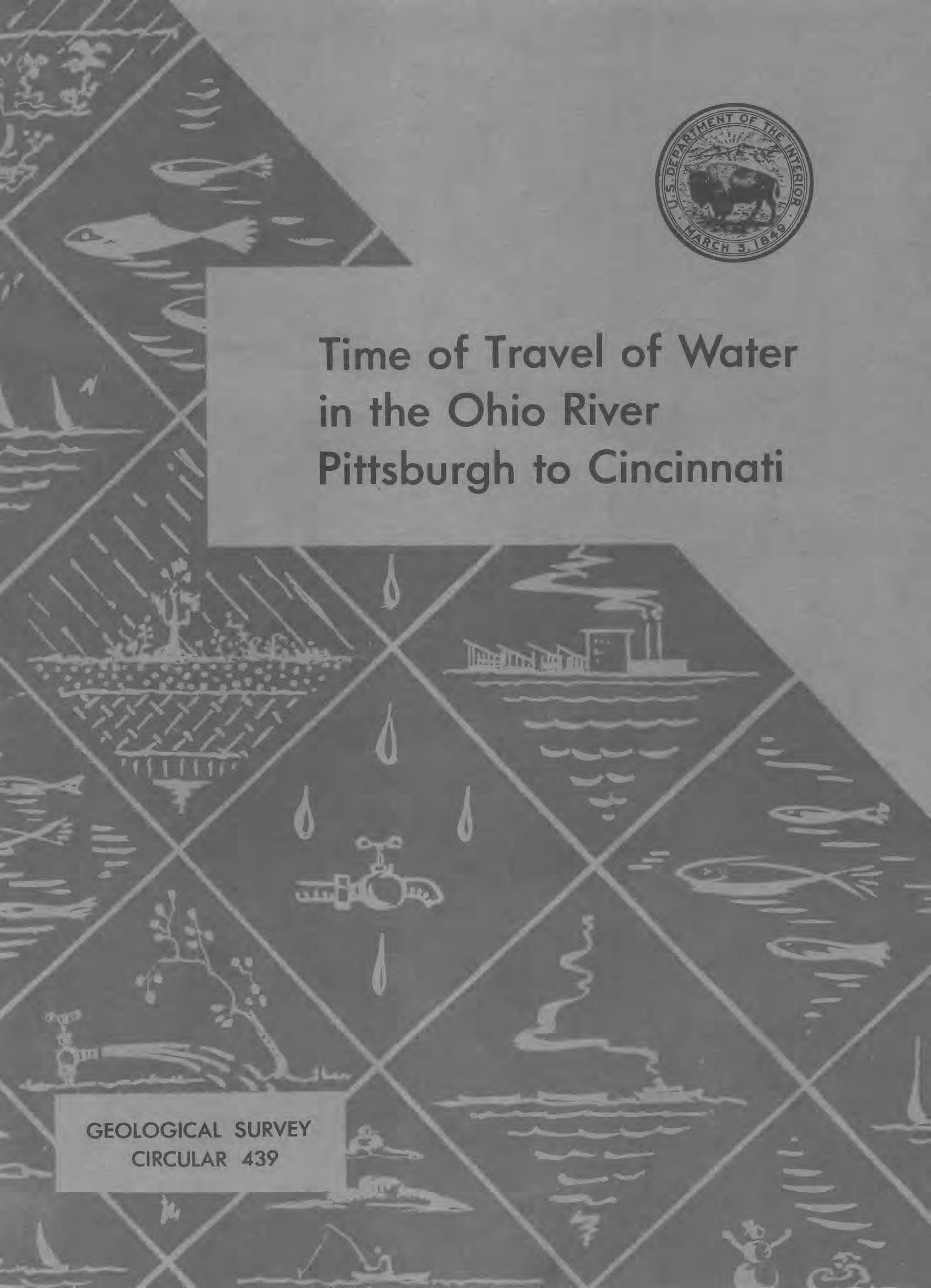

U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849

Time of Travel of Water in the Ohio River Pittsburgh to Cincinnati

GEOLOGICAL SURVEY
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Time of Travel of Water in the Ohio River Pittsburgh to Cincinnati

By R. E. Steacy

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ABSTRACT

This report presents a procedure for estimating the time of travel of water in the Ohio River from Pittsburgh, Pa., to Cincinnati, Ohio, under various river stage conditions. This information is primarily for use by civil defense officials and by others concerned with problems involving travel time of river water.

Tables and charts are presented to show, for a particular stage or discharge at Cincinnati, the average time it would take for water to travel through the entire reach from Pittsburgh, or through successive intermediate segments of the reach. For example, when the discharge at Cincinnati is 200,000 cfs, travel time from Pittsburgh to Cincinnati, a distance of 470 miles, averages about 7 days; and for discharges of more than 200,000 cfs, the travel time decreases very slowly with increasing discharge. When the discharge is 30,000 cfs, travel time is about 28 days; and for discharges of less than 30,000 cfs, the travel time increases very rapidly with decreasing discharge. Estimates of travel time at low discharge are subject to large errors.

Statistical analysis of the possible variations of upstream discharge for a given discharge at Cincinnati indicates that the shortest probable travel time from Pittsburgh to Cincinnati ranges from 56 percent of that under average conditions when the discharge at Cincinnati is 15,000 cfs to 93 percent of that under average conditions when the discharge at Cincinnati is 894,000 cfs.

A chart showing the time distribution of flow at Cincinnati is presented so that the probable travel time of Ohio River water can be determined for any time of the year. This chart provides information which, when applied to the time-of-travel chart, shows that the most probable travel time of water from Pittsburgh to Cincinnati ranges from 160 hours in February to 1,250 hours in September. Also presented is a flow-duration curve that can be used to predict future discharges and, subsequently, times of travel, for use in long-range planning. The procedure used to compute time of travel is described in sufficient detail to make it usable as a guide for similar studies on other rivers that have dams and pools in the reach being studied.

The computations for the time-of-travel charts were made as follows: (a) by dividing the reach between Pittsburgh and Cincinnati into four subreaches with a full-range streamgaging station at or near the ends of each; (b) by computing for each subreach mean velocities corresponding to various discharges at Cincinnati, using data obtained from river survey maps and data available from gaging station operations; (c) by assuming that any mass of contaminated water would travel at a rate equal to that of the mean velocity of the river water.

INTRODUCTION

The report presents a procedure by which the time of travel of water in the reach of the Ohio River between Pittsburgh, Pa., and Cincinnati, Ohio, can be estimated, provided that the river stage at Cincinnati is known. The gage at Cincinnati is used as an index of flow, and if the stage and the subsequent discharge at Cincinnati are not known, a special flow-frequency chart can be used to estimate the probable discharge at any time of year. For long-range planning, a flow-duration curve is presented for use in predicting the percent of time during which various flows will occur in the future.

The time-of-travel procedures in this report can be used to estimate the arrival time of possible accidental contamination from an upstream source, because dissolved contamination travels at the same speed as a unit mass of water. If a harmful contaminant were suddenly introduced in the reach of river under study, it might be necessary to stop diverting and using water downstream until the contamination drops to a harmless level. The time available before arrival of the contamination front at downstream critical points can be used to store emergency water supplies or to arrange for obtaining supplies from substitute sources. The time required for the contamination to drop to a harmless level cannot be estimated from this report because contaminants moving as suspended material travel more slowly than the water and the dissolved contamination. The study of the movement of suspended contaminants is outside the scope of this report. Other possible uses of information on time of travel of water are in quality-of-water studies of biochemical oxygen demand and in determining the optimum time for release of waste materials such as radioactive wastes.

The reach of river used in this study contains numerous navigation locks and dams that affect the natural velocity of flow. The data presented herein are based on the condition of the locks and dams in June 1958.

Three higher dams are presently under construction in the reach, and five additional high dams are tentatively proposed. Each of these will replace several old, low-head dams and will provide a much deeper channel. One of the effects of these new dams will be to increase the time of travel of water, particularly at low stages.

River survey maps prepared by the Louisville district of the Corps of Engineers were used in drawing the low-flow profile and in determining cross-sectional areas.

The methods used in developing the time-of-travel charts were based in part on suggestions by the Washington office staff of the Geological Survey, particularly J. K. Searcy and C. H. Hardison.

DESCRIPTION OF THE REACH

The Ohio River is formed by the confluence of the Monongahela and Allegheny Rivers at Pittsburgh, Pa., (fig. 1). The river flows southwestward to Cincinnati, augmented enroute by inflow from many tributaries. Several of these tributaries drain areas larger than 1,000 square miles; thus, the discharge varies at successive locations along the reach. The average discharge is about 32,000 cfs (cubic feet per second) at Pittsburgh and about 97,000 cfs at Cincinnati. The distribution of daily flow for the period 1948–57 at Cincinnati is shown by a flow-duration curve (fig. 2), and a breakdown of the same data by months is shown in figure 3.

The Ohio River has a series of locks and dams that provide a navigation channel 500 feet wide whose minimum depth is 9 feet. Table 1 shows the location of each lock and dam between Pittsburgh and Cincinnati, and the elevations of their pools. Most of the dams have movable crests that consist of hinged wickets supported by a sill near streambed level. At low flows, some or all of the wickets are raised to an erect position so that the dam thus formed creates a pool

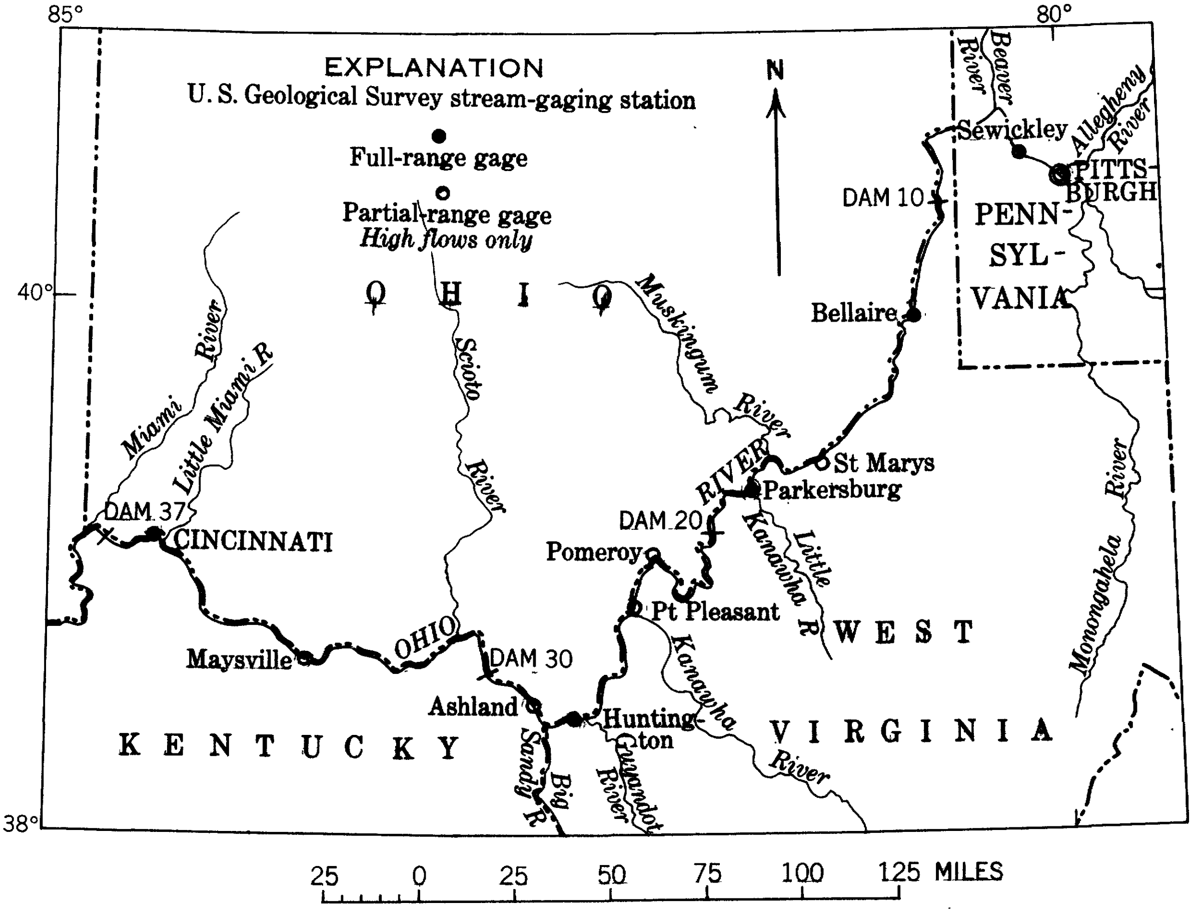

Figure 1.—Index map of Ohio River showing cities, principal tributary streams, and stream-gaging stations referred to in this report.

with sufficient depth for navigation. When at extremely low flows all the wickets of each dam are raised, the river becomes a series of nearly level pools, and the velocity of flow is very low.

Most of the cities and industries adjacent to the river divert water from the river for domestic, commerical, and industrial uses, but much of this water is returned to the river.

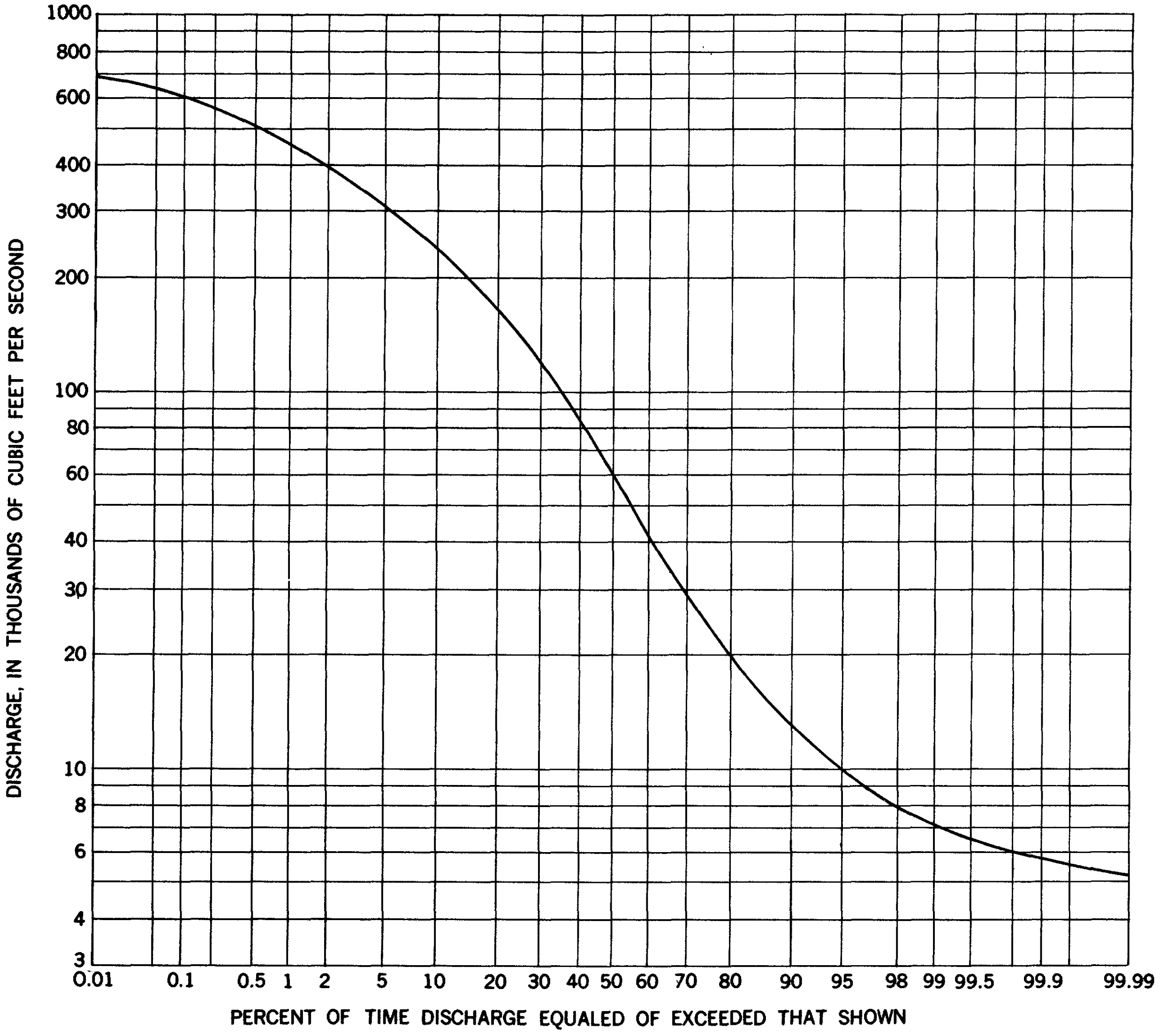

Figure 2.—Duration curve of daily flow, Ohio River at Cincinnati, Ohio, water years 1948—57.

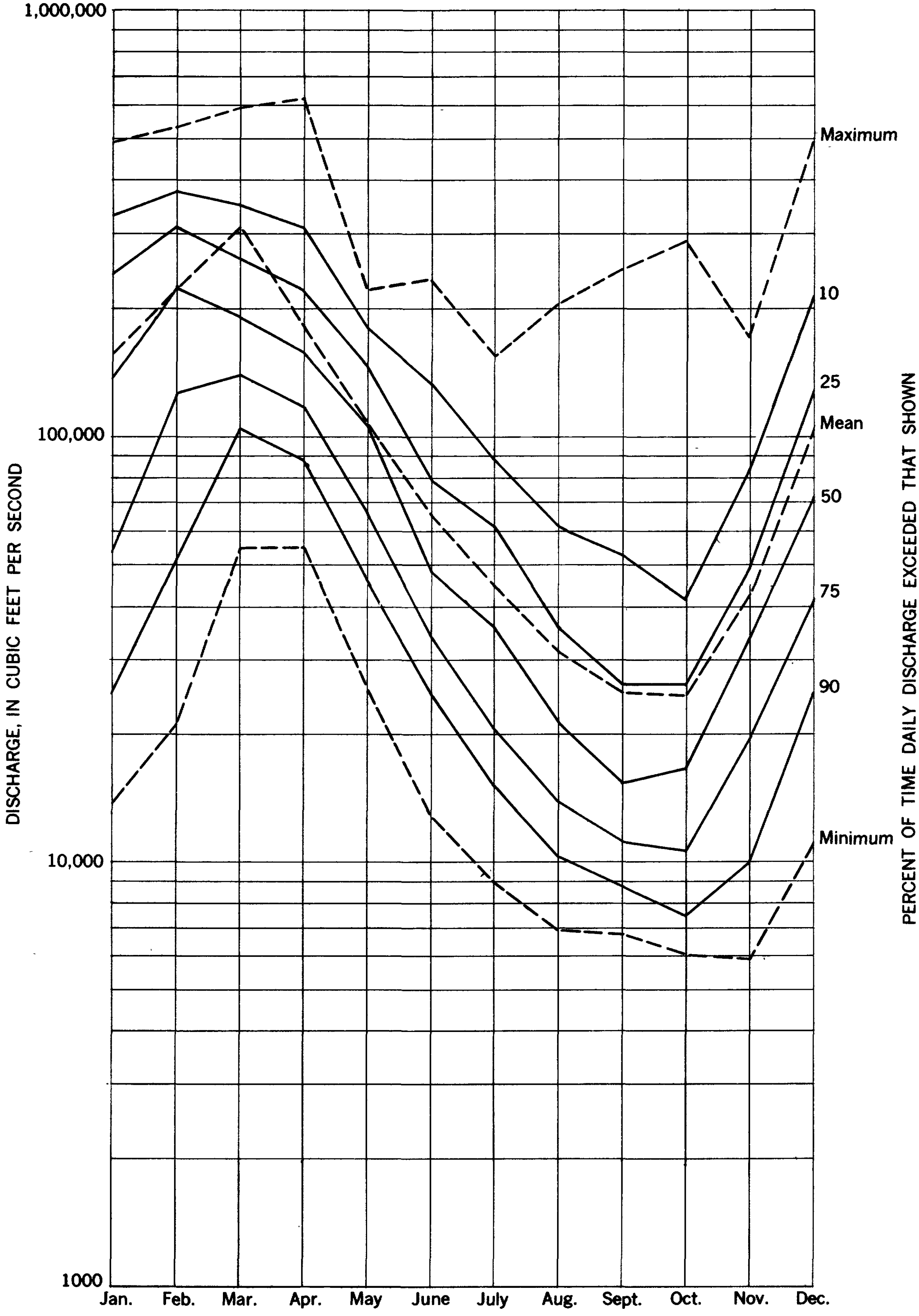

Figure 3.—Frequency of daily flow, by months, Ohio River at Cincinnati, Ohio, 1948-57.

Table 1.—*Locks and dams on the Ohio River between Pittsburgh, Pa., and Cincinnati, Ohio*

Lock designation	Distance downstream from Pittsburgh, Pa. (miles)	Upper pool elevation (feet above mean sea level)	Lock designation	Distance downstream from Pittsburgh, Pa. (miles)	Upper pool elevation (feet above mean sea level)
Emsworth	6.2	710.0	20	202.5	564.5
Dashields	13.3	692.0	21	214.6	557.0
Montgomery	31.7	682.0	22	220.9	551.4
7	36.5	662.6	23	231.4	543.6
8	46.4	655.7	Gallipolis	279.2	538.0
9	56.1	649.3	27	301.0	512.0
10	66.2	641.9	28	311.6	505.6
11	76.9	633.5	29	319.9	498.5
12	87.4	626.2	30	339.4	490.5
13	96.1	617.8	31	359.3	483.0
14	114.0	610.5	32	382.6	475.5
15	129.1	602.2	33	405.1	468.0
16	146.5	594.4	34	434.1	461.0
17	167.5	586.6	35	451.0	455.4
18	179.9	578.4	36	460.9	449.0
19	192.2	572.2	37	483.2	441.1

DISPERSAL EFFECT

The use of the time-of-travel data in this report to estimate the time of arrival of hypothetical contaminants depends on the assumption that the rate of travel of contaminants is the same as the mean velocity of water in the river channel. Actually, in some parts of the channel the flow rate exceeds the mean rate; in other parts the flow is less than the mean. The general results of this variation are shown schematically in figure 4. The diagram for point A represents the initial time distribution for a hypothetical contaminant in solution, and the diagrams for points B and C show the longitudinal variation

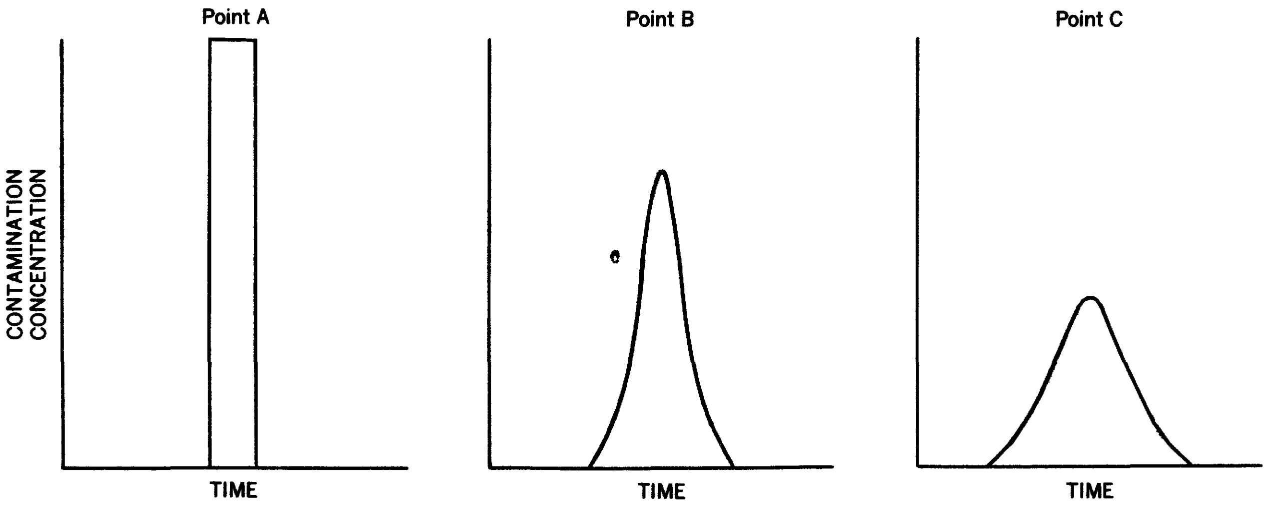

Figure 4.—Schematic diagram of dispersal effect.

in the concentration of the contaminant at given downstream cross sections of the stream channel. The distance between the two vertical lines at point A represents the time during which the contaminant is released. The height of the two lines indicates the concentration. The diagram for point B represents the redistribution of the contaminant after it has traveled some distance downstream from point A. The diagram for point C shows the more pronounced redistribution farther downstream. The widths between the bottom of the legs in the diagrams for points B and C represent the time interval between the first appearance and the disappearance of the contaminant at the given cross section, assuming that the contaminant was introduced at a uniform rate for a short period of time. According to these diagrams, a small concentration of the contaminant will arrive at a point downstream somewhat sooner than will the maximum concentration. Nevertheless, owing to the lack of detailed knowledge about the contributing variables, the dispersal effect is disregarded in this report, and the main mass of the contamination is assumed to travel at the mean velocity of the water.

BASIC DATA AND COMPUTATIONAL PROCEDURES

Various kinds of data on the Ohio River have been collected during many years, so that in the absence of direct observations of the time it takes water to travel through long reaches, the approximate time of travel can be estimated by computing the velocity of flow from data collected for other purposes.

Records of stage and discharge at 5 full-range and 5 partial-range stations operated by the U.S. Geological Survey on the Ohio River between Pittsburgh and Cincinnati were used in this study. The river miles below Pittsburgh and the drainage area for each of these stations are listed in table 2. Data collected at the gaging station at Sewickley, 11.8 miles below Pittsburgh were assumed to represent flow conditions at Pittsburgh.

The procedure used in this report for computing the time of travel of river water was to obtain (a) correlations between discharges at adjacent full-range gaging stations, (b) stage profiles showing the water surface elevation for selected flow conditions, (c) a weighted cross-sectional area at each of several stages in the reach between each pair of full-range gaging stations, and (d) the weighted mean velocity applicable to each of these reaches for each flow condition.

Table 2.—*River mileage and catchment drainage area at selected points on the Ohio River*

Point	Distance from Pittsburgh, Pa. (miles)	Drainage area (sq mi)
Pittsburgh, Pa.	0	19,050
Sewickley, Pa.[1]	11.8	19,500
Bellaire, Ohio [1]	96.4	25,170
St. Marys, W. Va.[2]	155.0	26,850
Parkersburg, W. Va.[1]	184.4	35,600
Pomeroy, Ohio[2]	265.4	40,500
Point Pleasant, W. Va.[2]	265.4	[3]52,760
Huntington, W. Va.[1]	311.6	55,900
Ashland, Ky.[2]	319.9	60,750
Maysville, Ky. (near)[2]	405.1	70,130
Cincinnati, Ohio[1]	470.5	76,580

[1] Full-range stream-gaging station.

[2] Partial-range stream-gaging station (high flows only).

[3] Below Kanawha River.

The correlations between the discharges were obtained by plotting the monthly mean discharge for simultaneous months for the period 1951–55 at adjacent full-range stream-gaging stations as described by Searcy (1960, p. 80). The correlations were very good. The top half of table 3 shows discharge figures computed from these correlations for selected Cincinnati discharges. These discharges are an estimate of the most probable simultaneous discharges to be expected at the upstream stations. For example, when the discharge at Cincinnati is 10,000 cfs, the most probable discharge at Huntington is 8,500 cfs and at Sewickley 4,150 cfs. The bottom half of table 3 shows the greatest discharge that would be expected 99 times out of 100. This discharge was computed from the standard error of estimate (Searcy, 1960, p. 74, 84), as explained in table 3, and was used to compute the discharge shown in the greatest discharge columns of table 4.

Table 3.—*Relation of discharge at Ohio River gaging stations, in cubic feet per second*

Average conditions

Cincinnati	SE[1]	Huntington	SE	Parkersburg	SE	Bellaire	SE	Sewickley[2]
10,000	0.0478	8,500	0.0447	5,850	0.0366	4,900	0.0305	4,150
15,000		12,700		8,700		7,350		6,200
20,000		16,800		11,500		9,700		8,200
30,000		25,200		17,400		14,600		12,300
50,000		42,000		28,800		24,300		20,400
80,000		67,500		46,500		39,500		33,000
150,000		126,000		87,500		74,000		62,000
250,000		209,000		144,000		121,000		101,000
500,000		420,000		292,000		246,000		205,000
894,000		750,000		525,000		440,000		368,000

Greatest probable discharge[3] (99 percent of time)

Cincinnati	$3\sqrt{\Sigma(1.5 \times SE)^2}$	Ratio	Huntington	$3\sqrt{\Sigma(1.5 \times SE)^2}$	Parkersburg	$3\sqrt{\Sigma(1.5 \times SE)^2}$	Bellaire	$3\sqrt{\Sigma(1.5 \times SE)^2}$	Ratio	Sewickley[2]
15,000	0.215	1.64	20,000	0.295 1.965	17,100	0.338 2.18	16,000	0.364	2.31	14,300
30,000			41,300		34,200		31,800			28,400
80,000			110,000		91,400		85,900			76,200
150,000			206,000		172,000		161,000			143,000
250,000			342,000		283,000		263,000			233,000
894,000			1,230,000		1,030,000		957,000			850,000

[1] SE is the standard error of estimate, in log units, of the correlation of monthly discharge at the adjacent stations.

[2] Discharge at Sewickley represents discharge at Pittsburgh.

[3] In the expression $3\sqrt{\Sigma(1.5 \times SE)^2}$, the constant 3 enlarges a standard error to give a range that encloses more than 99 percent of the probable values, and the constant 1.5 converts the standard error for monthly mean discharge to a standard error for daily mean discharge; this expression reduces to $4.5\sqrt{\Sigma(SE)^2}$ in which $\Sigma(SE)^2$ is the sum of the squares of the standard errors of the individual reaches. The antilog of this expression is the ratio which, when multiplied by the discharge for average conditions shown in the upper part of the table, gives the greatest probable discharge for the given discharge at Cincinnati.

Table 4.—*Computation of time of travel of Ohio River water from Pittsburgh to Cincinnati*

Discharge at Cincinnati (cfs)	Pittsburgh to Bellaire (96.4 mi)			Bellaire to Parkersburg (88.0 mi)			Parkersburg to Huntington (127.2 mi)			Huntington to Cincinnati (158.9 mi)			Total time Pittsburgh to Cincinnati (hours)
Average conditions													
	Aver-dis-charge (cfs)	Aver-veloc-ity (fps)	Time of travel (hours)	Aver-dis-charge (cfs)	Aver-veloc-ity (fps)	Time of travel (hours)	Aver-dis-charge (cfs)	Aver-veloc-ity (fps)	Time of travel (hours)	Aver-dis-charge (cfs)	Aver-veloc-ity (fps)	Time of travel (hours)	
10,000	4,525	0.23	615	5,375	0.39	331	7,175	0.33	565	9,250	0.50	466	1,977
15,000	6,775	.34	416	8,025	.59	219	10,700	.49	381	13,850	.74	315	1,331
20,000	8,950	.46	307	10,600	.78	166	14,150	.65	287	18,400	.98	238	998
30,000	13,450	.68	208	16,000	1.16	111	21,300	.97	192	27,600	1.44	162	673
50,000	22,350	1.15	123	26,550	1.90	68	35,400	1.60	117	46,000	2.05	114	422
80,000	36,250	1.85	76	43,000	2.85	45	57,000	2.40	78	73,750	2.70	86	285
150,000	68,000	2.95	48	80,750	4.18	31	106,750	3.75	50	138,000	3.65	64	193
250,000	111,000	3.85	37	132,500	5.10	25	176,500	4.80	39	229,500	4.40	53	154
500,000	225,500	4.90	29	269,000	6.20	21	356,000	6.20	30	460,000	5.50	42	122
894,000	404,000	5.50	26	482,500	7.00	18	637,500	7.20	26	822,000	6.40	36	106
Fastest probable conditions													
	Greatest dis-charge (cfs)	Greatest veloc-ity (fps)	Time of travel (hours)	Greatest dis-charge (cfs)	Greatest veloc-ity (fps)	Time of travel (hours)	Greatest dis-charge (cfs)	Greatest veloc-ity (fps)	Time of travel (hours)	Greatest dis-charge (cfs)	Greatest veloc-ity (fps)	Time of travel (hours)	
15,000	15,150	0.78	181	16,550	1.21	107	18,950	0.86	217	17,900	0.96	243	748
30,000	30,100	1.54	92	33,000	2.32	56	37,750	1.70	110	35,650	1.76	132	390
80,000	81,050	3.28	43	88,650	4.38	29	100,700	3.60	52	95,000	3.08	76	200
150,000	152,000	4.34	33	166,500	5.50	23	189,000	4.90	38	178,000	4.05	58	152
250,000	248,000	5.00	28	273,000	6.21	21	312,500	5.93	31	296,000	4.85	48	128
894,000	903,500	6.00	24	993,500	7.80	17	1,130,000	7.90	24	1,062,000	6.80	34	99

Note: One foot per second (fps) equals 0.682 miles per hour.

Stage profiles for the entire distance, Pittsburgh to Cincinnati, were obtained by plotting stages for selected flow conditions against stream locations expressed as river mileages downstream from Pittsburgh. For medium and high flows, the profiles were based on maximum daily stages recorded at all 10 gaging stations between Pittsburgh and Cincinnati during rises in March and October 1954. The rise of January 1954 was also used, but for the Huntington to Cincinnati reach only. For low flow, the profile was based on pool stage and thus shows the level water surface between dams and the abrupt drop of water surface at the dams.

Cross sections at 32 points midway between navigation dams were plotted from elevations on river survey maps of the Corps of Engineers. Elevations obtained from the appropriate profile were plotted on each of these 32 cross sections and the cross-sectional areas were measured. From these measured cross-sectional areas, weighted cross-sectional areas applicable to each of the 4 reaches between full-range gaging stations were obtained. The weighting factor was the distance between navigation dams, as each cross section was assumed to apply throughout the length of the pool of which it was the midpoint. In measuring cross-sectional areas, only the area of the main channel was used when overbank flow existed.

Mean velocities for the rise corresponding to each profile were obtained for each of the four reaches by averaging the peak discharges at the ends of the reach and by dividing the average discharge by the corresponding weighted cross-sectional area. For low-flow, or pool condition, the weighted cross-sectional area was divided by the monthly mean discharge for October 1953, a typical low-flow month.

The results of these computations were used to plot a curve of relation between discharge and mean velocity for each of the four reaches between full-range gaging stations. The mean velocities picked from these curves for selected discharges are shown in the top part of table 4. The selected discharges are the average of the discharges for the adjacent gaging stations shown in table 3 for arbitrary discharges at Cincinnati.

The final step was to compute the time of travel in the four reaches, Pittsburgh to Bellaire, Bellaire to Parkersburg, Parkersburg to Huntington and Huntington to Cincinnati, using the distance in miles and the velocities in feet per second. The results are shown in the top part of table 4.

COMPUTED TIME OF TRAVEL OF WATER

For convenience, the information in table 4 is plotted in figures 5 and 6. If the time of contamination at any point in the river and the discharge at Cincinnati are known, the time of arrival at any point in the reach can be estimated. Examples are given in the following section. The curves shown in figure 7, which are also based on data in table 4, can be used to interpolate between the curves shown in figures 5 and 6.

The average times of travel of water shown in figures 5, 6, and 7 contain errors from two sources. The first source is that the discharges at the four upstream gaging stations were estimated from correlations of monthly values. The estimated mean velocities, in turn, were based on results of these correlations. Thus, figures 5, 6, and 7 represent the average time of arrival for a given discharge. The bottom part of table 4 shows the time of travel under the condition that has only one chance in a hundred of being exceeded (labeled fastest probable conditions). This fastest probable condition is based on the possibility of error in estimating upstream discharge when only the discharge at Cincinnati is known. For a given discharge at Cincinnati, there is only one chance in a hundred that the upstream discharge will exceed the discharge obtained from the average relation by enough to give a time of travel shorter than that shown for the fastest probable conditions. These results are summarized in table 5. It is apparent from this table that a more precise prediction can be made at high flows than at low flows.

The second source of error is the variable velocity of the water in a given mass: not all of it travels at the mean velocity. For example, water delayed in stagnant and sluggish areas travels considerably slower than mean velocity; whereas, water at or near the surface in the main current travels faster than mean velocity.

So far as the movement of contaminants is concerned, time-of-travel estimates apply

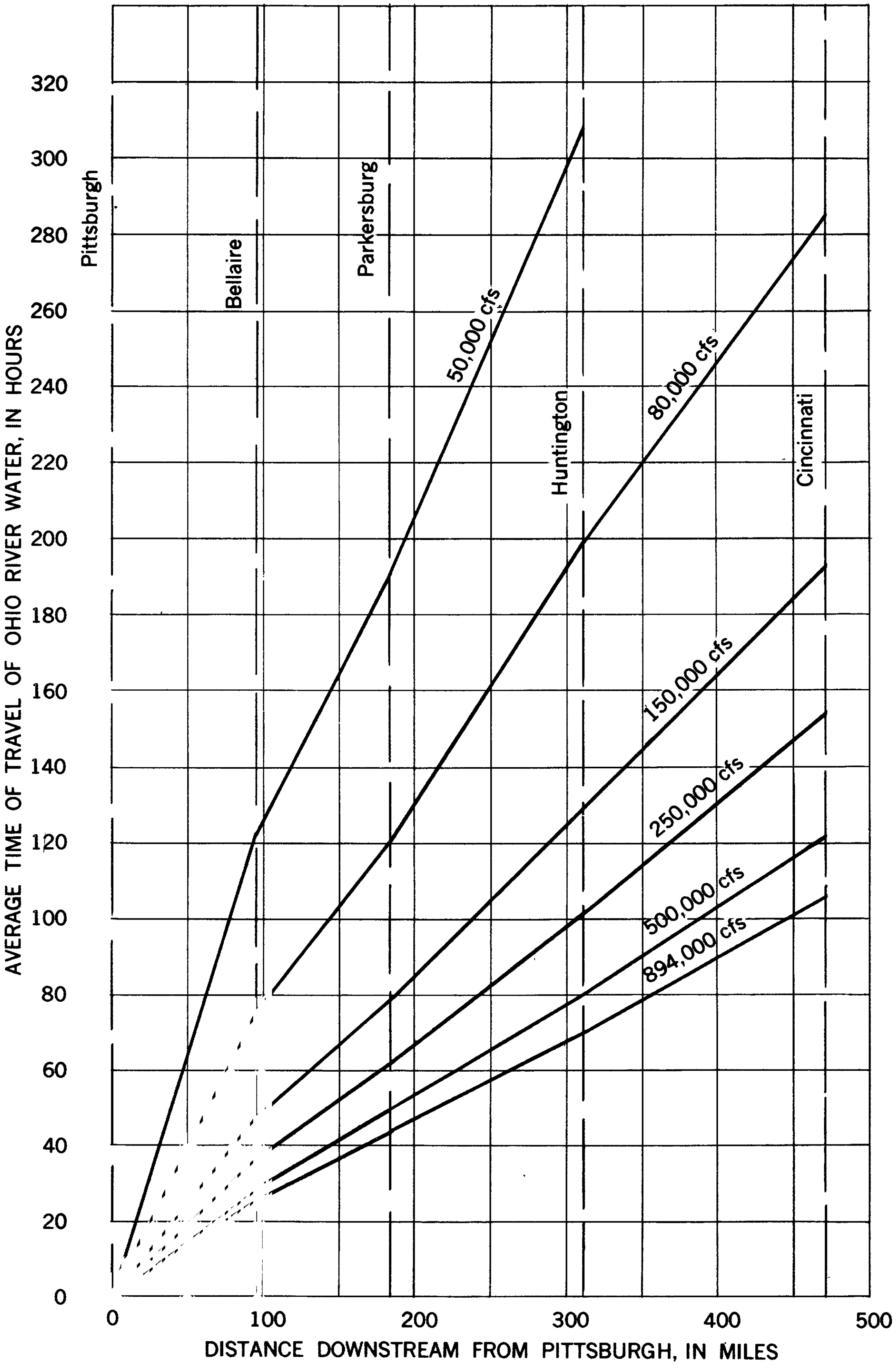

Figure 5.—Average time of travel of Ohio River water for discharges at Cincinnati, Ohio, of 50,000 or more cubic feet per second.

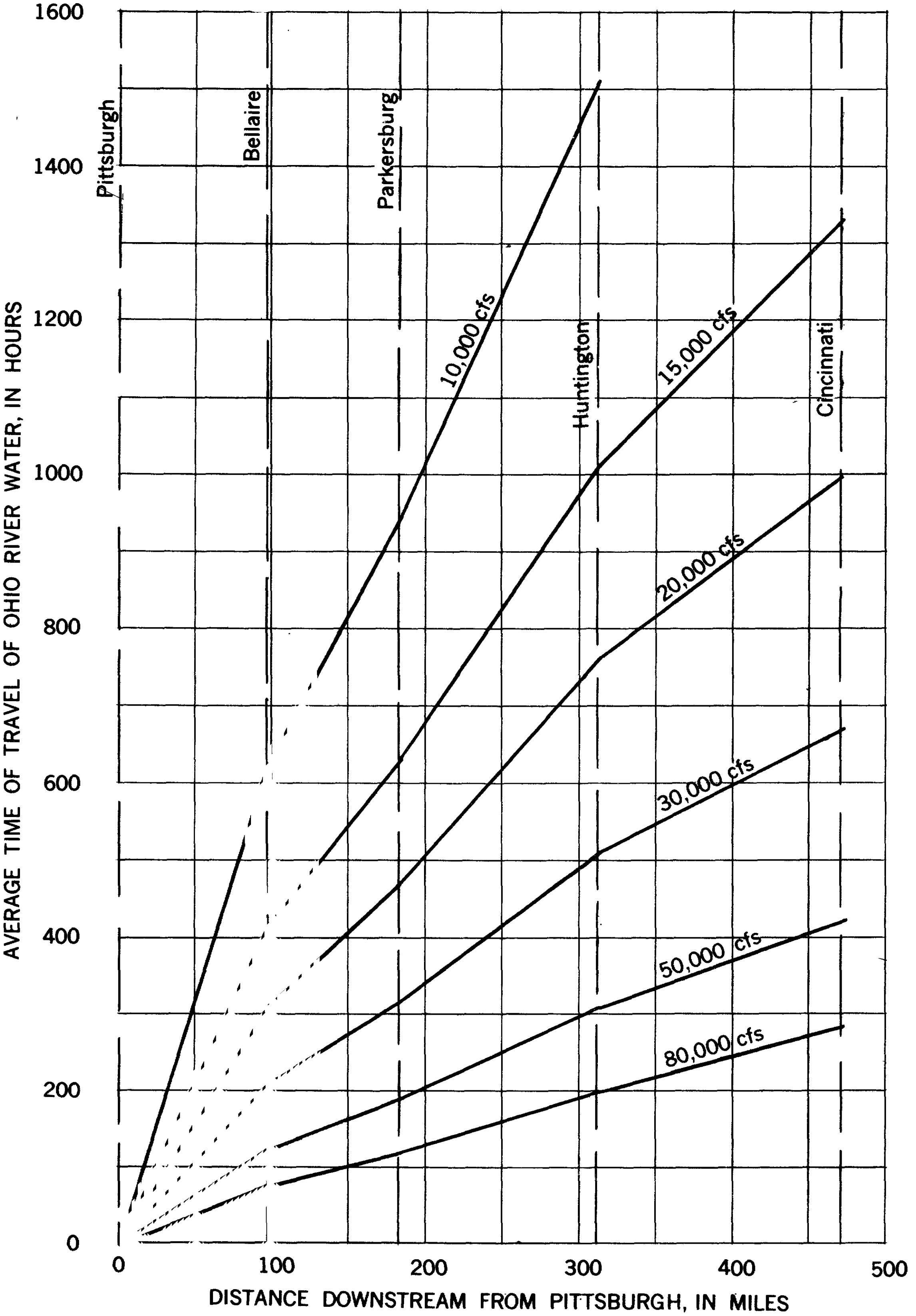

Figure 6.—Average time of travel of Ohio River water for discharges at Cincinnati, Ohio, between 10,000 and 80,000 cubic feet per second.

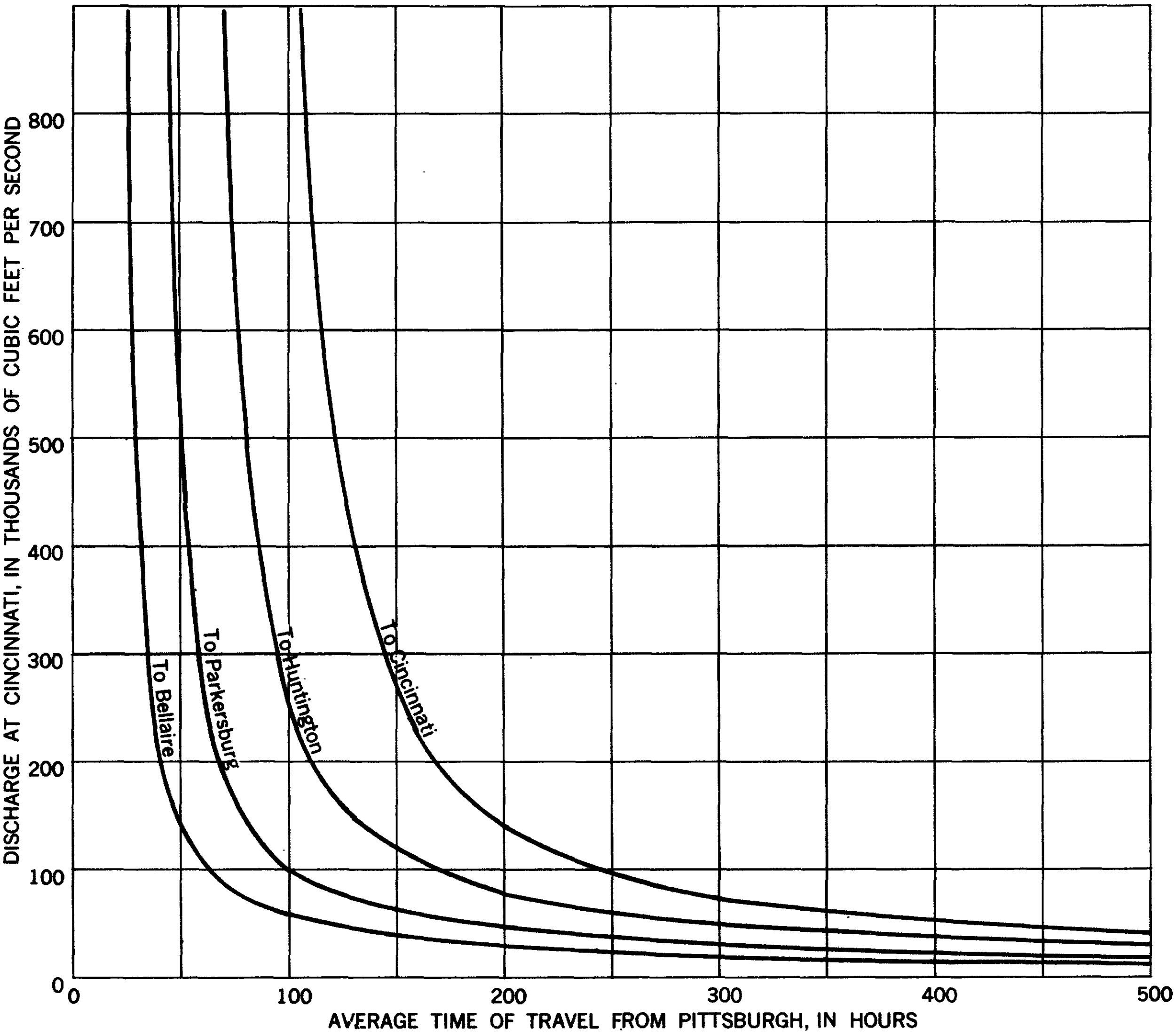

Figure 7.—Relation of discharge at Cincinnati, Ohio, to average time of travel of water from Pittsburgh, Pa., to selected downstream points.

Table 5.—*Time of travel of Ohio River water from Pittsburgh to Cincinnati*

Discharge and approximate stage at Cincinnati Suspension Bridge			Time of travel of water			
			Average conditions		Fastest probable conditions[1]	
Discharge (cfs)	Stage (feet)	Hours	Days	Hours	Days	Percent of average
894,000	78.8	106	4.4	99	4.1	93
250,000	36.9	154	6.4	128	5.3	83
150,000	25.9	193	8.0	152	6.3	79
80,000	16.6	285	12	200	8.3	70
30,000	12.5	673	28	390	16	58
15,000	12.0	1,331	55	748	31	56

[1] There is a 1-percent chance that travel time will be faster than that shown for fastest probable conditions.

only to contaminants in solution or suspension in the flowing water. Contaminants absorbed on sediment might be delayed in transit indefinitely, depending on whether the sediment is carried in suspension or as bedload, or whether it is deposited in the channel during a falling stage. Thus, only by making direct tests of the water could a completely reliable estimate be made of the time of arrival and the concentration of contamination or of the time required for the water to recover to a satisfactory quality.

EXAMPLES OF APPLICATION

TIME OF TRAVEL OF OHIO RIVER WATER FROM PITTSBURGH TO CINCINNATI

Table 5 and figures 5, 6, and 7 show that the average time of travel of water from Pittsburgh to Cincinnati may range from less than 5 days to more than 50, depending on the discharge If the discharge at Cincinnati is known, an approximate discharge can be obtained by entering figure 8 with readings from the gage at the downstream side of the Covington-Cincinnati suspension bridge. For example, at a gage-height reading of 30 feet, figure 8 shows the discharge to be 180,000 cfs. Figure 5 shows the time of travel corresponding to Cincinnati discharges of 150,000 cfs and 250,000 cfs. The discharge of 180,000 cfs is about one-third of the difference between these two discharges, for which the times shown on figure 5 are 193 hours and 154 hours respectively. The time required at 180,000 cfs is therefore 193 hours less one-third of the difference between 193 hours and 154 hours, or 180 hours. Figure 7 shows about the same travel time when the Cincinnati curve is entered with a discharge of 180,000 cfs.

The fastest probable travel time can be computed by using the information shown in table 5. For 150,000 cfs the fastest probable travel time is 79 percent of the average time.

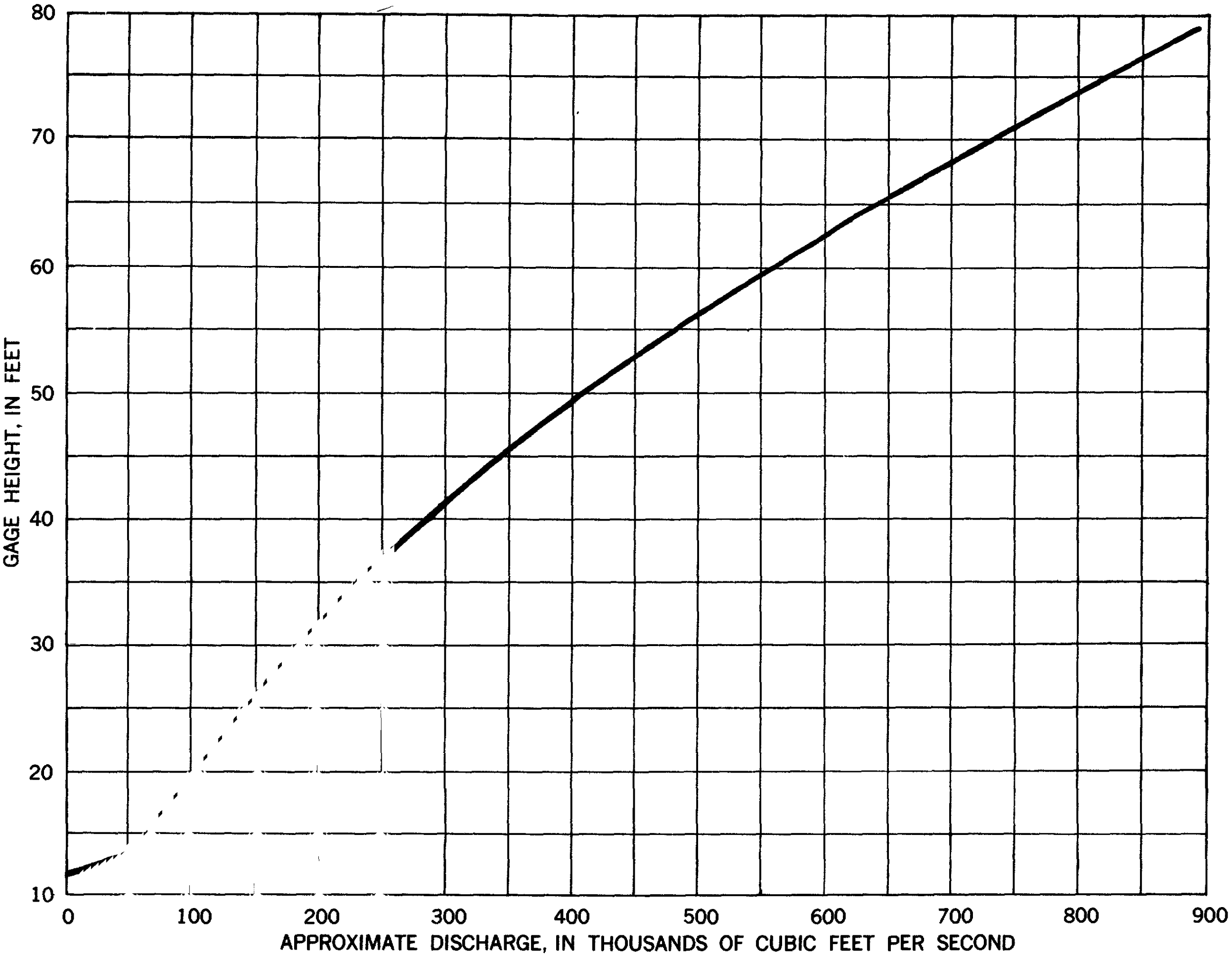

Figure 8.—Stage-discharge relation, Ohio River at Cincinnati, Ohio. The curve gives average discharge in cubic feet per second corresponding to gage readings from the suspension bridge at Cincinnati; a rating using water-surface slope must be used to obtain more accurate evaluations of discharge.

By interpolation, a value of 81 percent is obtained for 180,000 cfs, and the resulting fastest probable travel time is computed as 146 hours (0.81 x 180 equals 146 hours).

The information on the distribution of daily flow at Cincinnati shown in figures 2 and 3 can be combined with information in figures 5, 6, and 7 to give the probability of various times of travel. For example, from figure 2 the median discharge (at the 50-percent line) at Cincinnati is 60,000 cfs, and from figure 7 the corresponding travel time from Pittsburgh to Cincinnati is about 360 hours. Thus, for 50 percent of the time, the travel time from Pittsburgh to Cincinnati is at least 360 hours.

Similarly, from figure 3 the discharge that is exceeded 10 percent of the time during February is 380,000 cfs. For this discharge, figure 6 or figure 7 indicates that about 135 hours, or roughly 5½ days, will be the travel time. This means that there is a 90-percent probability that in February there will be at least a 5½ days delay between the introduction of a contaminant at Pittsburgh and its arrival at Cincinnati. By the same process, it can be seen that there is a 90-percent probability that there will be more than 20 days delay during October.

TIME OF TRAVEL OF WATER FROM ANY POINT ON THE OHIO RIVER

The average time of travel of water between other points on the Ohio River and Cincinnati can be readily computed. Assume an influx of contamination at Huntington, W. Va., and a gage reading of 30.0 feet at Cincinnati. According to figure 8, the discharge at Cincinnati would be 180,000 cfs. From figure 5, by interpolation, travel times between Pittsburgh and Cincinnati and between Pittsburgh and Huntington are 180 hours and 118 hours, respectively. The difference of 62 hours is the travel time from Huntington to Cincinnati. By similar computations, the travel time of water between other points can be determined. A more direct way to obtain the travel time of water between the cities at the ends of the four reaches is to use figure 7; for a discharge of 180,000 cfs, the travel times from Pittsburgh to Cincinnati and to Huntington are shown to be about 173 hours and 117 hours, respectively—a difference of 56 hours.

TIME OF TRAVEL OF WATER DURING LOW-FLOW PERIODS

Under low-flow conditions, when the Ohio River forms a series of pools through which flow is very slow, time of travel of water estimated by the procedure presented in this report may be substantially in error. Factors that affect travel time during pooled conditions are diffusion, wind action, lock operation, and changes in wicket settings. When the discharge at Cincinnati is less than 30,000 cfs, the time of travel from Pittsburgh is more than 600 hours under average conditions. Estimates of travel time of such great length are inaccurate, and the probability is great that there will be marked changes in discharge during the intervening period. With these uncertainties, frequent monitoring is advisable, to ensure that the downstream progress of a possible contaminant is known, and to aid in revising estimates of the time of arrival of the contaminant at critical points.

Revision of estimated travel time of water is illustrated in the following example. Assume that the accidental introduction of a contaminant at Pittsburgh takes place when the discharge at Cincinnati is 30,000 cfs. From table 4, the corresponding travel time from Pittsburgh to Cincinnati is 673 hours, and from Pittsburgh to Huntington is 511 hours. The actual time of travel to Huntington, however, is found by field observation to be 550 hours. The initial estimate of travel time from Pittsburgh to Cincinnati can now be improved as follows: The observed time to Huntington is plotted on figure 6 and its position is computed to be 16-percent of the distance from the 30,000 cfs line to the 20,000 cfs line. Then by projecting a line downstream at this percentage, a revised time of travel estimate of 720 hours from Pittsburgh to Cincinnati is obtained.

REFERENCE CITED

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