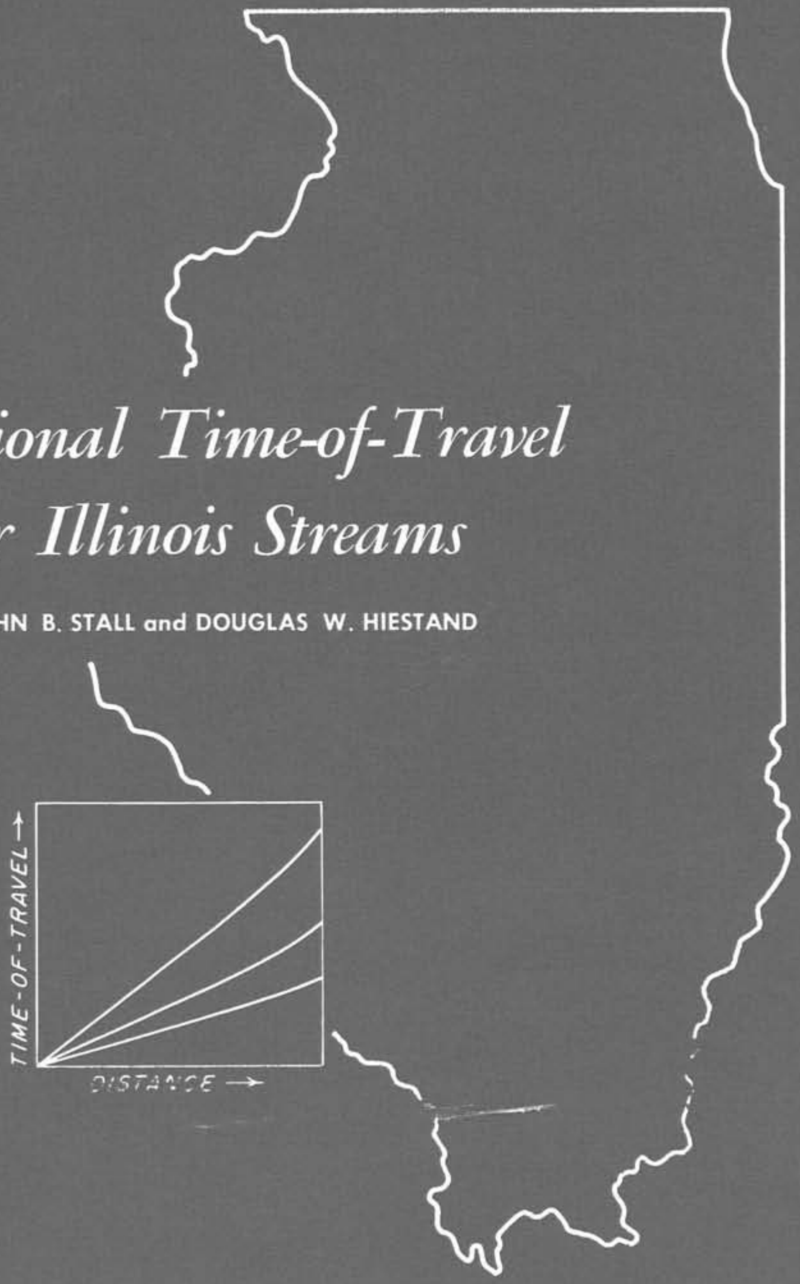
REPORT OF INVESTIGATION 63

STATE OF ILLINOIS

DEPARTMENT OF REGISTRATION AND EDUCATION

Provisional Time-of-Travel for Illinois Streams

by JOHN B. STALL and DOUGLAS W. HIESTAND



ILLINOIS STATE WATER SURVEY

URBANA

1969

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Indexing Terms: Dye tracers, hydraulic geometry, Illinois, streamflow, streams, time-of-travel, water pollution.

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Provisional Time-of-Travel for Illinois Streams

by John B. Stall and Douglas W. Hiestand

ABSTRACT

This report provides provisional estimates of **the** time-of-travel of a contaminant material in flowing streams. Graphical data are presented for 41 reaches of principal streams in Illinois Computed travel times for each stream reach are shown for high, medium, and low flow conditions, representing flow occurring at frequencies of 10, 50, and 90 percent of the days per year.

The time-of-travel computations were based on equations for stream velocity developed in a previous study of the hydraulic geometry of streams for 18 river basins in Illinois. Computed times-of-travel are shown to be reasonably accurate by comparison with actual times-of-travel measured by dye tracers. The computed travel times are most reliable at high flows, becoming less so at diminishing flow rates. In general, the travel time as computed can be interpreted as the minimum, which will be exceeded in many actual cases particularly at the lower flow conditions.

Advance information on the time-of-travel of materials in streams becomes highly important when the contaminant endangers downstream water users. The generalized results provided by this study will serve as useful estimates of travel times in streams until more direct and accurate measurements can be made.

INTRODUCTION

The flowing rivers and streams of Illinois represent a major water resource of the state. Because of the natural erosion of soil, all of these streams carry a load of sediment which varies from day to day. In addition to this load of natural material the streams of Illinois, as well as those of the rest of the United States, are continually being utilized to absorb and transport effluent material from *the* activities of man. Any foreign material introduced to a stream is carried downstream by the flowing water. If this material should represent a danger to some downstream water user, the speed at which it will travel to a location downstream becomes immediately a matter of concern.

The flow velocities of streams are highly variable, being much higher in flood times than during medium flows and very slow during low flows. For this reason it is not easy to make a general estimate as to the travel time of a material being carried downstream in a river. The present study is meant to provide generalized information regarding such travel times in streams and rivers.

Example Cases

Just how fast does a contaminant travel downstream? An occurrence in Illinois provides one example. On the afternoon of October 30, 1963, at Mattoon, a 2500-gallon tank full of industrial waste containing cyanide was discharged into Kickapoo Creek, a tributary of the Embarras River. On the afternoon of the following day, October 31, a farmer 2 miles southeast of Mattoon on Kickapoo Creek found five of his cows dead, apparently from drinking the waters of this creek. A sample of water taken from the stream at that time was later analyzed and found to contain 250 parts per million (ppm) of cyanide.

The State of Illinois Sanitary Water Board, immediately notified of the stream condition, assigned technical personnel on an around-the-clock basis to the job of collecting and analyzing samples from this stream. This effort, which lasted almost a month, was oriented toward determining the exact strength of the contaminant at various locations along the stream and to providing information on the location of the leading edge of the contaminant. One of the principal concerns was the public water supply intake for the city of Newton located on the Embarras River about 72 stream miles downstream. The condition of the river at Newton was continuously monitored, of course, but the city also took emergency measures to drill wells to provide water from groundwater.

Figure 1 shows a series of concentration curves based on data from the Sanitary Water Board which indicate the decrease in concentration of this contaminant and its movement downstream from Mattoon to Newton. The flow in

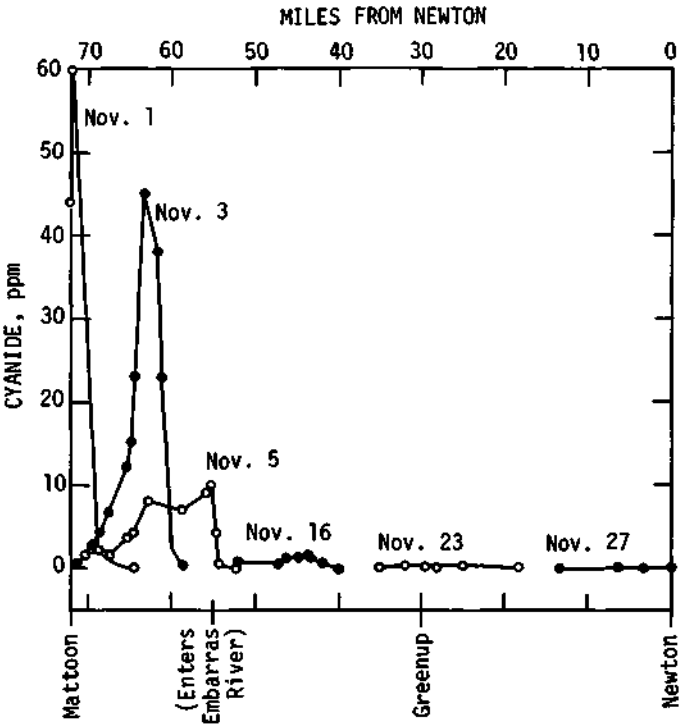

Figure 1. Reduction in concentrations of an actual cyanide contaminant spilled into Kickapoo Creek and Embarras River at Mattoon as it moved downstream 72 miles to Newton

Kickapoo Creek and the Embarras River during this period was very low. The first concentration curve, at the left of figure 1, is for November 1 and shows a high concentration of 60 ppm of cyanide near Mattoon. The curve for two days later, November 3, shows that the maximum concentration was 45 ppm and that the material had moved about 10 miles downstream during these two days. Another two days later on November 5, the concentration curve shows a maximum concentration of about 10 ppm, and even lower concentrations appear on November 16 and 23 as the material moved on downstream.

The U. S. Public Health Service drinking water standards provide for a tolerable amount of 0.2 ppm of cyanide in raw water utilized for drinking water. Figure 1 shows that on November 27 discernible amounts of the contaminant were found at the Newton water intake, and for a reach of 10 to 15 miles upstream, but fortunately, the concentrations at this time were all of trace amounts, 0.01 to 0.03 ppm. Since these concentrations were only a tenth of that tolerated by the drinking water standards, it was determined that the water was usable for public supply. Approximately 27 days had elapsed since the original alert to this danger. During this time, the wells at Newton had been completed, and on November 27 the city began using groundwater on a temporary basis. Later, the city established regular use of the wells, and no longer uses water from the Embarras River as a primary source for public water supply.

As depicted in figure 1, the contaminant in this case moved rather slowly, taking 27 days to travel the 72 miles downstream. If the flow in the stream had been higher, the contaminant would have been diluted to a greater degree, but the time-of-travel downstream would undoubtedly have been much faster. This could have made the emergency more acute. This case illustrates the value of having advance information as to the general magnitude of the time-of-travel of materials through any stream in Illinois.

In another case described by Moore and Kin (1969) a similar emergency arose from a train wreck which caused an estimated 1200 gallons of contaminant containing 2800 pounds of cyanide to be drained into Buck Creek and the White River in Indiana. Similar emergency measures were taken to follow the slug of contaminant downstream to the city water intake at Seymour, Indiana. Time-of-travel estimates were made by the U. S. Geological Survey. Also in this case efforts were made to treat the cyanide by means of a hypochlorite solution to reduce its danger. The authors concluded that this waste can be destroyed by treatment in the stream when necessary to protect public health and the downstream water users.

Provisional Nature of Results

The use of the word *provisional* for the results of this study is meant to convey that these results are generalized and provide an approximate answer, for use until a more complete program can be carried out. During the past few years the State Water Survey has initiated a continuing program to measure directly the time-of-travel of Illinois streams by using dye tracers. This program is being conducted by the Water Quality Section of the Survey, and has recently been intensified in order to provide, as soon as possible, improved results for time-of-travel in Illinois streams. Such information will be published as it becomes available.

Acknowledgments

The results described in this report have been compiled by the authors as a part of the regular program of evaluation of Illinois water resources conducted by the Illinois State Water Survey, William C. Ackermann, Chief. This work was carried out in the Hydrology Section under the direction of H. F. Smith, Head. The actual field measurements on time-of-travel obtained from dye studies on Illinois streams were made by Thomas A. Butts, under the direction of Ralph L. Evans, Head of the Survey's Water Quality Section at Peoria. Computation work was carried out by Douglas Hiestand, Assistant Hydrologist, under the supervision of John B. Stall, Engineer. Helpful advice has been provided by Tsung Yang, Associate Hydrologist. Other Water Survey personnel participating in this project were John W. Brother, Jr., Chief Draftsman, who prepared the illustrations, and Mrs. J. Loreena Ivens, Technical Editor, who edited the final report.

The primary technical methodology on which this re-

port is based was developed under a research project *Hydraulic Geometry of Illinois Streams*, carried out during 1966-1968 at the Water Survey and partially financed under the matching funds program of the Office of Water Resources Research, U. S. Department of Interior, under grant 14-01-0001-1021 to the Water Resources Center of the University of Illinois. Considerable help was given by Dr. Ben B. Ewing, Director of the Water Resources Center.

Data for time-of-travel from dye tracer measurements for the White River in Indiana were provided by Malcolm D. Hale, District Chief, U. S. Geological Survey, Indianapolis.

METHODOLOGY

Hydraulic Geometry

The results of a study of the hydraulic geometry of Illinois streams (Stall and Fok, 1968) have been used to provide a basis for provisional estimates of the time-of-travel in Illinois streams. The term hydraulic geometry describes a consistent pattern in which the width, depth, and velocity of flow in a stream change along the course of the stream at a constant frequency of discharge. These characteristics constitute an interdependent system which can be described by a series of graphs or a set of equations.

In the 1968 project, data from 166 stream gaging stations in Illinois were used to develop the parameters that define the hydraulic geometry for 18 principal river basins in Illinois. Stream characteristics were related to the frequency of discharge and to the drainage area as independent variables.

As an example of the results of that study, the five hydraulic geometry equations which were developed for the Kaskaskia River Basin in south-central Illinois are given here. These are:

$$\ln Q = 0.95 - 5.88\,F + 1.02 \ln A_d \tag{1}$$

$$\ln A = 1.21 - 4.60\,F + 0.88 \ln A_d \tag{2}$$

$$\ln V = -0.26 - 1.28\,F + 0.14 \ln A_d \tag{3}$$

$$\ln W = 1.47 - 1.39\,F + 0.50 \ln A_d \tag{4}$$

$$\ln D = -0.26 - 3.21\,F + 0.38 \ln A_d \tag{5}$$

in which Q is discharge in cubic feet per second (cfs) : A is cross-sectional area in square feet (sq ft); V is mean velocity in feet per second (fps); and W and D are stream width and depth in feet. The designation ln signifies a logarithm to the base *e*. F is the frequency of occurrence of a daily discharge expressed as a decimal, and the term A_d is drainage area in square miles (sq mi).

In equations 1 to 5 the frequency of occurrence F is limited to the range from 10 to 90 percent of the days per year. The value of this frequency is read from a duration curve of daily flows, or discharges, at a stream gaging station. The drainage area parameter A_a is expressed in square miles as measured from a map, and represents the upstream drainage area of the stream at any point under consideration.

Equations 1 to 5 were developed on the basis of theoretical considerations. The overall study in Illinois confirmed that these stream parameters are sufficiently related to constitute a determinant system. The evaluation of this pattern and its representation by these equations proved valuable from a theoretical standpoint in providing better understanding of the basic nature of stream development.

Dye Measurements in Indiana

As a part of the project on hydraulic geometry it was felt desirable to field-check one of the five general equations because of the theoretical nature of the research. It was determined that the equation relating average stream velocity to the frequency of discharge and the drainage area could be subjected to a field test. In order to accomplish such a check, data were obtained for time-of-travel as measured directly in the field by the use of dye tracers.

The time-of-travel of contaminants in streams is a matter which is being investigated at many places in the United States. Fluorescent dyes are now used extensively to measure travel time in streams and to solve particular water resource problems (Buchanan, 1964; Harris, 1968; and Bauer, 1968). The use of dye tracers for the field measurements of the time-of-travel in the stream is now a routine practice, as described by Wilson (1968).

Considerable data on time-of-travel were available for the 160-mile reach of the West Fork of the White River between Muncie and Spencer, Indiana. Engineers of the U. S. Geological Survey had made a number of determinations of travel times by using fluorescent dye tracers during 1965-1967. These travel-time measurements had been made at both high flows and low flows for the entire reach of the West Fork. The picture in figure 2 shows a slug of dye tracer in a stream in Indiana. The dye retains its identity in this form for a short distance downstream until complete mixing takes place.

For the check of the hydraulic geometry research, stream gaging data were obtained for 28 stations within this Indiana basin, and a set of hydraulic geometry equations was developed. The velocity equation as described by Stall and Fok (1968) was used to make theoretical computations of the time-of-travel through this reach of the White River in Indiana. Figure 3 shows the comparison of computed and measured travel times for this river at high flows and low flows. For the lower flows, the measured travel time is somewhat longer than the computed time. Part of this difference is due to the presence of two man-made

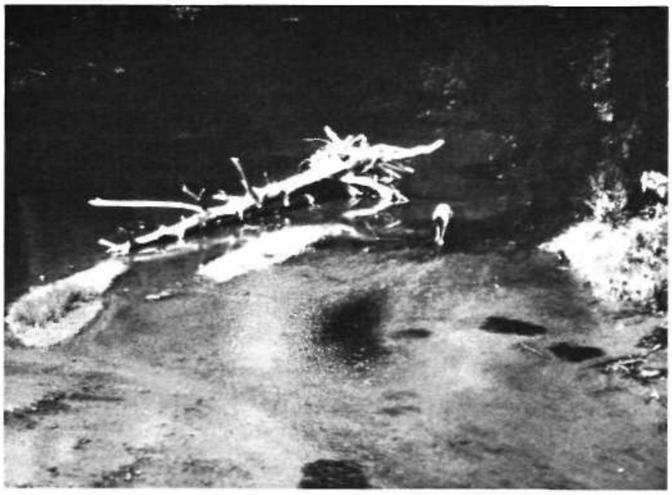

Figure 2. Dose of fluorescent dye appears as a dark discolorant to the flowing water (Photo courtesy M. D. Hale, U. S. Geological Survey, Indianapolis)

channel dams which retard low flows in the reach from Nora to Indianapolis.

Figure 3 shows that for relatively high flows the computed travel times provide a good estimate of the actual travel times. At relatively low flows, the measured travel times are often longer than those generally computed by hydraulic geometry considerations. It is believed that conditions in a natural stream are often similar to that created by the man-made dams, so that actual travel times at low flows can be considerably greater than those computed from theoretical considerations. The research in Illinois showed that the relatively high flows, those occurring about 10 percent of the days each year, seemed to be best related to the hydraulic geometry factors. One reason is that the higher flows have been instrumental in carving the streambed, whereas the lower flows are riding in a bed created by hydraulic conditions different from their own.

Further, at relatively high flows, the surface profile of the stream which determines its flow characteristics is approximately equal to the slope of the streambed. At low flows, however, the streambed has many localized pool-and-riffle conditions. That is, for a long reach of the channel at low flows, the water may be pooled and have effectively a zero gradient. Then a short reach of the stream will provide a riffle, which means that a significant drop in elevation of the streambed occurs in a relatively short reach of the stream. For a low flow condition, then, the effective slope of the water surface is greatly different from that of the theoretical general slope of the streambed.

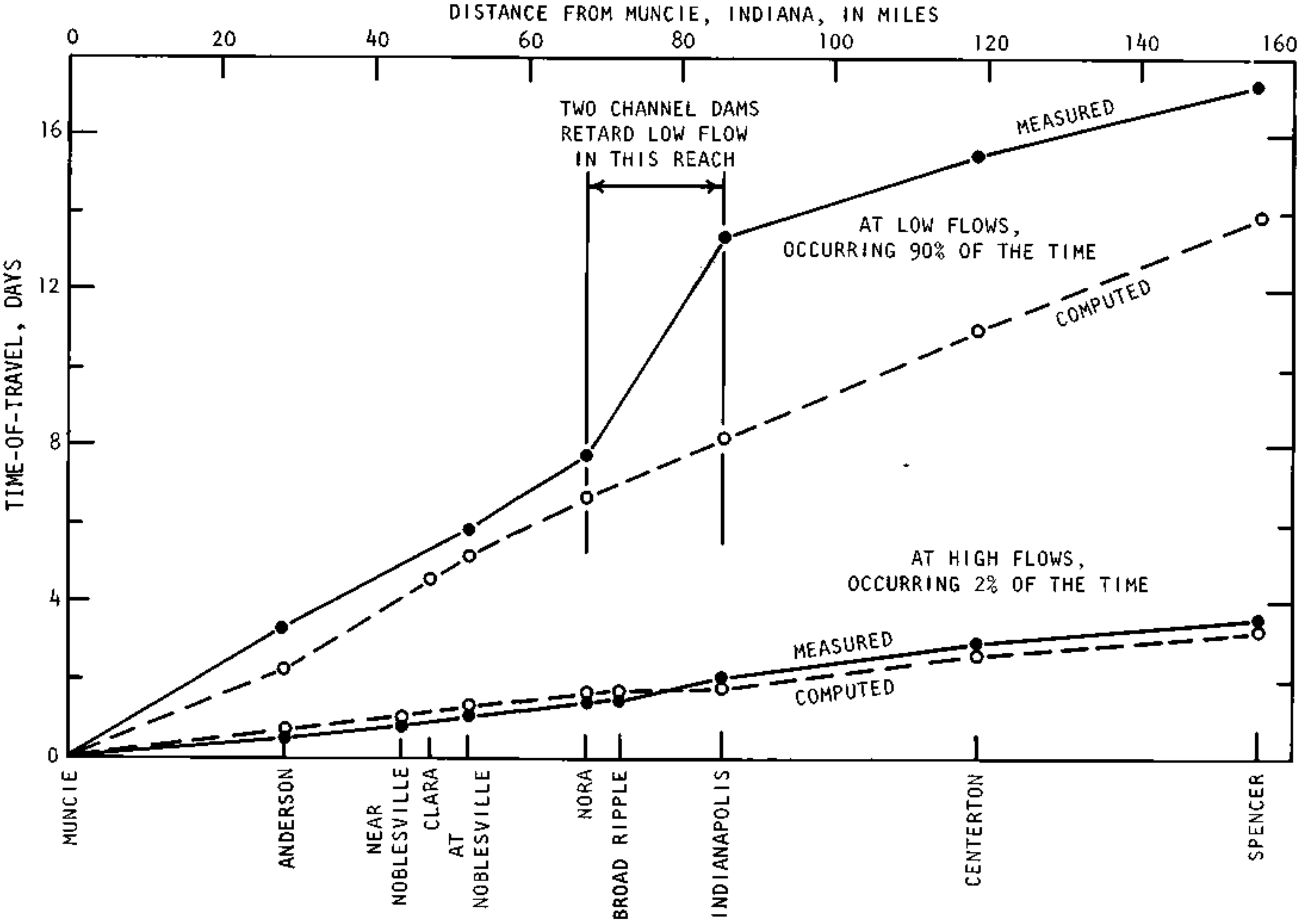

Figure 3. Measured and computed time-of-travel from Muncie to Spencer, Indiana, in West Fork of the White River

This pool-and-riffle condition holds back the flow and causes the travel time through this reach of stream to be much longer than that which would be computed. Also, this type of condition is beyond the range of streamflows of the general hydraulic geometry equations, the lowest of which were those exceeded 90 percent of the days each year.

Dye Measurements in Kaskaskia River

During July 1968, a time-of-travel study was made of the upper reach of the Kaskaskia River in Illinois by the Water Quality Section of the Water Survey. Dye tracers were introduced at Bondville, which is almost the headwaters of the Kaskaskia, and the concentration was checked at a number of stations toward Ficklin about 25 miles downstream. A separate run was then made by injecting the dye into the Kaskaskia at Ficklin and tracing it downstream to Allenville, a distance of about 40 miles. These actual field measurements of the time-of-travel were compared with the travel times obtained by using velocities in the Kaskaskia computed from equation 3.

In order to compute time-of-travel, solutions were made of equation 3 for three different arbitrarily selected flow rates: for *high* flow, F=0.10; for *medium* flow, F=0.50; and for *low* flow, F=0.90. These frequencies are, of course, those representing the daily discharges expected to be exceeded 10, 50, and 90 percent of the days each year Velocity computations were made for various reaches along the upper Kaskaskia River, a distance of about 65 miles. The three resultant time-of-travel graphs are shown in figure 4. The distance is shown in miles from Allenville at zero miles to Bondville at 65 miles upstream. Travel in days is the cumulative time-of-travel for the flow from any point along the river to reach the downstream end of this river reach at Allenville. The curves in figure 4 have been prepared to represent the time-of-travel of the leading edge of the dye, as is explained later.

The curve at lower right in figure 4 shows the actual, measured time-of-travel for the dye tracer run on July 9-10, 1968, made at a *high flow* rate. The difference between the reading for Bondville at mile 65 and that for Ficklin at about mile 39 shows that the total travel time was about 1.25 days. The computed curve for *high flows* in figure 4 shows at Bondville a total time-of-travel of 2.4 days to Allenville, and at Ficklin about 1.2 days time-of-travel to Allenville. The difference between these two readings gives a computed travel time between Bondville and Ficklin of about 1.2 days. This checks almost exactly with

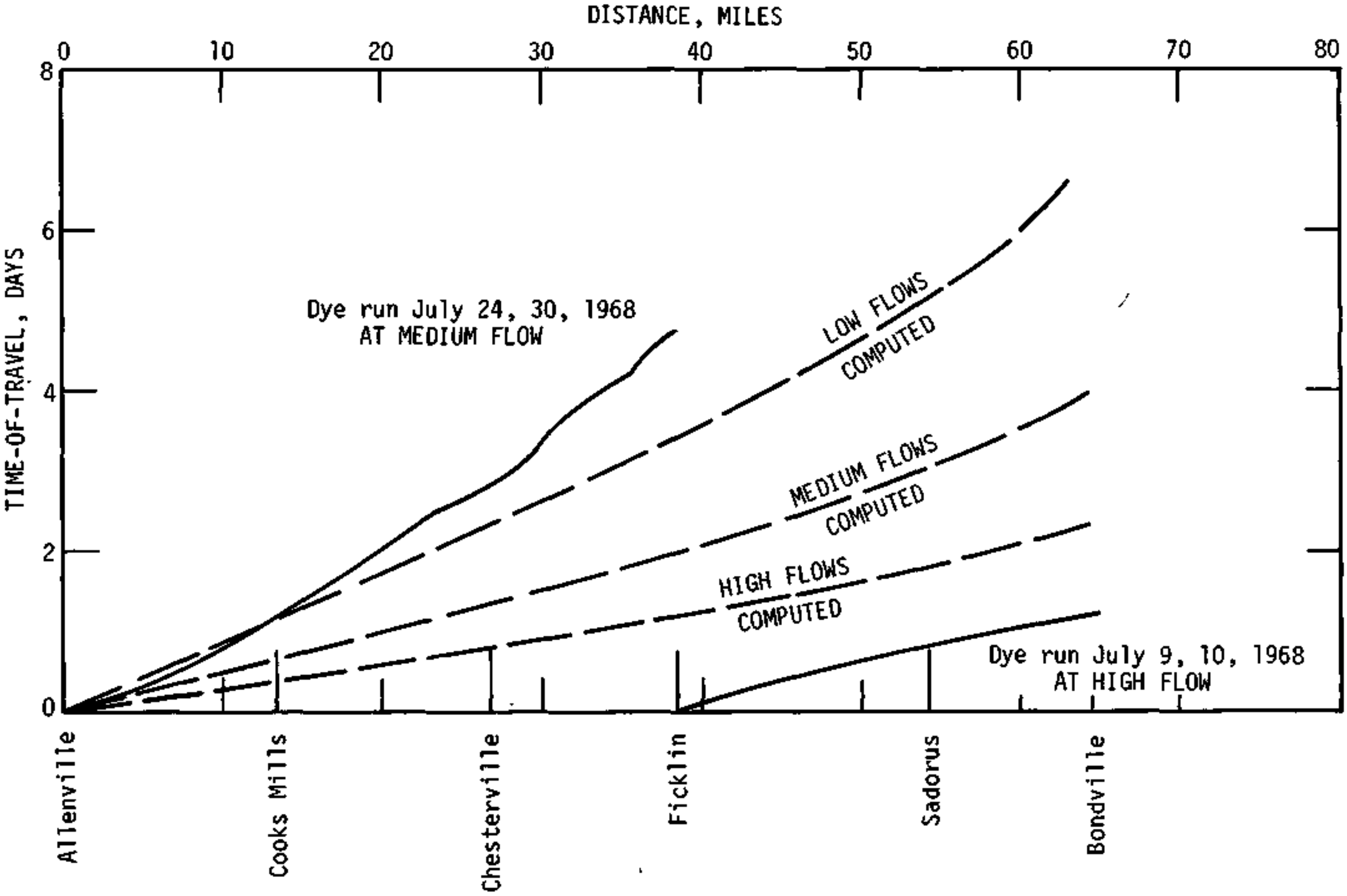

Figure 4. Computed time-of-travel of leading edge of a dote of dye tracer, for upper reach of Kaskaskia River from Bondville to Allenville, and actual travel times for two dye runs

the measured dye run. Consequently, it is considered that this dye run confirms to an excellent degree the computed travel times shown in figure 4 for high flows.

The curve in figure 4 for the dye run on July 24-30, 1968, shows actual measured time-of-travel at a *medium flow* rate. The total time-of-travel from Ficklin to Allenville was about 4.8 days. In comparison, the computed curve for medium flows shows an estimated time-of-travel from Ficklin to Allenville of about 2.0 days. In this case the actual travel time was more than double that estimated from the generalized graph based on hydraulic geometry.

Of the eight cases available to date in Illinois by which it was possible to compare computed times-of-travel with measured times-of-travel by dye studies, the above case at medium flow is the worst example. All of the other travel times computed at medium flow rates gave more reliable results than that explained above. Consequently, it is believed that the travel times, as computed, can generally be interpreted as the minimum travel time probable, and that in many cases, one can expect that actual travel times will be longer than those computed, especially at medium and low flows. Generally, at high flows the computed travel times should be accurate.

Dispersion of a Contaminant

If a. contaminant is considered stable or conservative, there will be a constant total amount of *the* material remaining in the stream as it is carried downstream. If the material is considered nonconservative, the amount of the material will become smaller as it goes downstream as a result of deterioration or of chemical reaction with either the air, water, or streambed. Because the stability of each contaminant or material is different, it is not possible to make any general prediction as to the ablation of the total amount of the material as it goes downstream. In some cases there would be no loss; in other cases the material would vanish in a very short time.

When a material such as a dye or other contaminant is introduced into a stream in a relatively solid dose, it is immediately subject to the turbulence caused by the various velocities present in the stream. As a consequence the contaminant is mixed or dispersed to some degree. It is well known that there is considerable variation in the flow velocity throughout a cross section of a stream, as is illustrated by the typical stream cross section in figure 5. Here it can be seen that, for a small element of the streamflow at the top of the stream near the center, the velocity will be considerably higher than it is near the streambed. This difference means that the dye or contaminant will be carried downstream by the fastest-moving element of the stream and, at the same time, will begin to be dispersed throughout the cross section. After a period of time, the dye will be carried by all elements of the stream water.

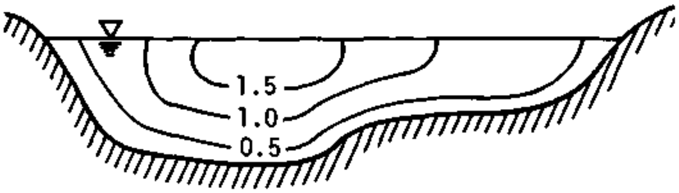

Figure 5. Typical lines of equal velocity in a stream cross section

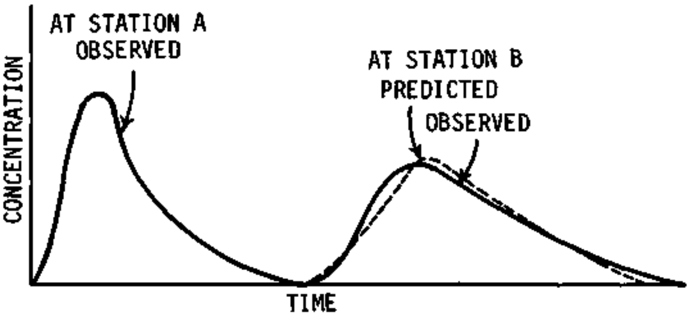

Figure 6. Concentration curves at two stream sections, A and B, illustrating curve predicted at downstream station B by Fischer routing procedure

A study of Fischer (1968) provides a theoretical approach to the determination of the rate at which dispersion actually occurs in a natural stream. Figure 6 gives a general concept of the Fischer dispersion procedure. It shows a concentration curve at a given location, A, on the stream as observed. A computation based upon the conditions in the natural stream then makes it possible to predict the shape of a concentration curve at another station at location B, a known distance downstream. The Fischer procedure has been shown to be valid for natural streams (Fischer, 1968). Studies are under way in Illinois to evaluate further the Fischer dispersion coefficient and the possibilities for its use in computing dispersion in Illinois streams. At the present time there are insufficient data from natural streams to allow generalization of the dispersion properties.

The principle of dispersion is illustrated in a practical example in figure 7, which shows actual dye concentration curves, as measured by the State Water Survey in a time-of-travel study on the Vermilion River in Illinois, for the reach between Streator and a bridge near the Patterson School 14.9 miles downstream. This dye run was made on November 15 and 16, 1967. The flow in this reach of the stream was that expected to be exceeded 27 percent of the days of the year, mat is, F=0.27, a relatively high flow. The time is in hours after the dye was introduced at Streator. A sharply-pointed dye concentration curve at the left represents the situation 1.3 miles below the point of dye injection at the Streator Dam. The three downstream curves have successively lower peaks and longer durations. The data in figure 7 merely illustrate what can be expected to occur by the natural process of dispersion in any stream. In this case the dye tracer was considered to be stable; the total amount of the dye did not dissipate to any important extent during the study.

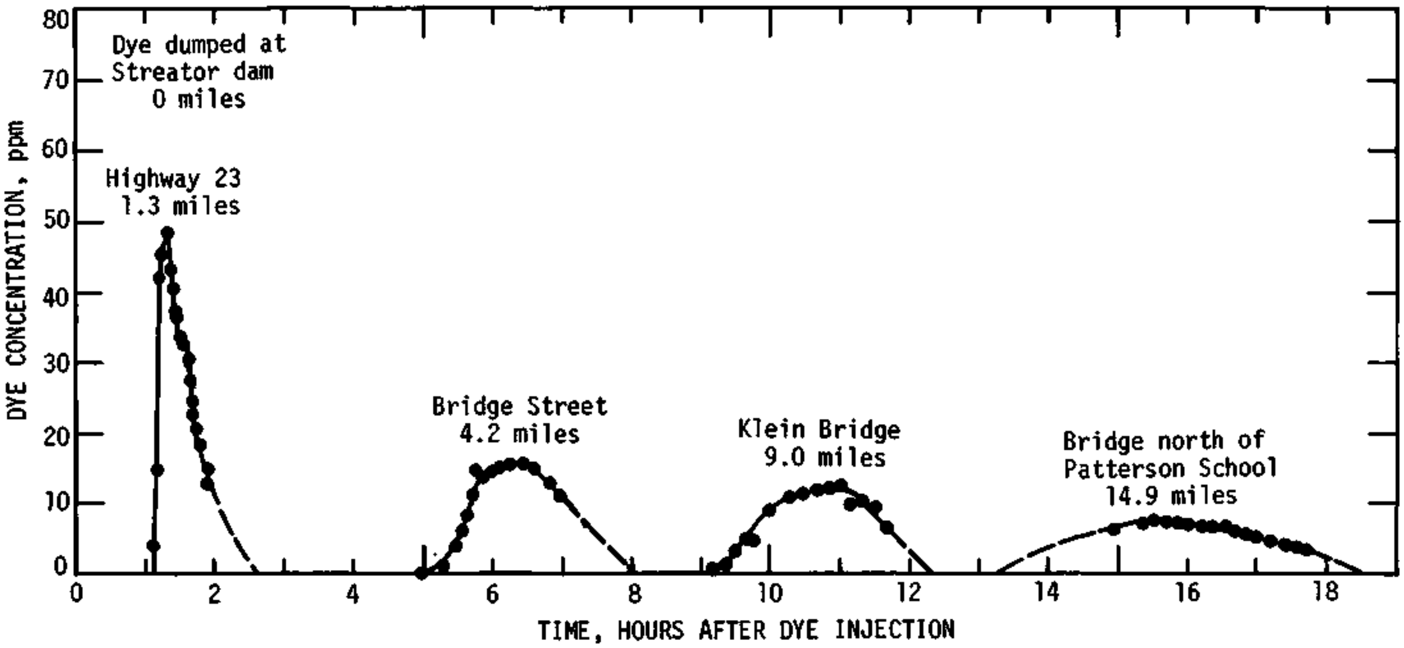

Figure 7. Concentration curves of a dye tracer introduced into the Vermilion River at Streator, showing dispersion of dye as it travels downstream

Velocities of Peak and Leading Edge

Figure 5 showed that the velocities within the stream cross section are highly variable, and figure 7 shows that, as a slug of dye material or contaminant is moved downstream, the velocity of the leading edge of the dye is faster than that of the peak concentration. Figure 7 also shows that the concentration at the peak becomes less as time passes. As a result of studies to date, data from eight separate dye runs were available for various streams in Illinois. Also available were data from dye studies carried out by the U. S. Geological Survey in Indiana. All of these cases were generalized, and the travel time of the peak concentration was compared with that of the leading edge of the dye.

As a generalization, it was deemed acceptable to use as the relation between these relative velocities

$$V_l = 1.25 V_p \qquad (6)$$

where V_l is **the velocity** of **the** leading edge of **the** dye and V is **the** velocity of **the** peak **concentration** of the dye. This generalization seems valid and has been used throughout this project to provide the time-of-travel of the leading edge of the dye.

Time-of-Travel for Tributaries

Although this report gives time-of-travel graphs only for the main stem of streams, it is recognized that a contaminant often might be spilled into a tributary of a stream system. The travel times in these tributaries usually will be short. If a definite estimate is desired, the time-of-travel graph for the headwaters of the particular river basin may be used. Because the computed travel times are a function of the drainage area, the travel times in smaller tributaries throughout the basin are similar to the travel times in the most upstream, or headwaters, portion of the basin, as shown on the graphs for the river main stem.

Illinois River

Flow conditions within the Illinois River proper are subject to special considerations for several reasons. As most significant, an average of 1500 cfs of Lake Michigan water is diverted through the Illinois River, and the entire river is regulated for navigation. The main stem of the Illinois River was not included in the hydraulic geometry study described earlier (Stall and Fok, 1968), because of manmade conditions of diversion and regulation. In order to provide time-of-travel estimates, a special approach was used.

Figure 8 shows a profile of the main stem of the Illinois River from the mouth where it joins the Mississippi River at Grafton to its origin near Morris, 273 miles upstream. The origin of the Illinois River is the confluence of the Des Plaines and Kankakee Rivers near Dresden Island, upstream from Morris. The irregular solid line in figure 8 shows the actual profile of the river bed.

Water levels in the Illinois River are controlled for navigation purposes by a series of locks and dams. As shown in figure 8, the water-level elevation above Grafton is maintained in the Alton pool, formed behind the Alton lock and dam on the main stem of the Mississippi River at Alton. Upstream at mile 80 is the La Grange lock and dam, at mile 158 is the Peoria lock and dam, at mile 231 is the Starved Rock lock and dam, at mile 244 is the Marseilles lock, at mile 247 is the Marseilles dam, and at mile

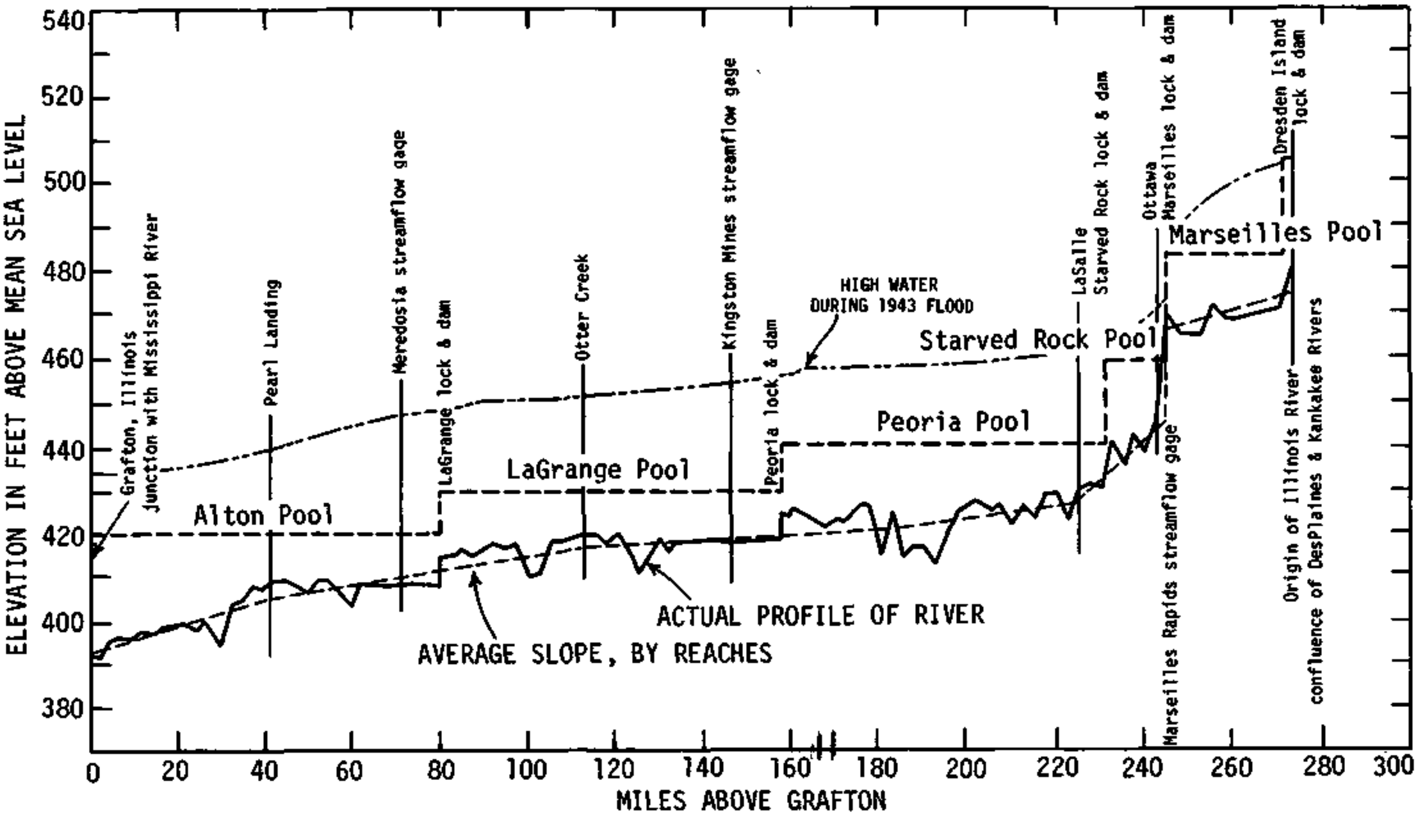

Figure 8. Profile of Illinois River from its origin at Dresden Island near Morris to Its mouth at Grafton (From U. S. Army Corps of Engineers Charts, 1957)

271 is the Dresden Island lock and dam. The uppermost chain-dotted line in figure 8 shows the high water which occurred during the 1943 flood on the Illinois River.

On the main stem of the Illinois River are three permanent-record stream gaging stations operated by the U. S. Geological Survey. These are located (figure 8) at Meredosia, mile 71; at Kingston Mines, mile 145; and at Marseilles Rapids, mile 247. Actual measurements of discharge at these gaging stations are taken regularly in order to maintain a good rating curve for determining discharges. These discharge measurements provide flow velocities. Velocities at three flow rates have been generalized and are shown in table 1. The duration of daily flows at these three stream gaging stations have been tabulated for the standard period 1950-1964, and a duration curve of daily discharges has been plotted for each station. From these duration curves the discharges expected to be exceeded for 90, 50, and 10 percent of the days per year were read. These three flow values in cubic feet per second, described for this report as low, medium, and high flows, are also shown in table 1 for each of the three stream gaging stations.

Table 1 indicates that the flow velocities at the Marseilles Rapids gaging station are considerably higher than those at Meredosia and Kingston Mines, which is consistent with the slope of the streambed shown by the river profile in figure 8. A dashed line through the actual pro-

Table 1. Average Flow Velocities at Three Stream Gaging Stations on Illinois River

Gaging station Paging station	Flow *(cfs)* and Telocity (fps) for given flow conditions Low flows F=0.90	 Med. flows F=0.50	 High flows F=0.10
At Meredosia, mile 71	5,900 1.0	13,300 1.4	40,000 2.4
At Kingston Mines, mile 145	4,850 0.9	9,600 1.25	26,100 2.0
At Marseilles Rapids, mile 247	4,300 2.9	7,000 3.7	16,600 5.6

Table 2. Length, Slope, and Velocity for Six Reaches of Illinois River, for Low, Medium, and High Flows

Miles above Grafton	Beach	Length of reach	Average slope of reach *(miles)*	Flow velocity (/ps) from gaging station or from flg. 9* Low *(ft/mi)*	 Medium flows flows	 High flows
0	Mouth. Grafton					
	to	42	0.31	(1.35)	(1.8)	(2.9)
42	Pearl Landing					
	to	70	0.14	1.0	1.4	2.4
112	Otter Creek					
	to	112	0.11	0.9	1.25	2 0
224	La Salle					
	to	18	0.94	(1.8)	(2.4)	(3.8)
242	Ottawa					
	to	2	10.4	2.9	3.7	5.6
224	Marseilles Lock					
	to	29	0.28	(1.3)	(1.7)	(2.8)
273	Origin, Morris					

*Velocities *from figure 9 are shown in parentheses* file of the-river in figure 8 shows a generalized or averaged slope for various reaches of the river. Information on length and average slope of six reaches of the river is presented in table 2.

Figure 9 depicts a relation between mean flow velocity in feet per second and the stream slope in feet per mile. The plotted points are derived from the actual observed flow velocities at the three stream gaging stations (table 1). The three straight lines in figure 9 represent the relation of mean flow velocity to stream slope at low, medium, and high flows. This relation was then used to read appropriate mean velocities for the three reaches of the Illinois River in table 2 for which no actual flow velocities are available from gaging stations.

The flow velocities 'in table 2 have been used to compute time-of-travel in the main stem of the Illinois River. These times-of-travel are considered to have accuracy comparable with those used throughout this report for other streams in Illinois.

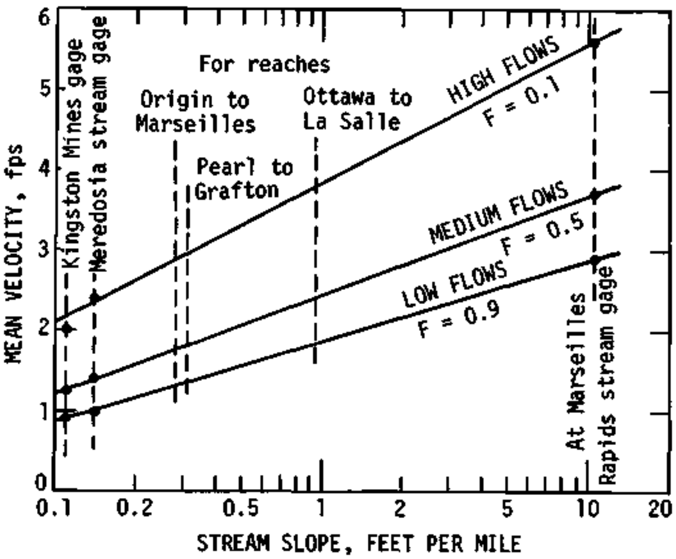

Figure 9. Generalized relation of mean flow velocity to mean slope of the river bed, Illinois River main stem

RESULTS

Time-of-Travel Graphs

The principal results presented in this report are graphical. A time-of-travel graph is presented in the appendix for each of 41 different stream reaches within Illinois as listed on page 12. Streams are listed in general order from north to south in Illinois. The location of each of these reaches is shown on a map accompanying this report *(see pocket inside back cover).* The graph for each section of stream is similar to the primary results given for the main stem of the Kaskaskia River in figure 4. Principal results in each graph are the three curves showing time-of-travel for the reach of stream for flow rates of high, medium, and low flows. Distance is given in miles above the downstream end of the reach. The names of towns, highways, stream gages, or other local reference points are shown to help the reader identify various locations along the stream. These stream distances have been measured from U. S. Geological Survey topographic maps having a scale of 1 inch equals 1 mile. The time-of-travel is given in days and can be read from any point on the stream system to the outlet.

Flow Frequency Data

On each of the time-of-travel graphs, the three curves for high, medium, and low flows represent generalized flow conditions at frequencies of 10, 50, and 90 percent of the time. These have been derived and generalized from the total amount of streamflow data available in Illinois from 166 stream gaging stations used in the original research on hydraulic geometry. Of these 166 stations, 73 are located on the main stems of streams for which time-of-travel graphs are presented. For these streams it is possible to provide an actual flow rate which is equivalent to the flow frequencies of 10, 50, and 90 percent of the days each year on the time-of-travel graphs.

Table 3 contains a complete listing of the 73 gaging stations in Illinois which are located on the stream reaches contained in this report. All but 3 of the 41 stream reaches have at least one gaging station. The actual discharges in cubic feet per second for frequency values of F=0.10, 0.50, and 0.90 are given for each station, which is listed by name and U. S. Geological Survey identification number.

How to Use These Results

The user of this report can obtain a time-of-travel estimate by a relatively straightforward procedure. First it is necessary to refer to the map in the back pocket of this report to locate the reach of stream on which information is desired. Next, the appropriate time-of-travel graph can be located in the appendix of this report. Third, an estimate must be made as to flow conditions prevailing in the river. As an initial estimate the flow can be termed either high, medium, or low, in order to determine which of the three curves on the graph to use. High flow is approximately bank full. If there is a stream gaging station on the stream reach in question, the actual discharge rate can be obtained from that station and compared with that over the long term as indicated in table 3, being either high, medium, or low. After the appropriate curve has then been determined, an estimate can be made of the travel time from any point on the stream system to the outlet. Also, the difference between these readings for any two points would provide the travel time between two intermediate points.

Table 3. River Reaches Showing Low, Medium, and High Flow Rates at Gaging Stations

USGS number	Station	Flow (cfs) Low F=0.90	Flow (cfs) Medium F=0.50	Flow (cfs) High F=0.10
Rock River, origin to Rockford				
5-4230	West Branch Rock River near Waupun, Wis.	1.1	5.5	50
5-4255	Rock River at Watertown, Wis.	33	202	1,150
5-4305	Rock River at Afton, Wis.	430	1,160	3,780
5-4375	Rock River at Rockton	1,130	2,450	7,550
Rock River, Rockford to mouth at Rock Island				
5-4435	Rock River at Como	1,480	3,400	10,900
5-4465	Rock River near Joslin	1,710	3,800	13,300
Sugar River				
5-4365	Sugar River near Brodhead, Wis.	139	228	540
Pecatonica River				
5-4325	Pecatonica River at Darlington, Wis	50.5	107	300
5-4345	Pecatonica River at Martintown, Wis.	226	423	1,260
5-4355	Pecatonica River at Freeport	266	540	1,600
Kishwaukee River				
5-4385	Kishwaukee River at Belvidere	53	165	630
Green River				
5-4475	Green River near Geneseo	75	280	1,300
Fox River, Fox Lake to mouth				
5-5500	Fox River at Algonquin	164	450	1,910
5-5525	Fox River at Dayton	360	1,000	3,860
Des Plaines River				
5-5290	Des Plaines River near Des Plaines	5.4	62.8	610
5-5325	Des Plaines River at Riverside	23	146	1,070
Du Page River				
5-5399	West Branch Du Page River near West Chicago	1.0	85	52
5-5405	Du Page River at Shorewood (formerly Troy)	39	107	521
Kankakee River				
5-5150	Kankakee River near North Liberty, Ind.	73	118	415
5-5155	Kankakee River at Davis, Ind.	260	385	750
5-5175	Kankakee River at Dunn's Bridge, Ind.	470	1,000	2,530
5-5180	Kankakee River at Shelby, Ind.	600	1,180	2,780
5-5205	Kankakee River at Momence	655	1,470	4,210
5-5275	Kankakee River near Wilmington	840	2,570	9,450
Iroquois River				
5-5210	Iroquois River at Rosebud, Ind.	4.5	13	54
5-5220	Iroquois River near North Marion, Ind	12	56	305
5-5225	Iroquois River at Rensselaer, Ind.	14	72	413
5-5245	Iroquois River near Foresman, Ind.	22	150	990
5-5250	Iroquois River at Iroquois	26	204	1,360
5-5260	Iroquois River near Chebanse	66	593	4,130
Illinois River, origin to Peoria				
5-5435	Illinois River at Marseilles	4,300	7,000	16,600
Illinois River, Peoria at mouth at Grafton				
5-5685	Illinois River at Kingston Mines	4,850	9,600	26,100
5-5855	Illinois River at Meredosia	5,900	13,300	40,000
Vermilion River, Illinois River Basin				
5-5545	Vermilion River at Pontiac	3.4	57	682
5-5555	Vermilion River at Lowell	13.5	220	1,780
Mackinaw River				
5-5675	Mackinaw River near Congerville	7.6	107	1,070
Spoon River				
5-5695	Spoon River at London Mills	31	214	1,390
5-5700	Spoon River at Seville	53	416	2,080
La Moine River				
	None			
Sangamon River, origin to Lake Decatur				
5-5710	Sangamon River at Mahomet	4.6	64	605
5-5720	Sangamon River at Monticello	8.8	110	935
5-5725	Sangamon River near Oakley	12	150	1,275
Sangamon River, Lake Decatur to mouth				
5-5830	Sangamon River near Oakford	261	1,178	7,680
South Fork				
5-5760	South Fork Sangamon River near Rochester	6.0	119	1,150
Salt Creek				
5-5785	Salt Creek near Rowell	8.4	58	534
5-5820	Salt Creek near Greenview	97	360	2,630
Sugar Creek				
5-5815	Sugar Creek near Hartsburg	14	60	469
Kickapoo Creek				
5-5800	Kickapoo Creek at Waynesville	2.3	36	284
5-5805	Kickapoo Creek near Lincoln	5.8	49	398
Macoupin Creek				
5-5870	Macoupin Creek near Kane	4.6	55	814
Kaskaskia River, origin to Shelbyville Reservoir				
5-5900	Kaskaskia River at Bondville	0.2	3.0	21
5-5904	Kaskaskia River near Pesotum	14	25	165
Kaskaskia River, Shelbyville to Carlyle Reservoir				
5-5920	Kaskaskia River at Shelbyville	8.0	240	2,310
5-5925	Kaskaskia River at Vandalia	30	445	3,860
Kaskaskia, Carlyle to mouth				
5-5930	Kaskaskia River at Carlyle	56	589	5,100
5-5950	Kaskaskia River at New Athens	130	1,040	9,900
Shoal Creek				
5-5940	Shoal Creek near Breese	9.1	75	990
Silver Creek				
5-5944.5	Silver Creek near Troy	0.5	3.3	124
Vermilion River, Wabash River Basin				
3-3390	Vermilion River near Danville	47	332	2,175
Salt Fork				
	None			
Embarras River, origin to Lake Charleston				
3-3434	Embarras River near Camargo	2.3	47	520
Embarras River, Charleston to mouth				
3-3455	Embarras River at Ste. Marie	27	354	2,770
Little Wabash River				
3-3789	Little Wabash River at Louisville	3.9	84	1,660

Table 3 (Concluded)

USGS number	Station	Flow (*cfs*) Low *F*=0.90	Medium *F*=0.50	High *F*=0.10
3-3795	Little Wabash River below Clay City	4.6	120	2,600
3-3815	Little Wabash River at Carmi	28	512	8,100
Skillet Fork				
3-3803.5	Skillet Fork near Iuka	0.2	7.7	295
3-3805	Skillet Fork at Wayne City	0.8	31	1,115
Big Muddy River				
5-5960	Big Muddy River near Benton	2.1	41	1,293
5-5970	Big Muddy River at Plumfield	4.5	86	2,357
5-5995	Big Muddy River at Murphysboro	16	320	5,860
Little Muddy River				
	None			
Beaucoup Creek				
5-5990	Beaucoup Creek near Matthews	4.9	20	582
North Fork Saline River				
3-3823.5	North Fork Saline River near Ridgway	0	30	1,750
3-3825	Saline River near Junction	8.3	140	3,950
South Fork Saline River				
3-3821	South Fork Saline River near Carrier Mills	1.7	19	800
Cache River				
3-6120	Cache River at Forman	1.0	41	540

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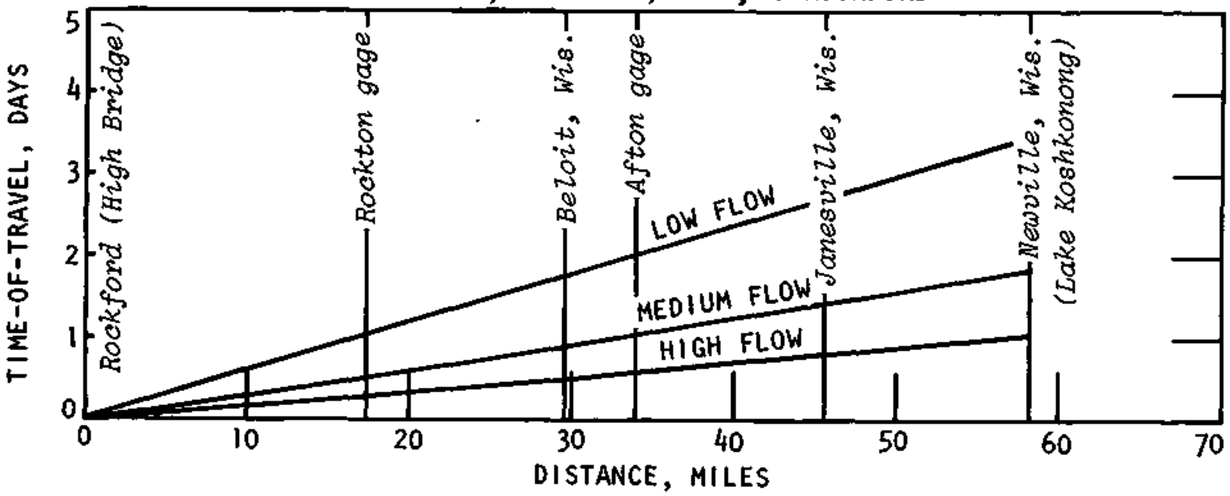
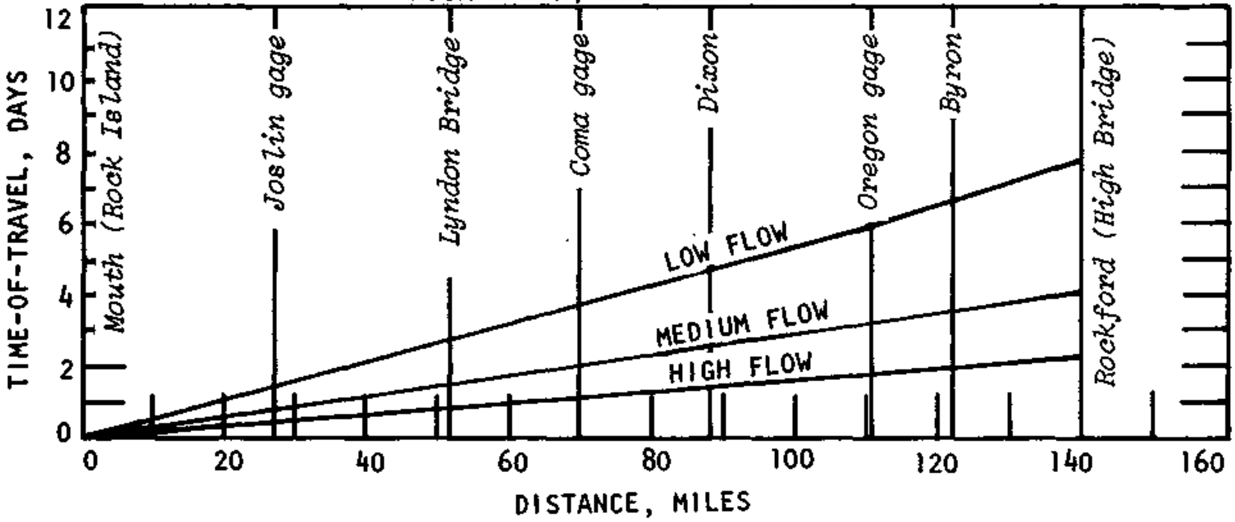
APPENDIX

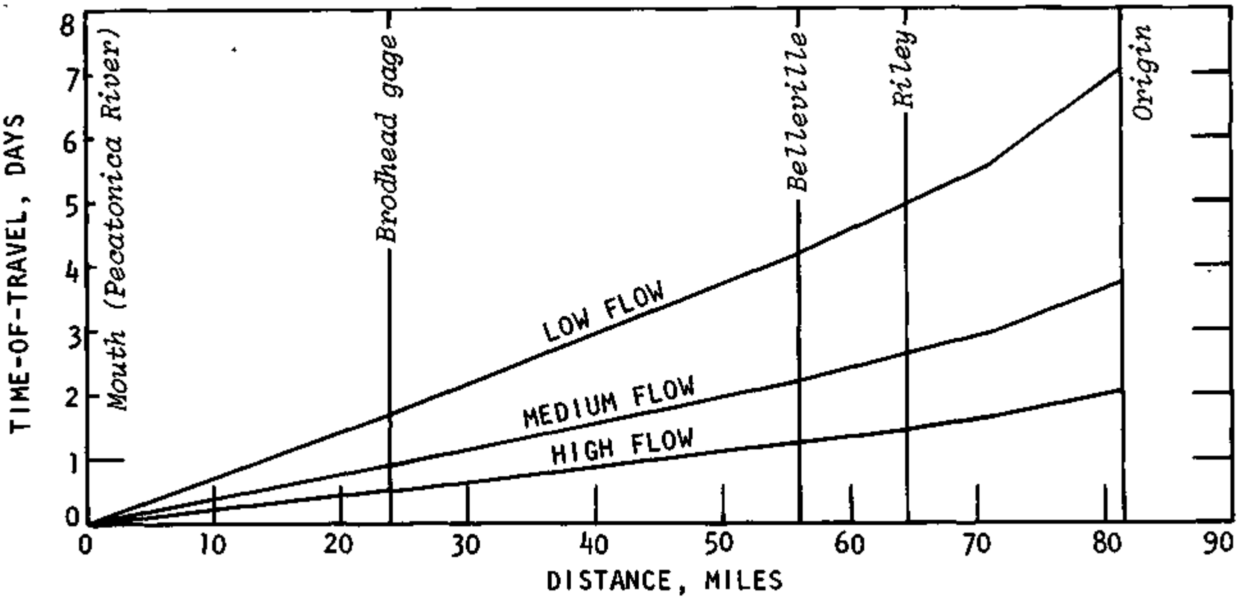
Order of Presentation of Time-of-Travel Graphs for 41 River Reaches

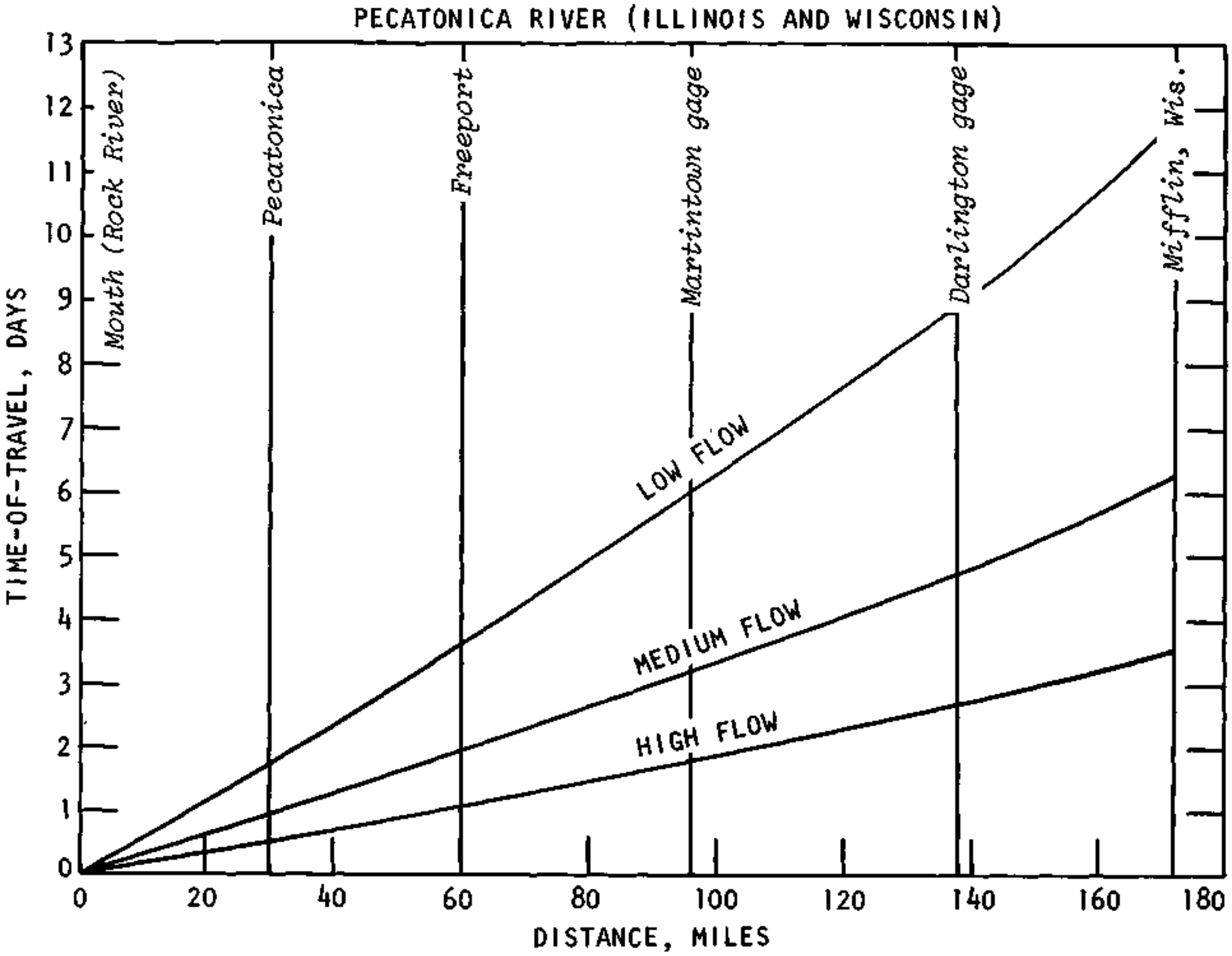
(Listed in general order from north to south in Illinois)

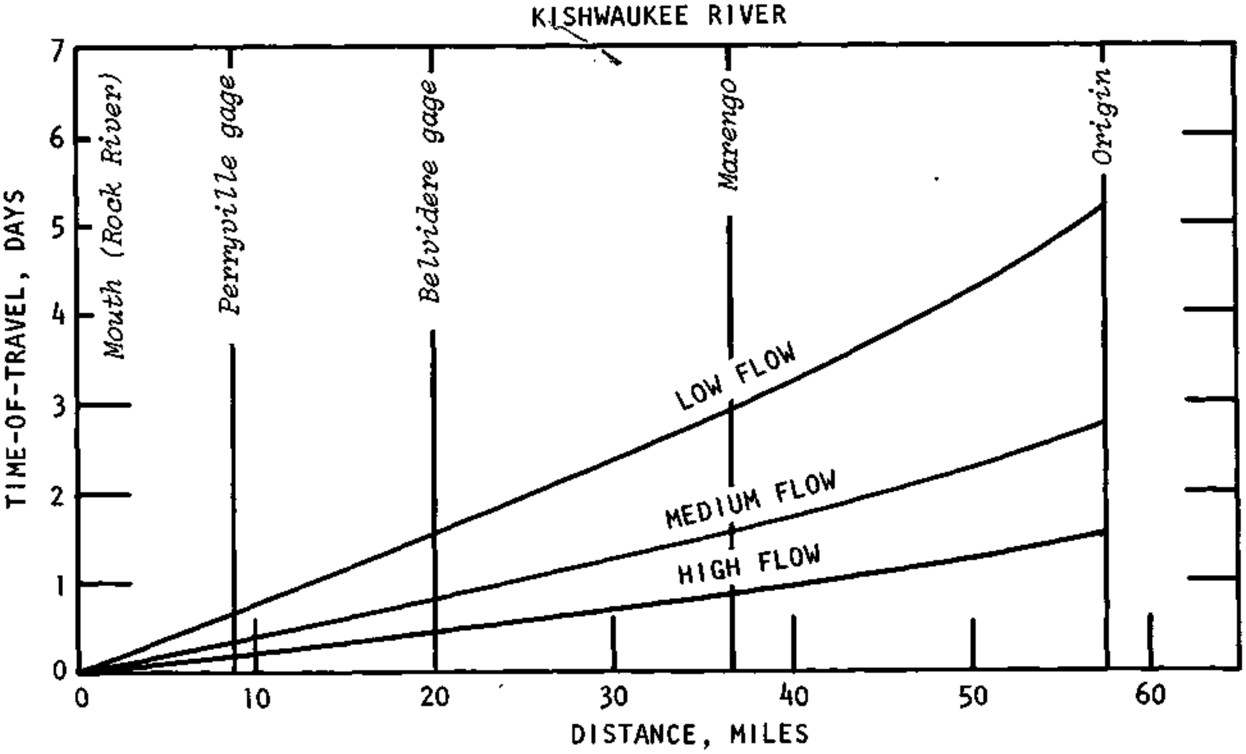
PAGE

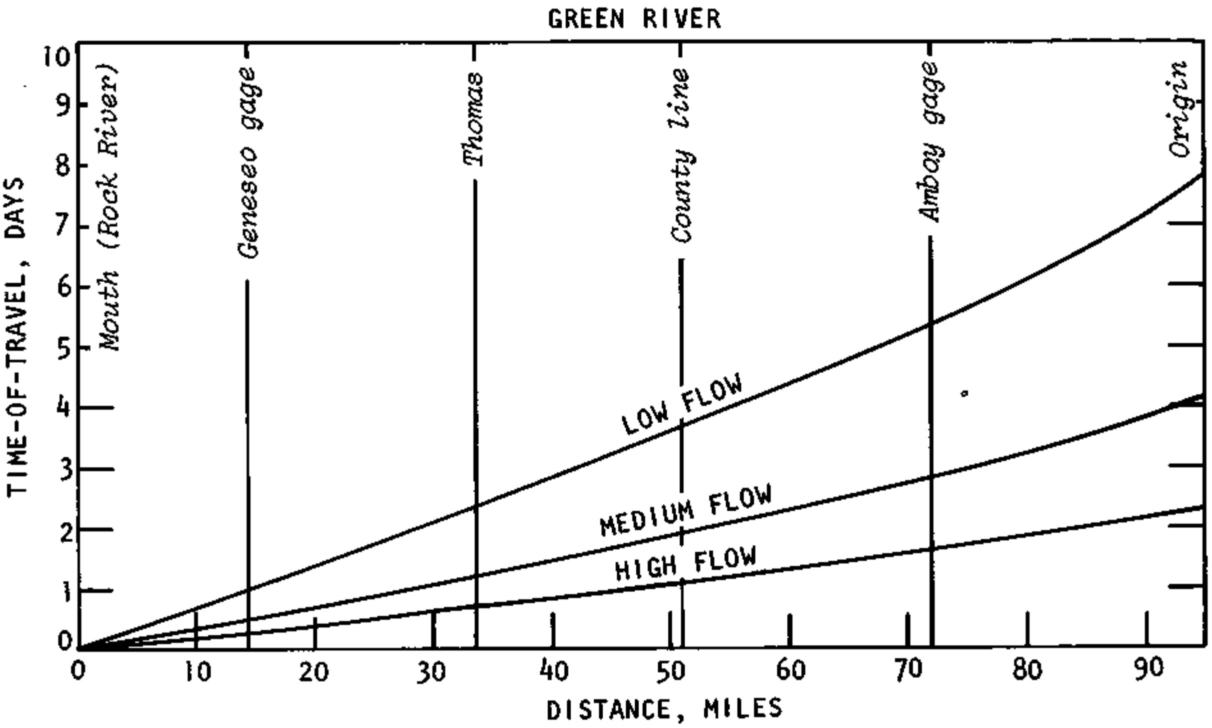

ROCK RIVER, NEWVILLE, WIS., TO ROCKFORD

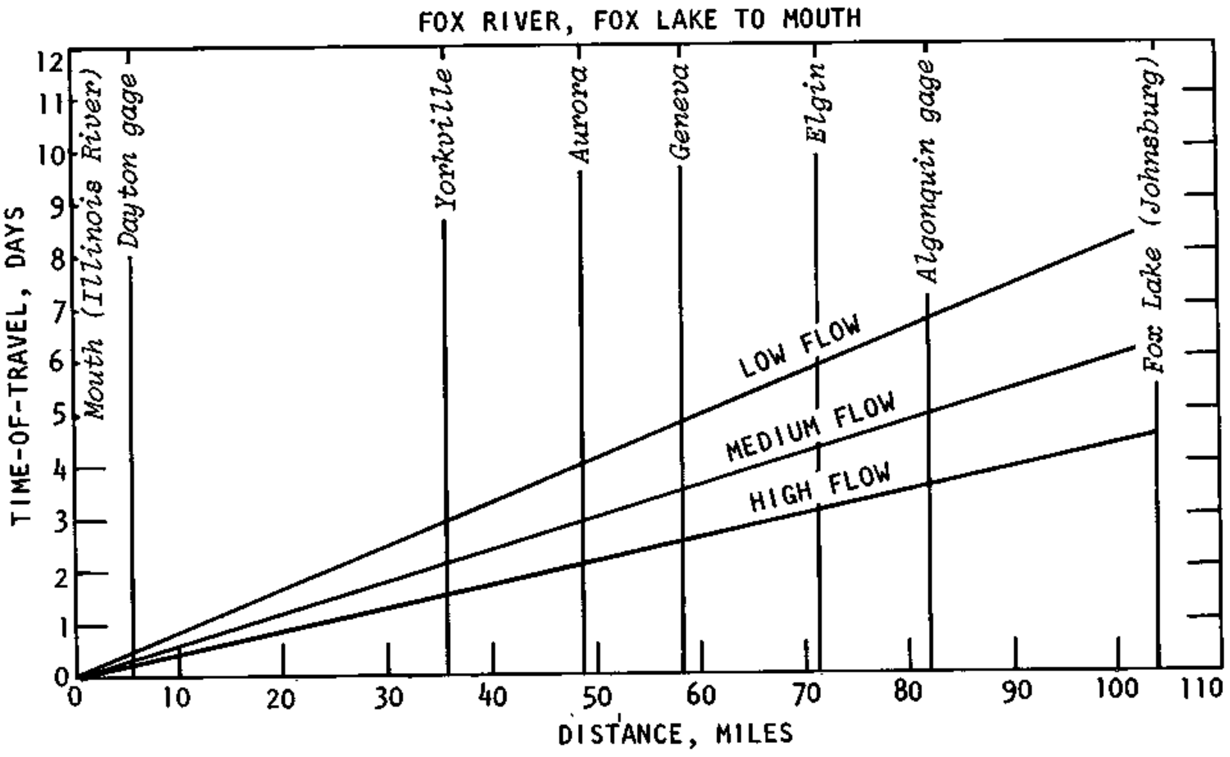

ROCK RIVER, ROCKFORD TO MOUTH

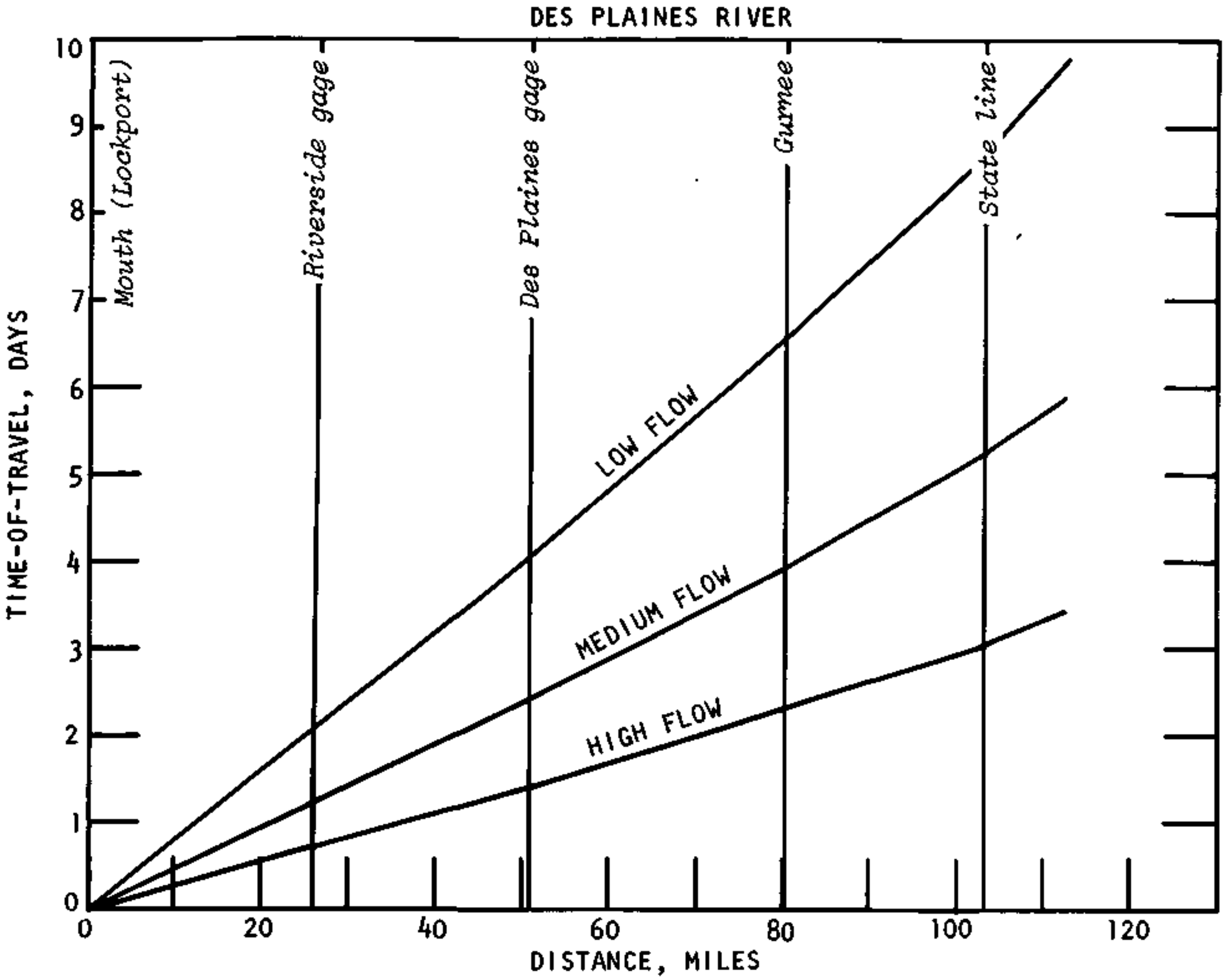

SUGAR RIVER (ILLINOIS AND WISCONSIN)

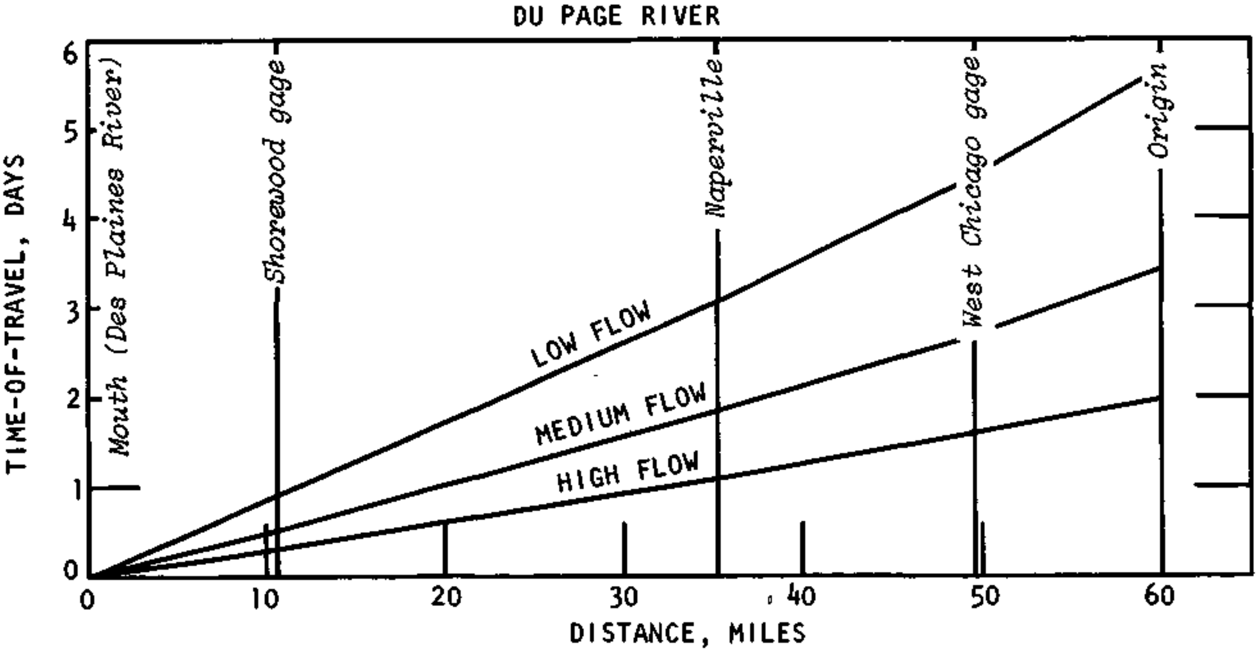

PECATONICA RIVER (ILLINOIS AND WISCONSIN)
TIME-OF-TRAVEL, DAYS
DISTANCE, MILES
0
1
2
3
4
5
6
7
8
9
10
11
12
13
0
20
40
60
80
100
120
140
160
180
Mouth (Rock River)
Pecatonica
Freeport
Martintown gage
Darlington gage
Mifflin, Wis.
LOW FLOW
MEDIUM FLOW
HIGH FLOW


KISHWAUKEE RIVER
TIME-OF-TRAVEL, DAYS
DISTANCE, MILES
0
1
2
3
4
5
6
7
0
10
20
30
40
50
60
Mouth (Rock River)
Perryville gage
Belvidere gage
Marengo
Origin
LOW FLOW
MEDIUM FLOW
HIGH FLOW

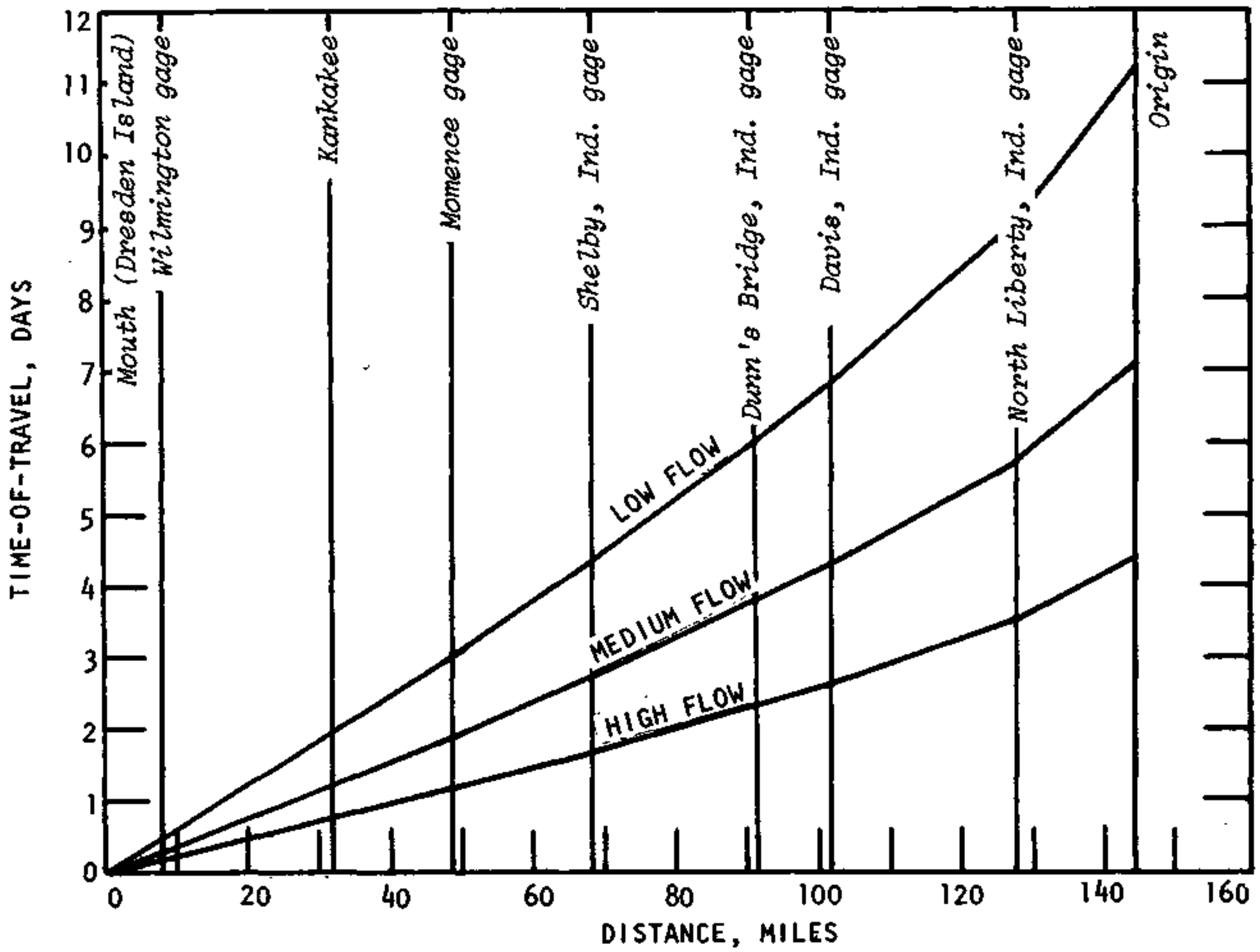

GREEN RIVER
TIME-OF-TRAVEL, DAYS
DISTANCE, MILES
0
1
2
3
4
5
6
7
8
9
10
0
10
20
30
40
50
60
70
80
90
Mouth (Rock River)
Geneseo gage
Thomas
County line
Amboy gage
Origin
LOW FLOW
MEDIUM FLOW
HIGH FLOW


FOX RIVER, FOX LAKE TO MOUTH
TIME-OF-TRAVEL, DAYS
DISTANCE, MILES
0
1
2
3
4
5
6
7
8
9
10
11
12
0
10
20
30
40
50
60
70
80
90
100
110
Mouth (Illinois River)
Dayton gage
Yorkville
Aurora
Geneva
Elgin
Algonquin gage
Fox Lake (Johnsburg)
LOW FLOW
MEDIUM FLOW
HIGH FLOW

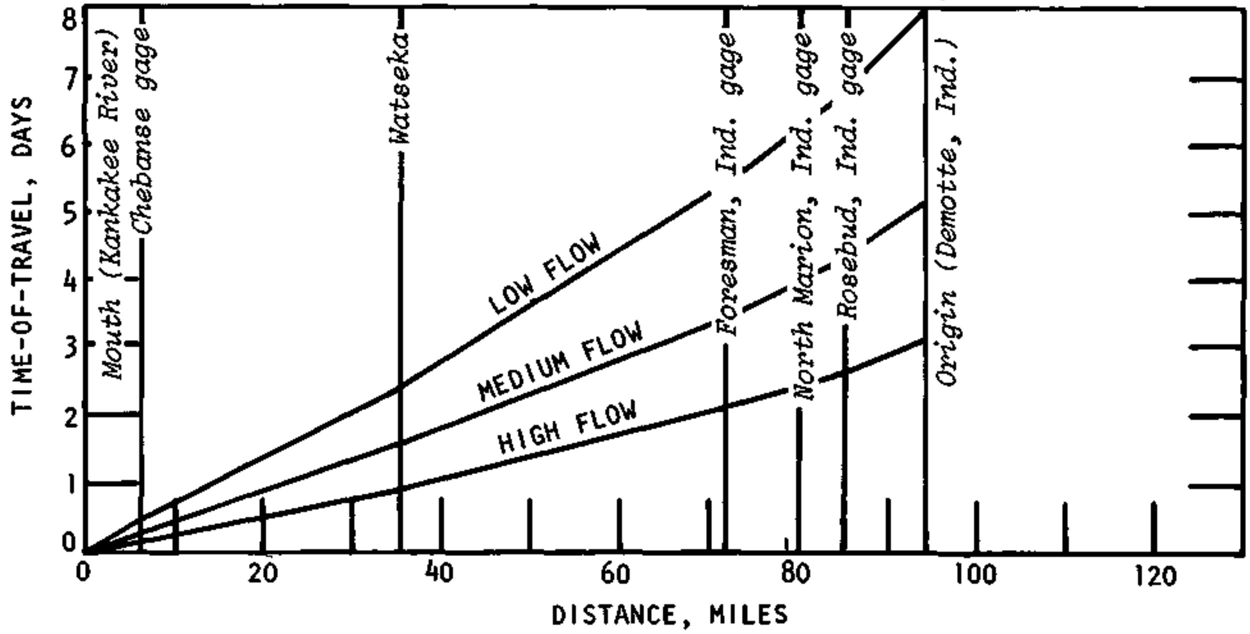

DES PLAINES RIVER
TIME-OF-TRAVEL, DAYS
DISTANCE, MILES
Mouth (Lockport)
Riverside gage
Des Plaines gage
Gurnee
State line
LOW FLOW
MEDIUM FLOW
HIGH FLOW
0
1
2
3
4
5
6
7
8
9
10
0
20
40
60
80
100
120

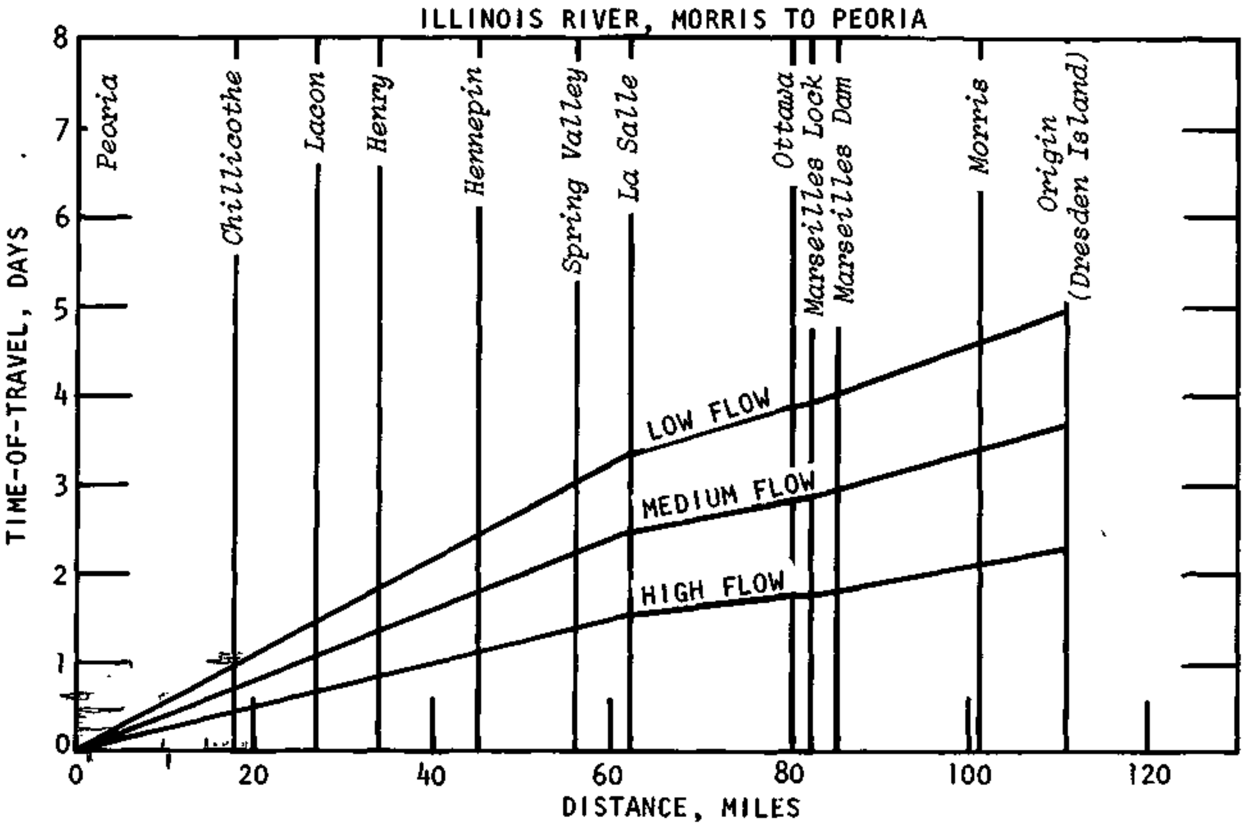

DU PAGE RIVER
TIME-OF-TRAVEL, DAYS
DISTANCE, MILES
Mouth (Des Plaines River)
Shorewood gage
Naperville
West Chicago gage
Origin
LOW FLOW
MEDIUM FLOW
HIGH FLOW
0
1
2
3
4
5
6
0
10
20
30
40
50
60

KANKAKEE RIVER (INDIANA AND ILLINOIS)

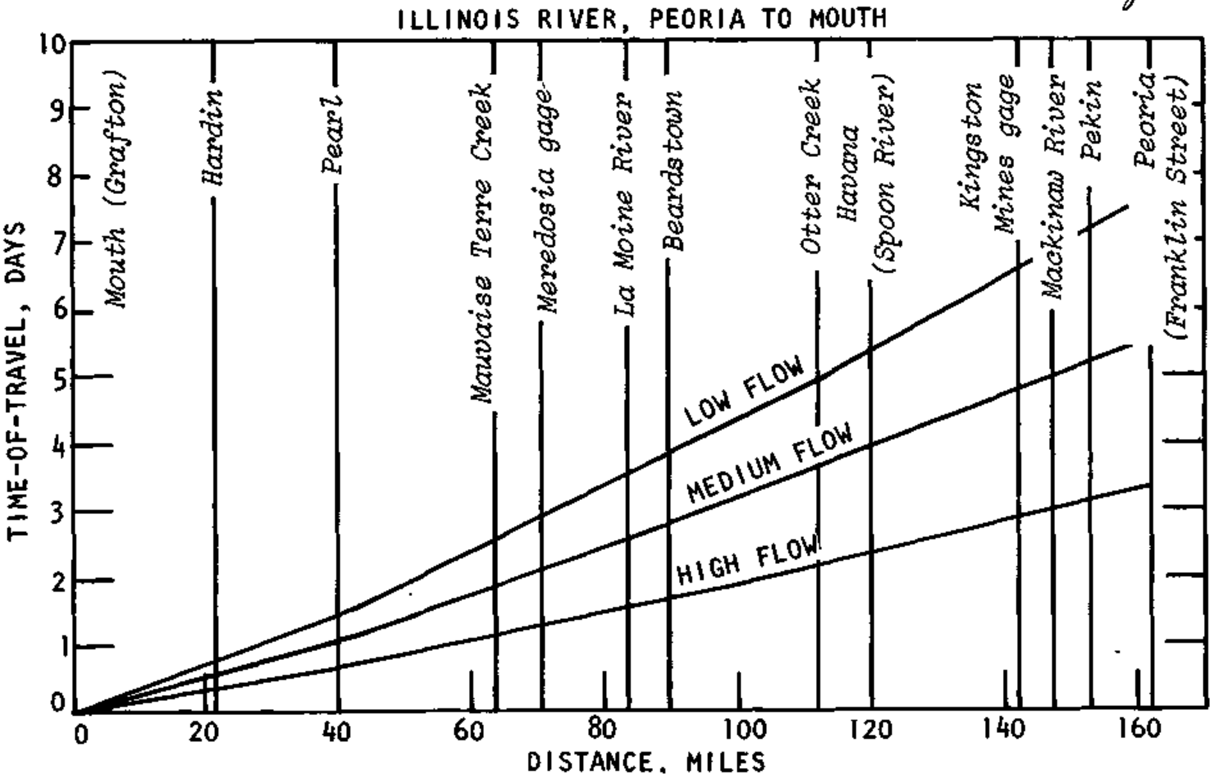


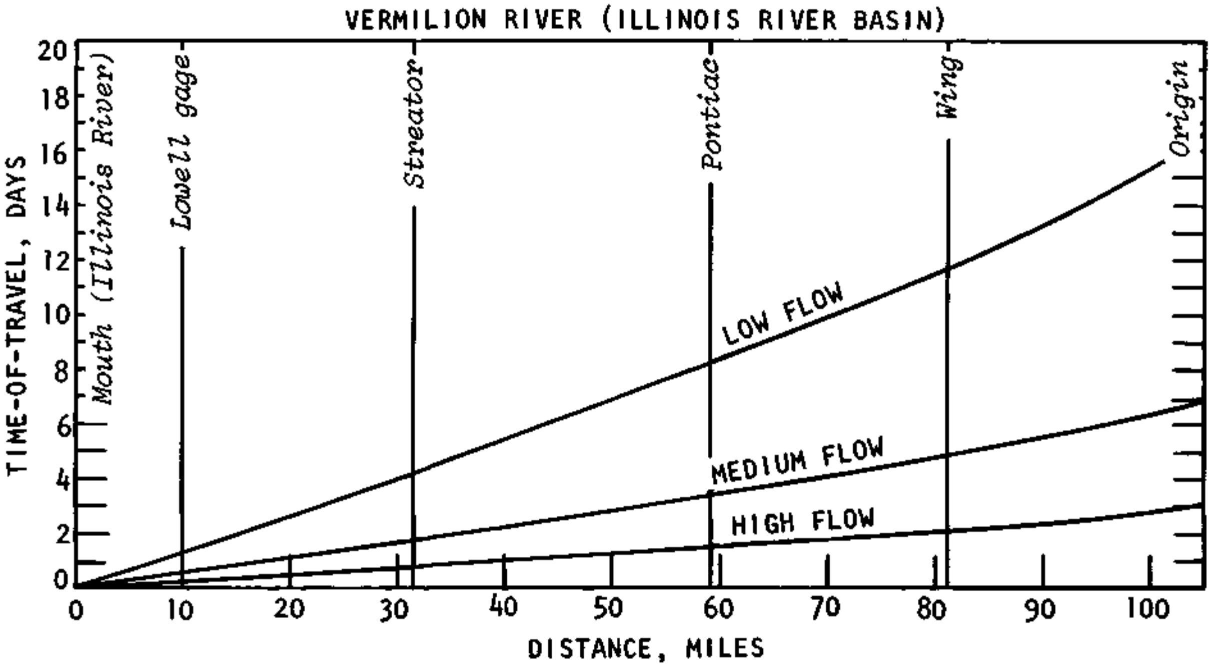
IROQUOIS RIVER (INDIANA AND ILLINOIS)

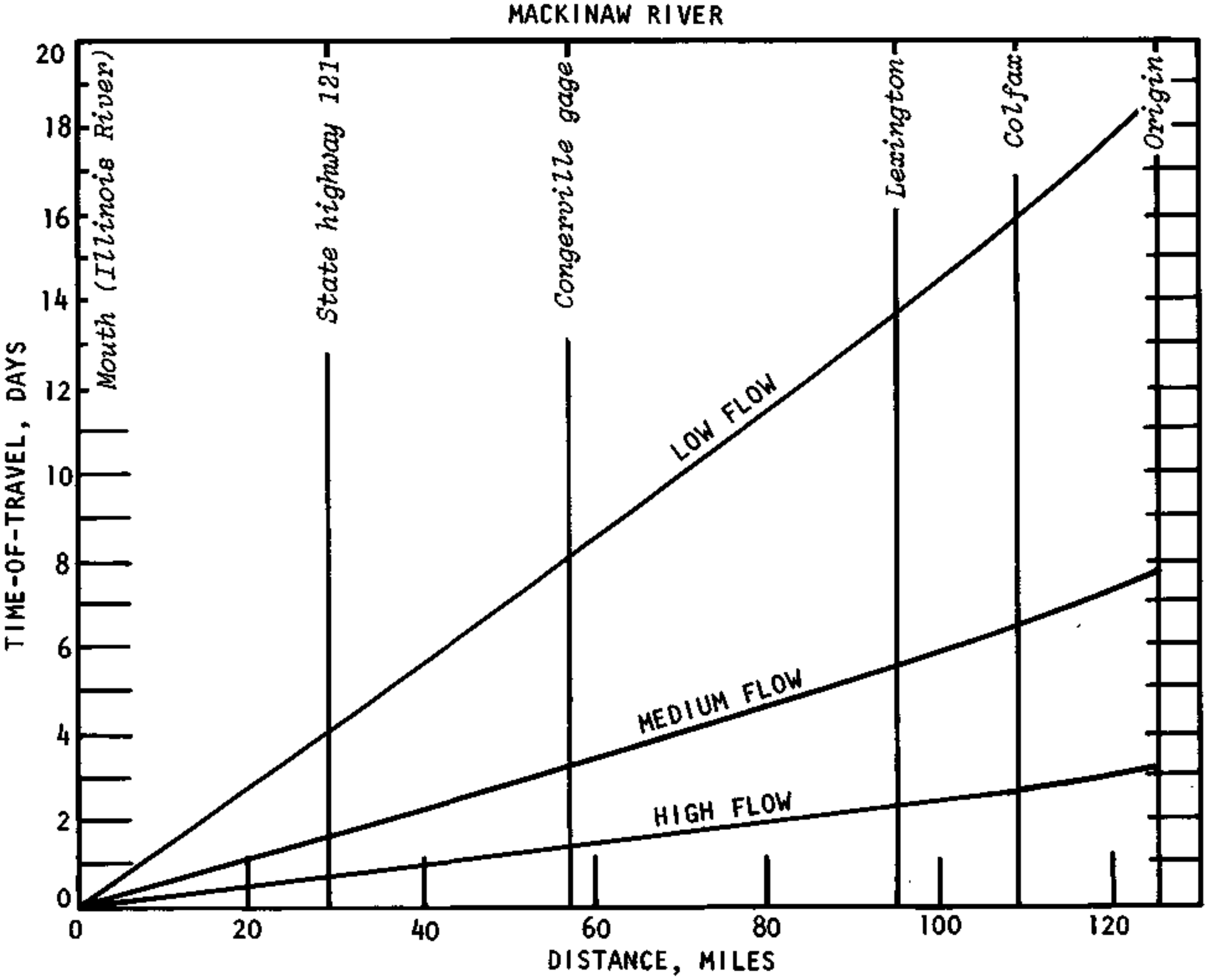


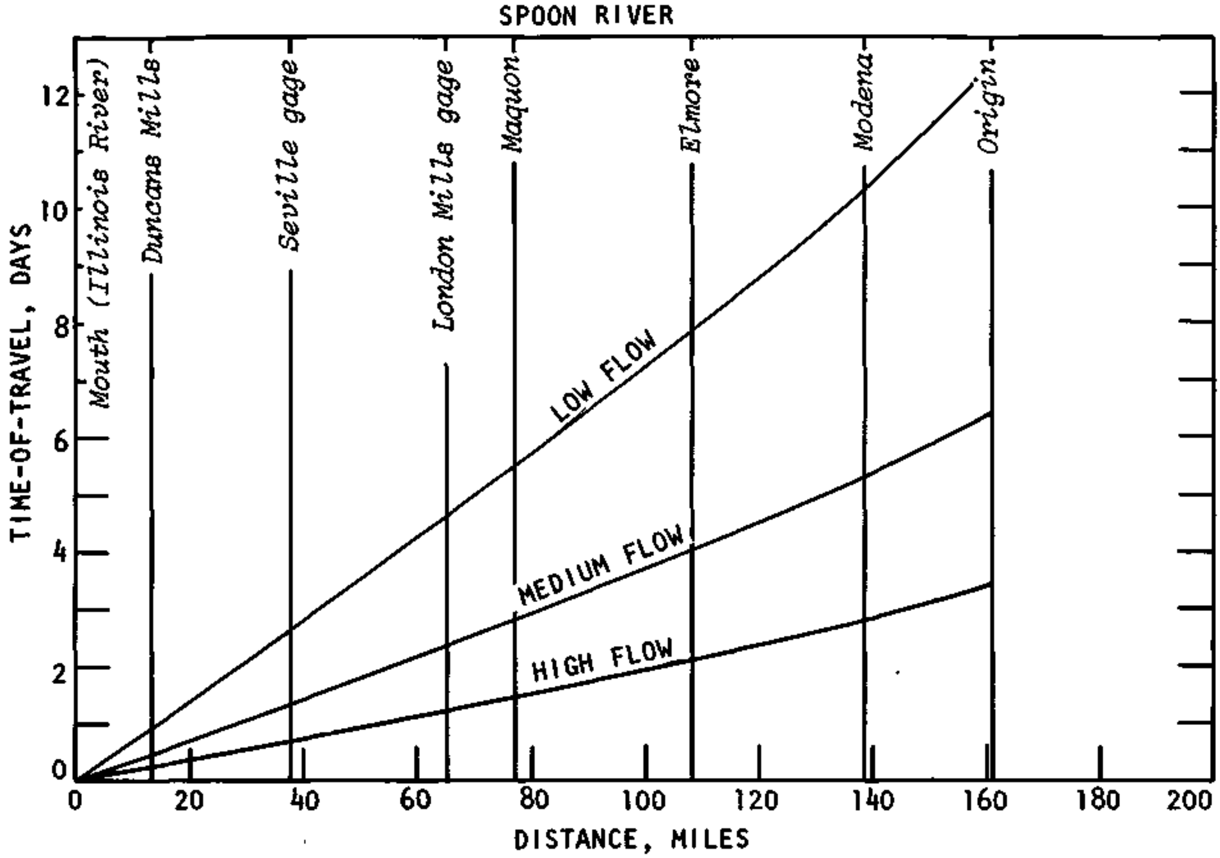

ILLINOIS RIVER, MORRIS TO PEORIA

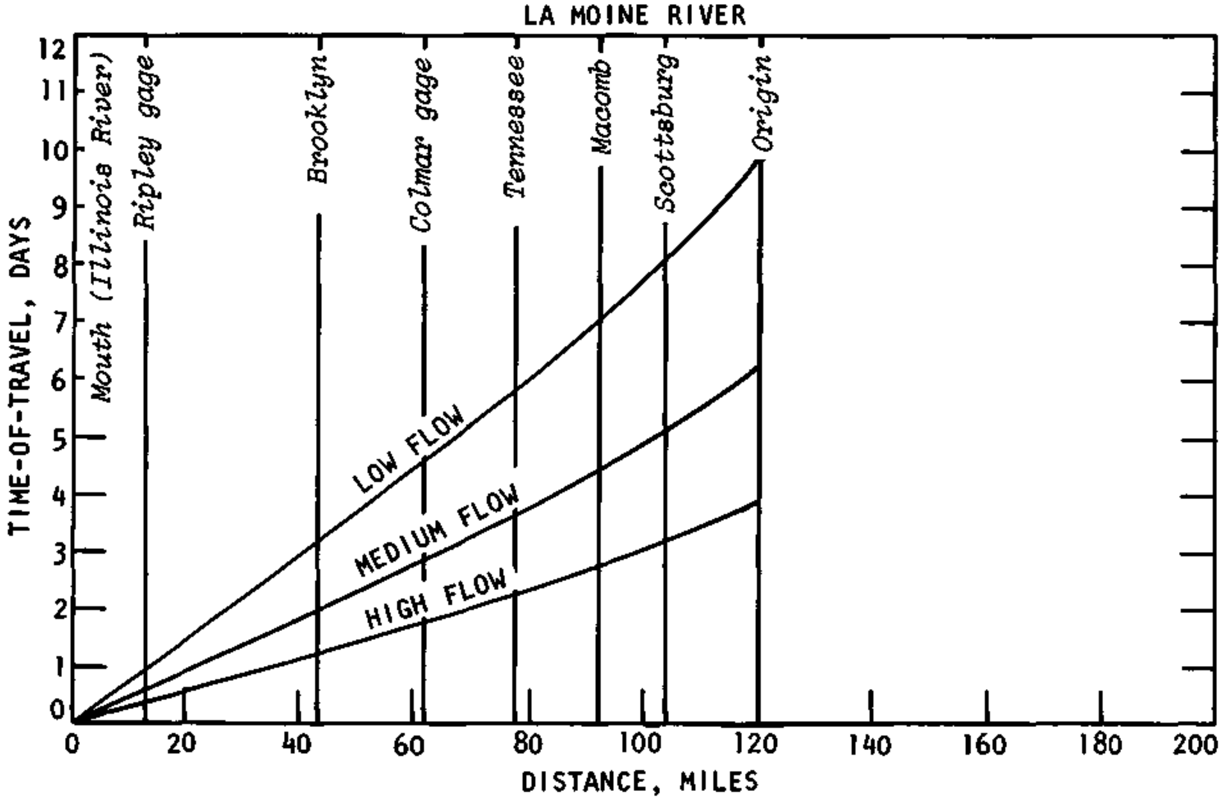
Ranges from 1 day at low flow to less than half of a day at high flow


ILLINOIS RIVER, PEORIA TO MOUTH

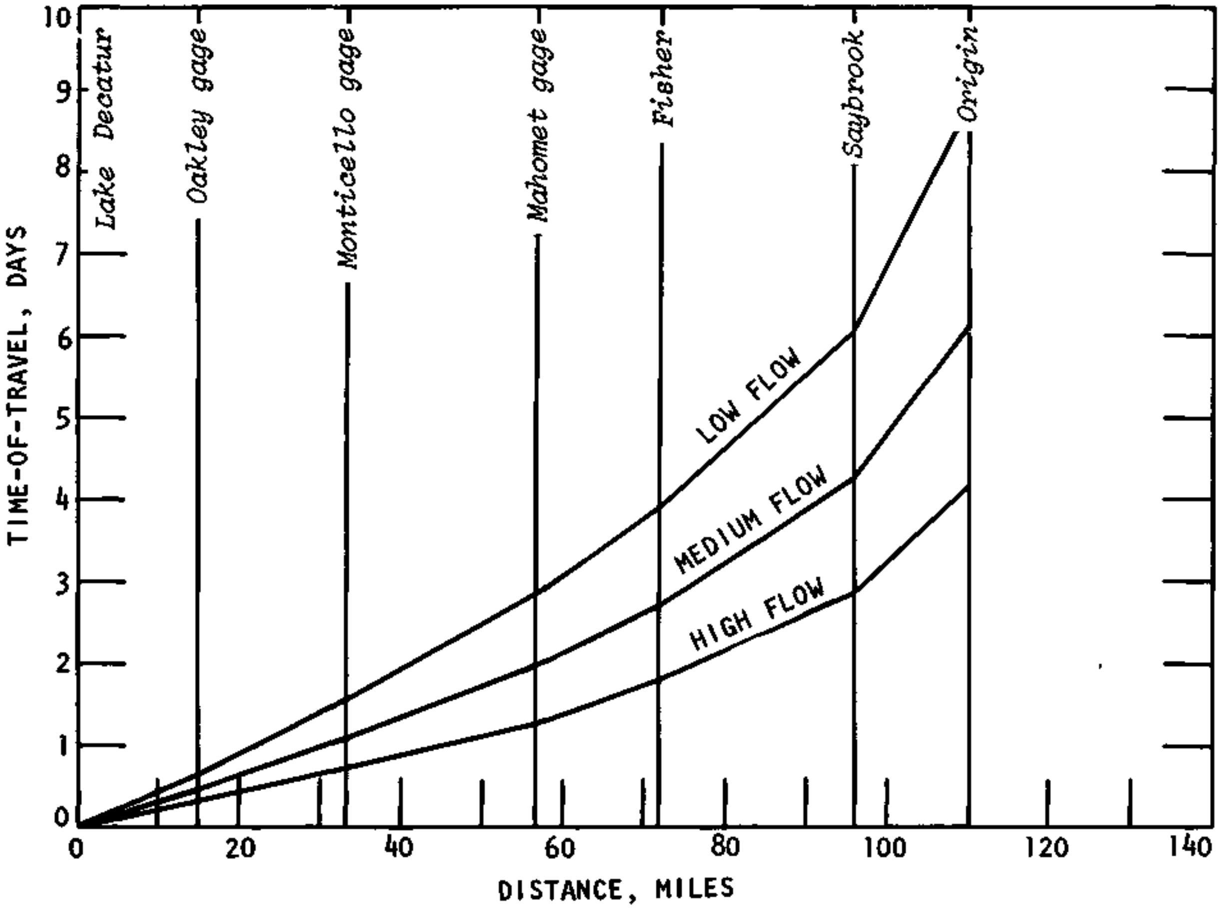

VERMILION RIVER (ILLINOIS RIVER BASIN)


MACKINAW RIVER

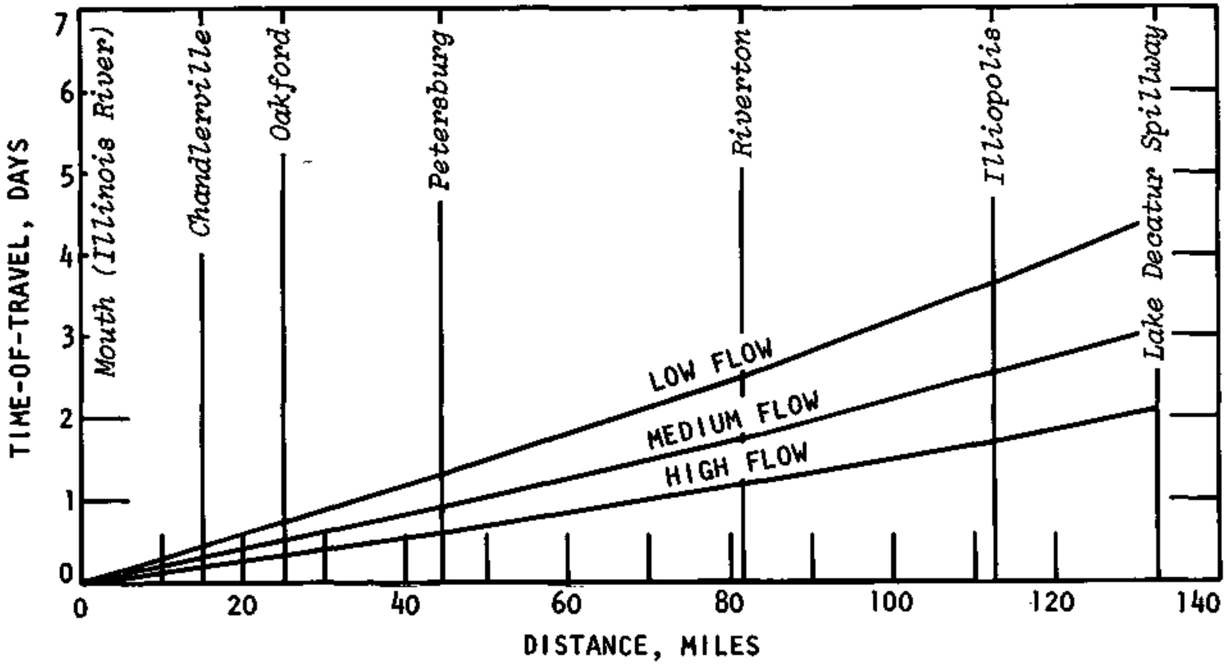

SPOON RIVER
TIME-OF-TRAVEL, DAYS
DISTANCE, MILES
Mouth (Illinois River)
Duncans Mills
Seville gage
London Mills gage
Maquon
Elmore
Modena
Origin
LOW FLOW
MEDIUM FLOW
HIGH FLOW
0
2
4
6
8
10
12
0
20
40
60
80
100
120
140
160
180
200

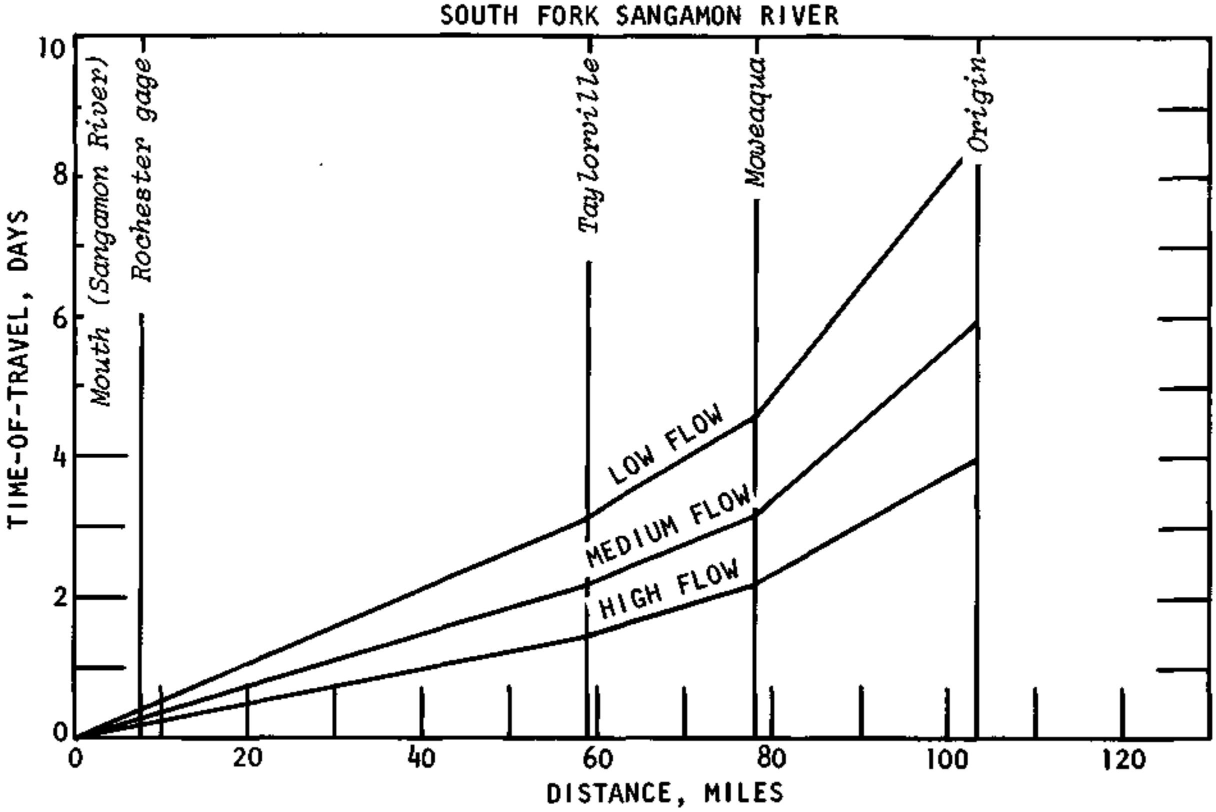

LA MOINE RIVER
TIME-OF-TRAVEL, DAYS
DISTANCE, MILES
Mouth (Illinois River)
Ripley gage
Brooklyn
Colmar gage
Tennessee
Macomb
Scottsburg
Origin
LOW FLOW
MEDIUM FLOW
HIGH FLOW
0
1
2
3
4
5
6
7
8
9
10
11
12
0
20
40
60
80
100
120
140
160
180
200

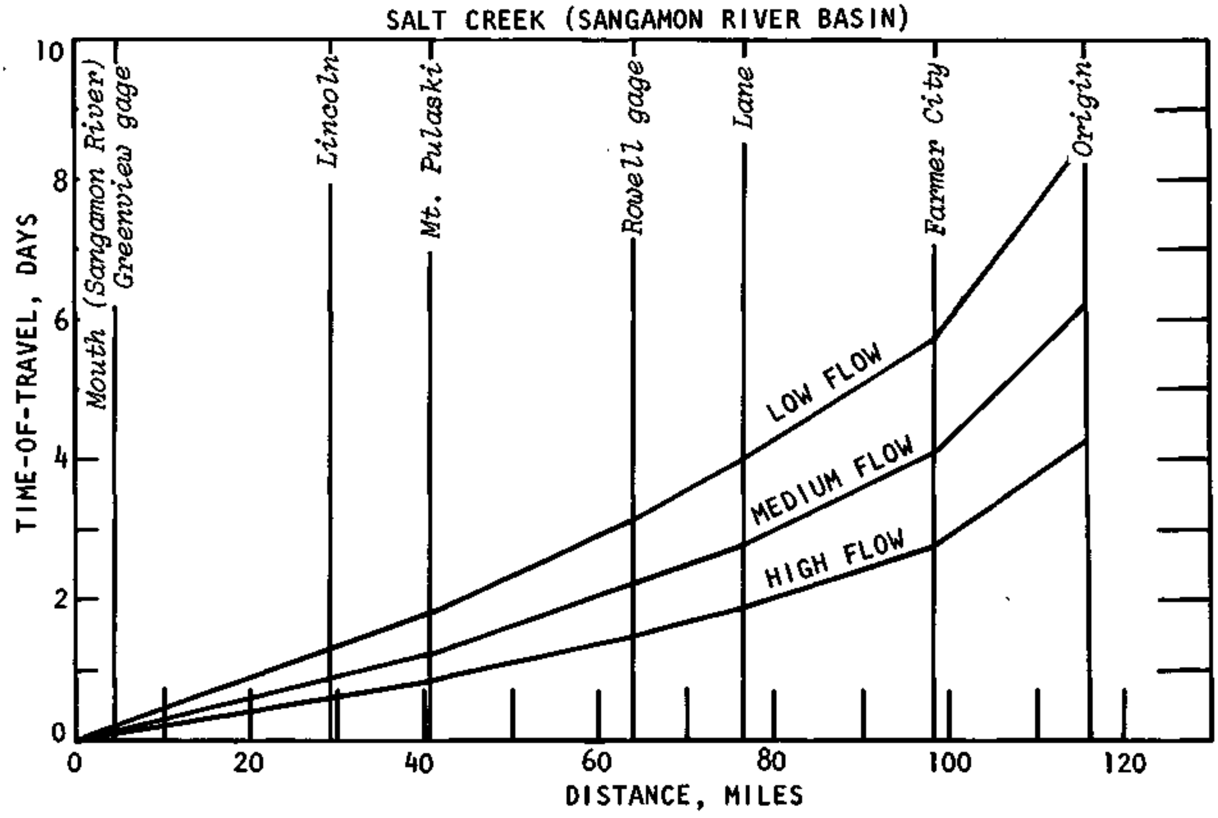
SANGAMON RIVER, ORIGIN TO LAKE DECATUR

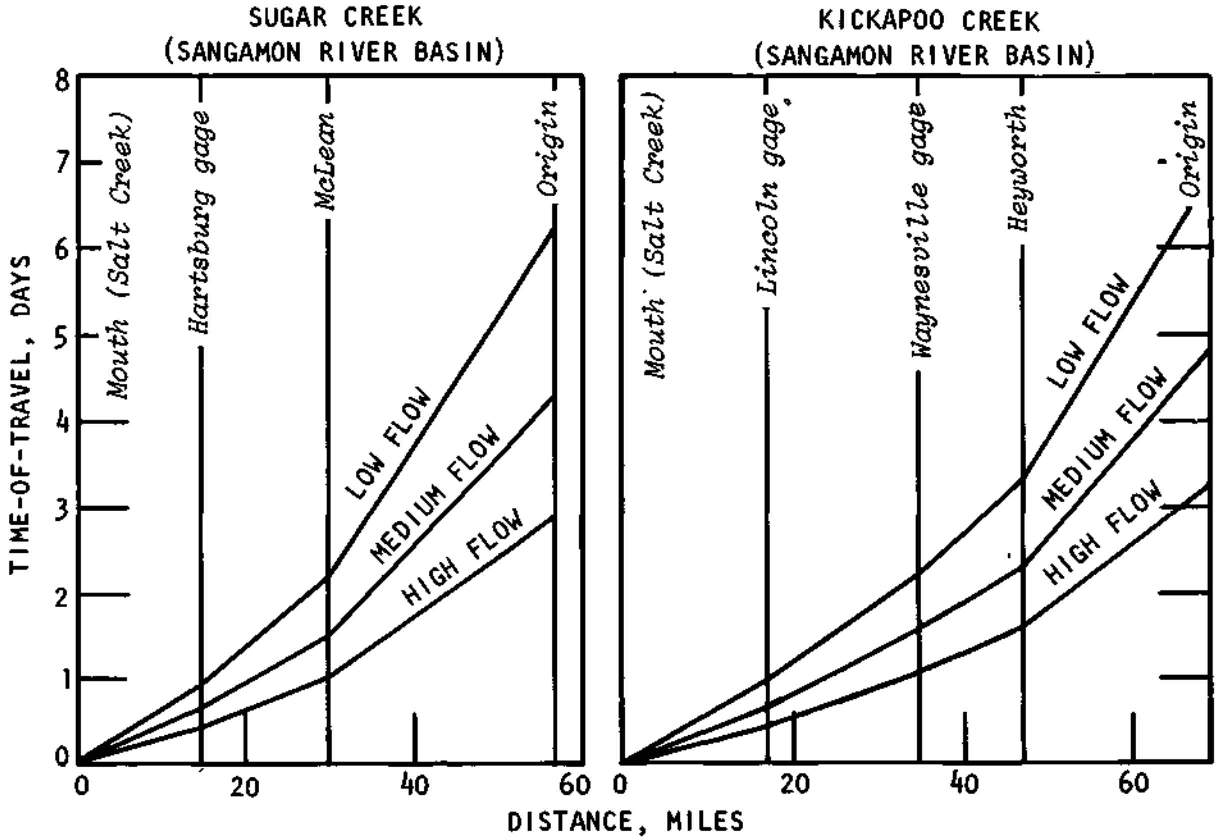


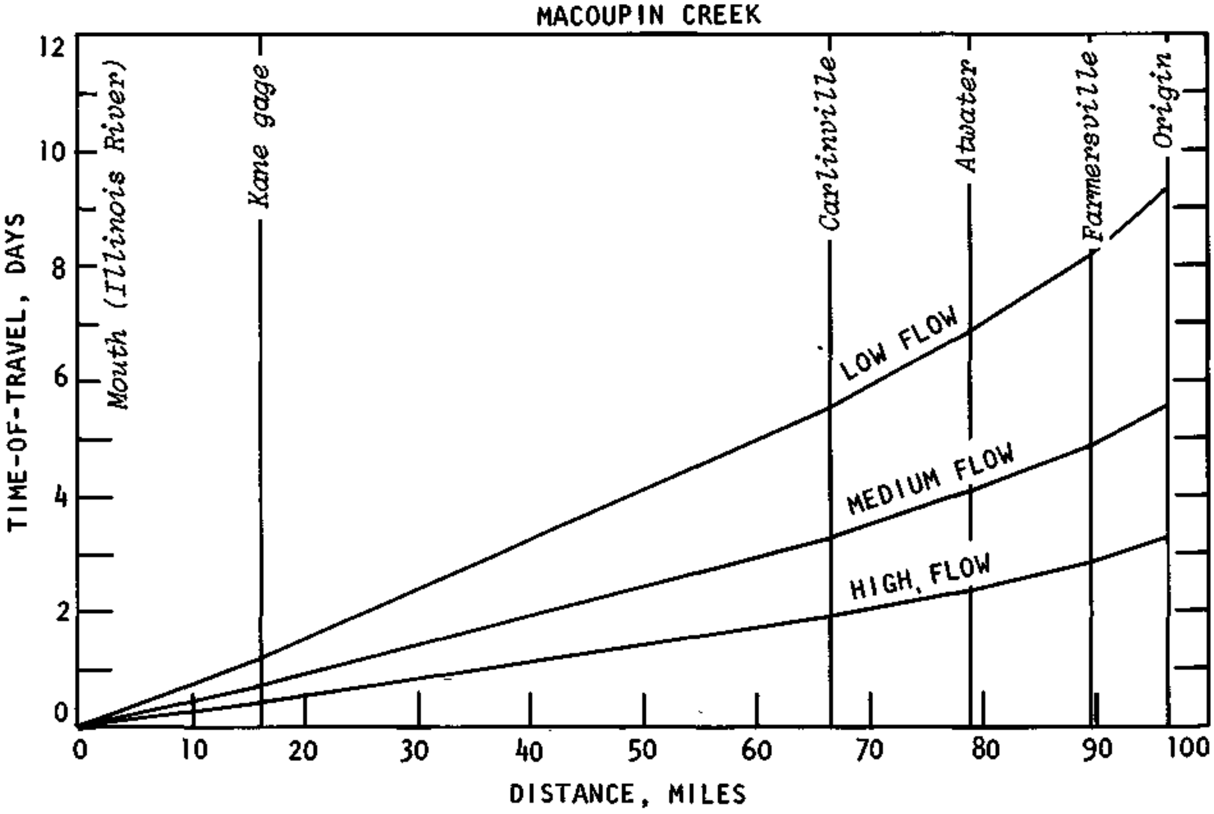
SANGAMON RIVER, LAKE DECATUR TO MOUTH

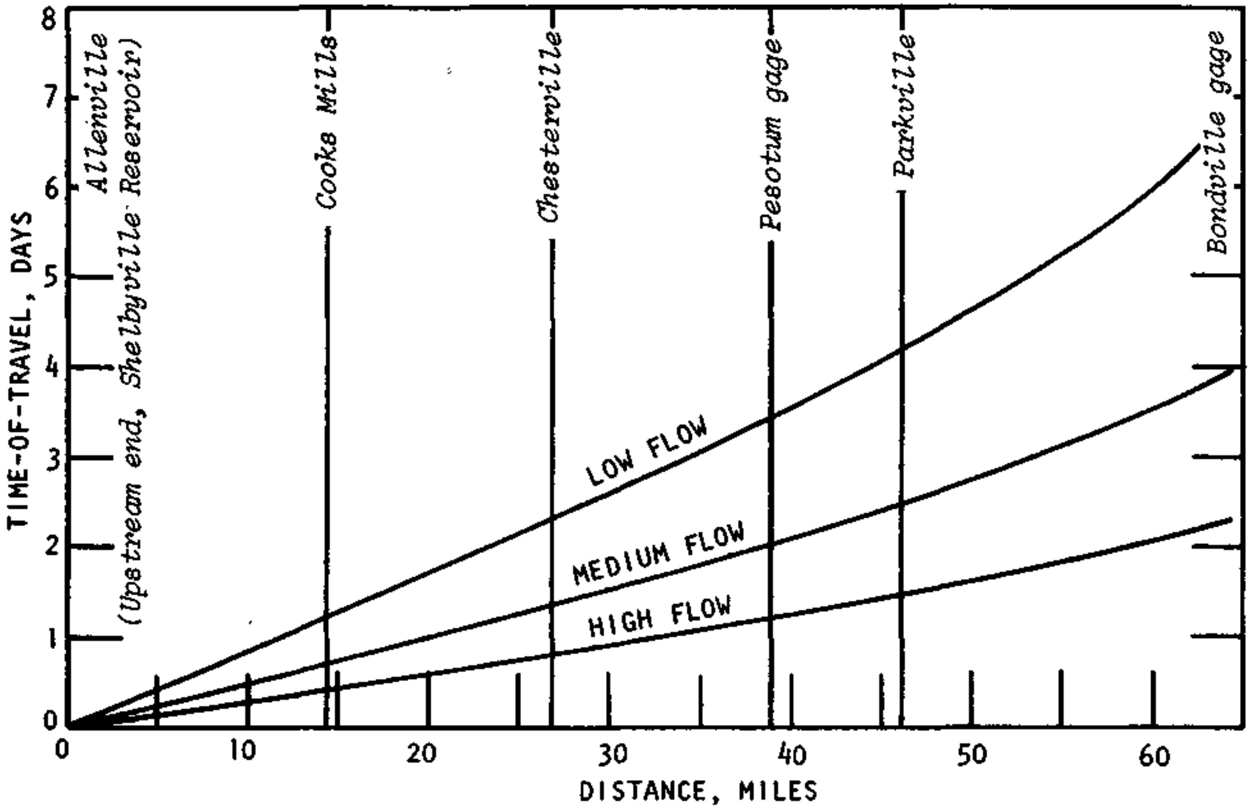


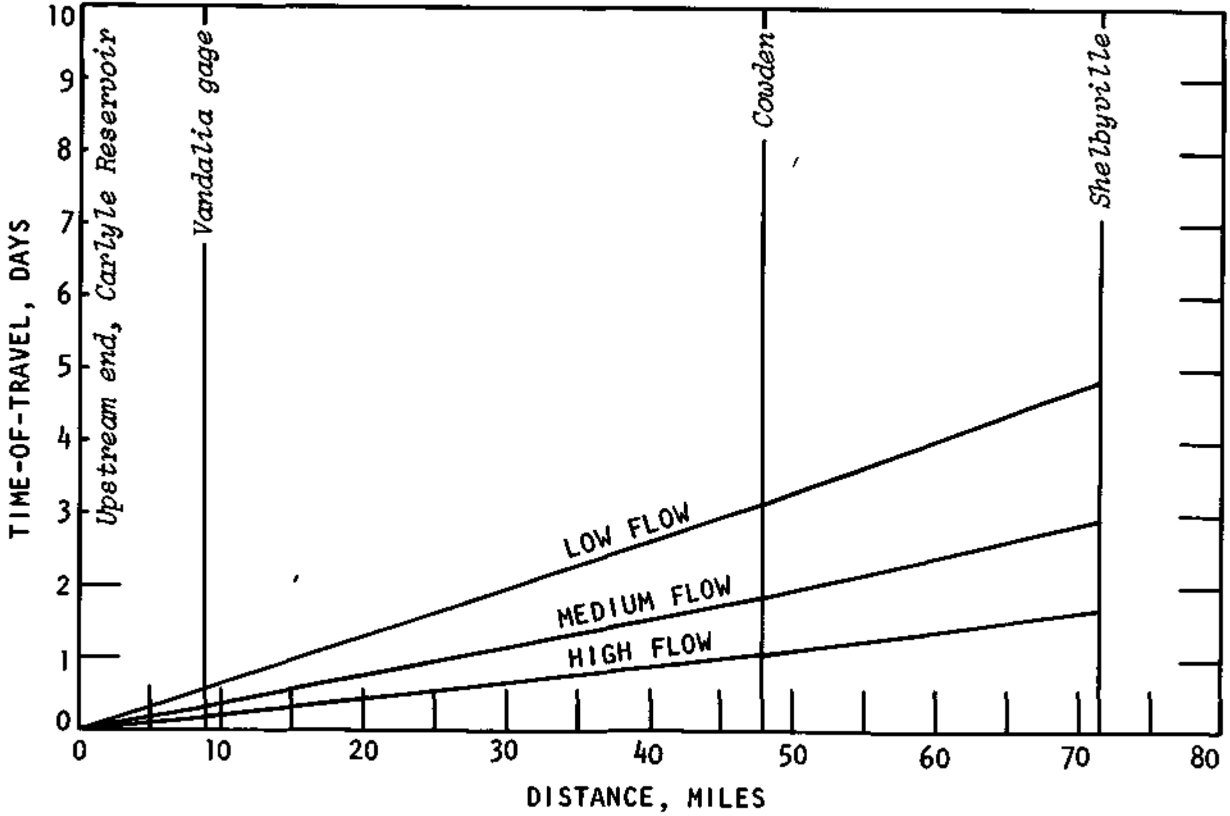

SOUTH FORK SANGAMON RIVER
TIME-OF-TRAVEL, DAYS
DISTANCE, MILES
0
2
4
6
8
10
0
20
40
60
80
100
120
Mouth (Sangamon River)
Rochester gage
Taylorville
Moweaqua
Origin
LOW FLOW
MEDIUM FLOW
HIGH FLOW

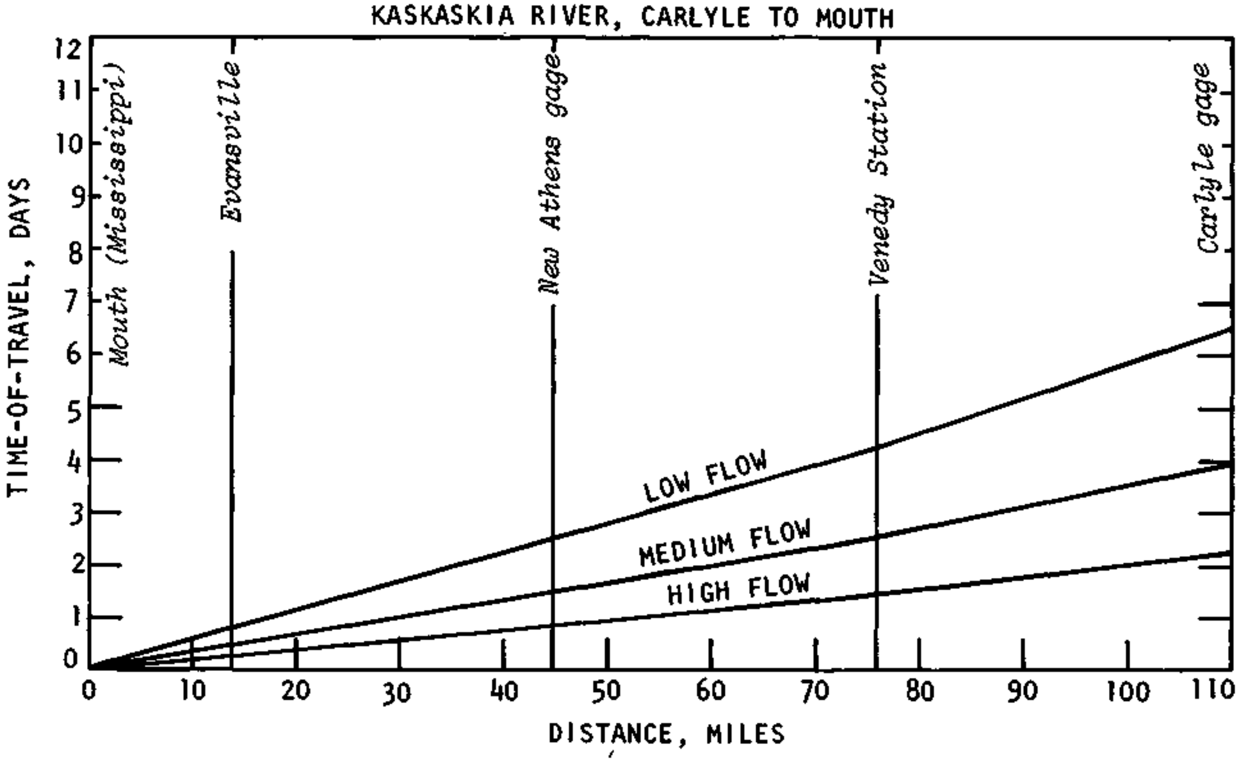

SALT CREEK (SANGAMON RIVER BASIN)
TIME-OF-TRAVEL, DAYS
DISTANCE, MILES
0
2
4
6
8
10
0
20
40
60
80
100
120
Mouth (Sangamon River)
Greenview gage
Lincoln
Mt. Pulaski
Rowell gage
Lane
Farmer City
Origin
LOW FLOW
MEDIUM FLOW
HIGH FLOW

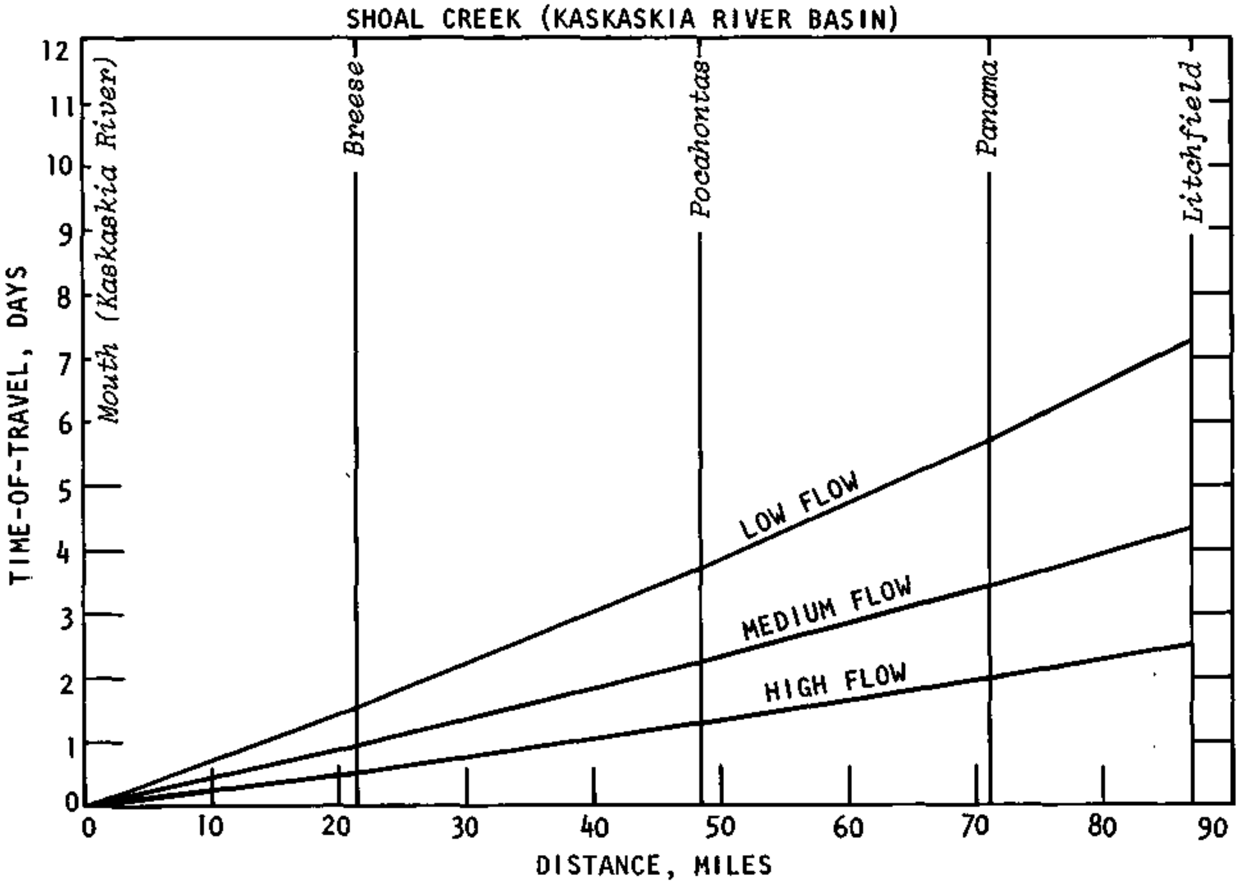

SUGAR CREEK
(SANGAMON RIVER BASIN)
KICKAPOO CREEK
(SANGAMON RIVER BASIN)
TIME-OF-TRAVEL, DAYS
0
1
2
3
4
5
6
7
8
Mouth (Salt Creek)
Hartsburg gage
McLean
Origin
LOW FLOW
MEDIUM FLOW
HIGH FLOW
Mouth (Salt Creek)
Lincoln gage
Waynesville gage
Heyworth
Origin
LOW FLOW
MEDIUM FLOW
HIGH FLOW
0
20
40
60
0
20
40
60
DISTANCE, MILES

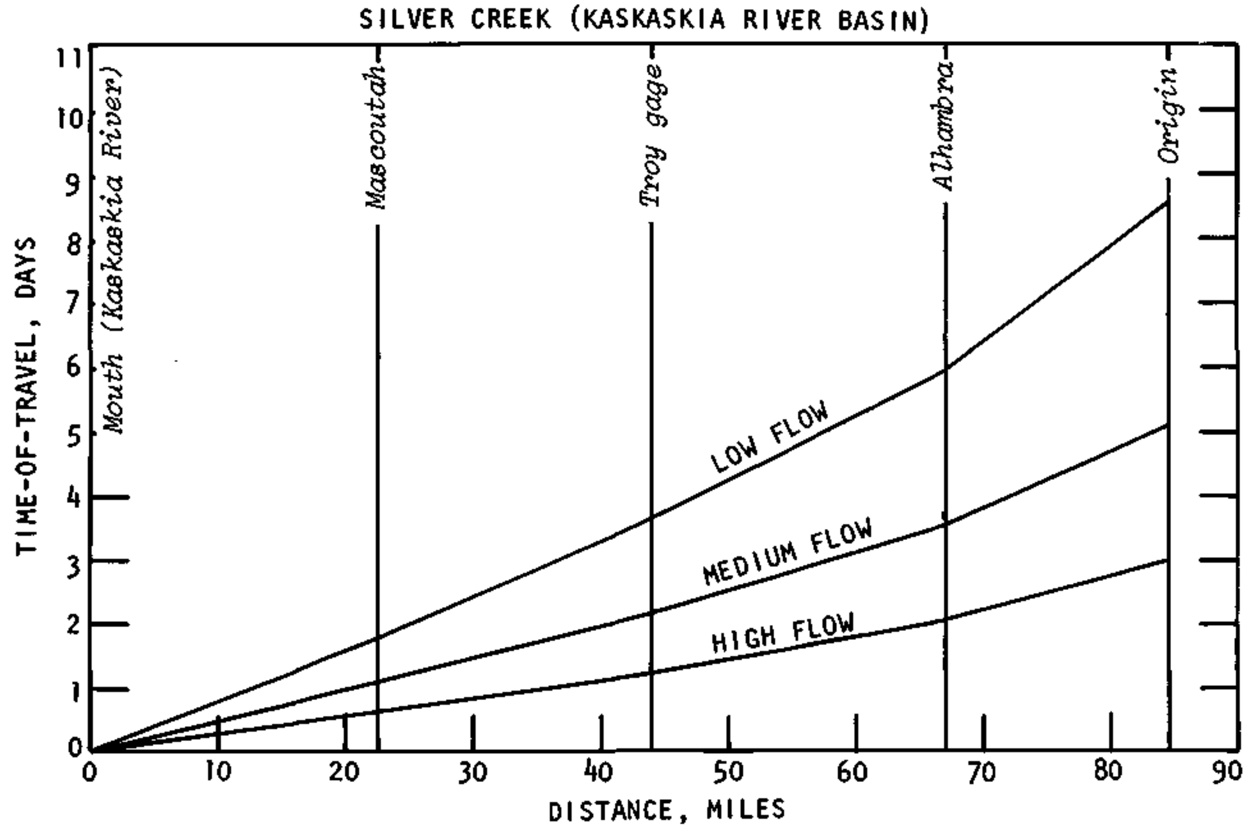

MACOUPIN CREEK
TIME-OF-TRAVEL, DAYS
0
2
4
6
8
10
12
Mouth (Illinois River)
Kane gage
Carlinville
Atwater
Farmersville
Origin
LOW FLOW
MEDIUM FLOW
HIGH FLOW
0
10
20
30
40
50
60
70
80
90
100
DISTANCE, MILES


KASKASKIA RIVER, ORIGIN TO SHELBYVILLE RESERVOIR

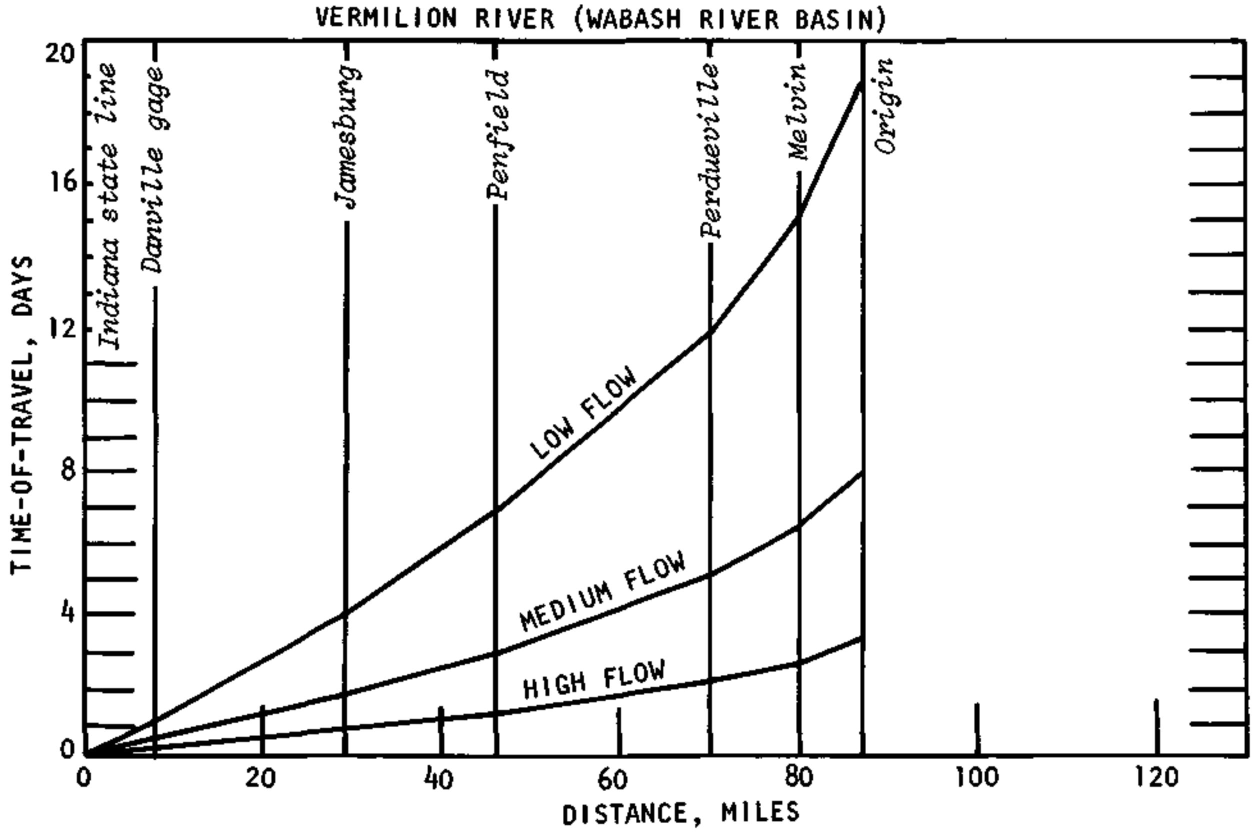

KASKASKIA RIVER, SHELBYVILLE TO CARLYLE RESERVOIR


KASKASKIA RIVER, CARLYLE TO MOUTH
TIME-OF-TRAVEL, DAYS
DISTANCE, MILES
Mouth (Mississippi)
Evansville
New Athens gage
Venedy Station
Carlyle gage
LOW FLOW
MEDIUM FLOW
HIGH FLOW
0
1
2
3
4
5
6
7
8
9
10
11
12
0
10
20
30
40
50
60
70
80
90
100
110


SHOAL CREEK (KASKASKIA RIVER BASIN)
TIME-OF-TRAVEL, DAYS
DISTANCE, MILES
Mouth (Kaskaskia River)
Breese
Pocahontas
Panama
Litchfield
LOW FLOW
MEDIUM FLOW
HIGH FLOW
0
1
2
3
4
5
6
7
8
9
10
11
12
0
10
20
30
40
50
60
70
80
90

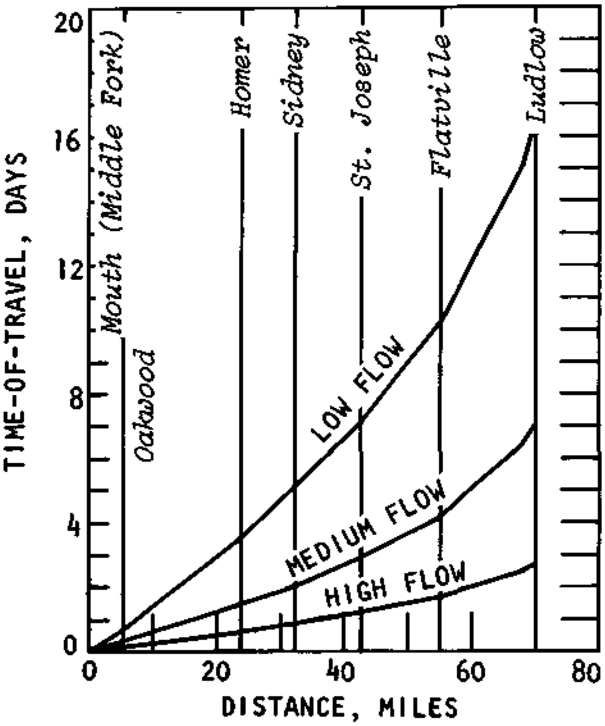


SILVER CREEK (KASKASKIA RIVER BASIN)

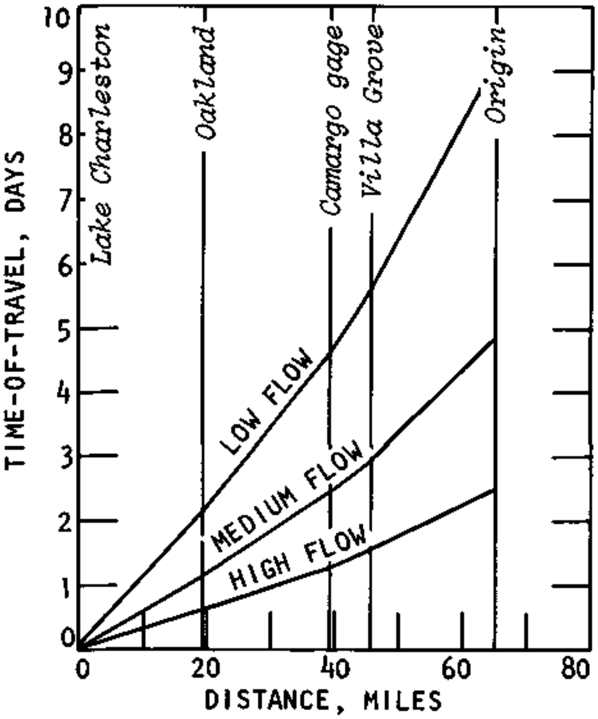


VERMILION RIVER (WABASH RIVER BASIN)

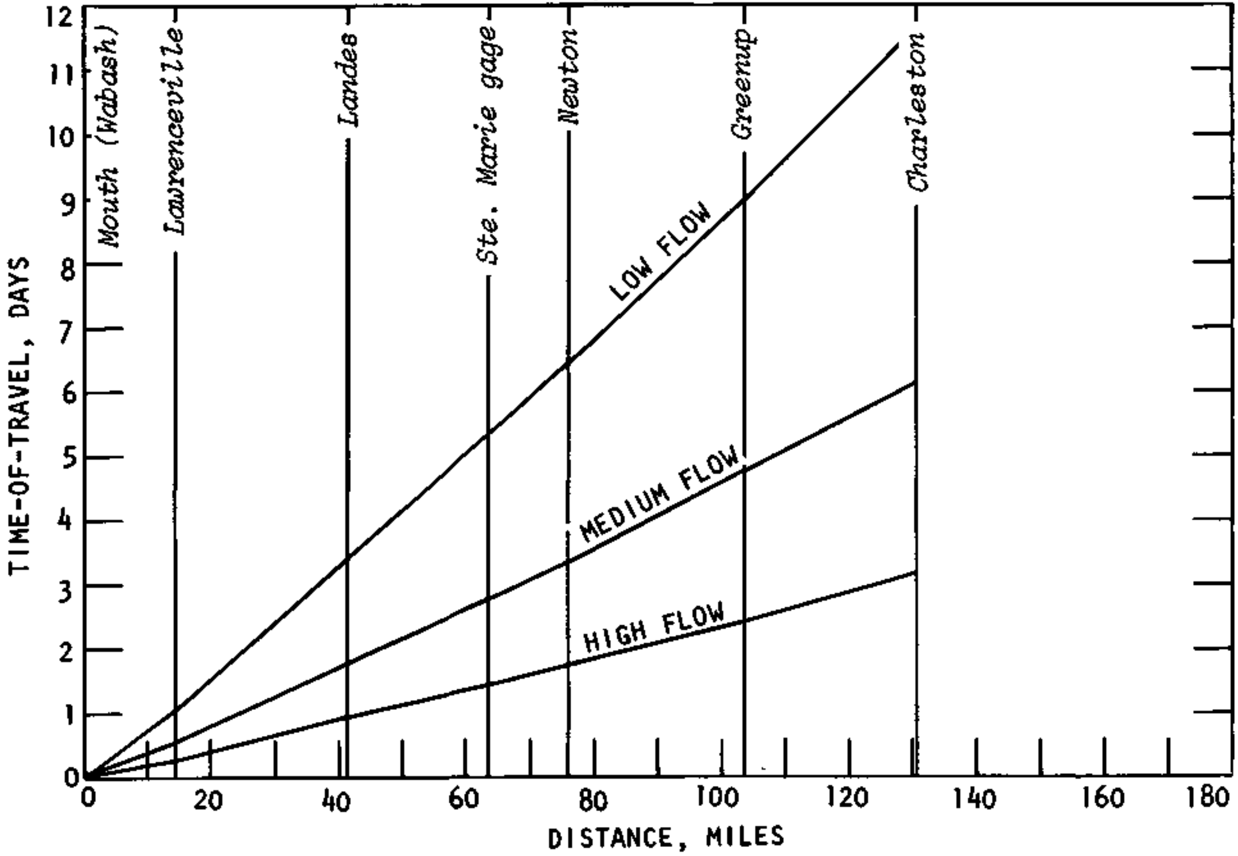
SALT FORK, VERMILION RIVER
(WABASH RIVER BASIN)

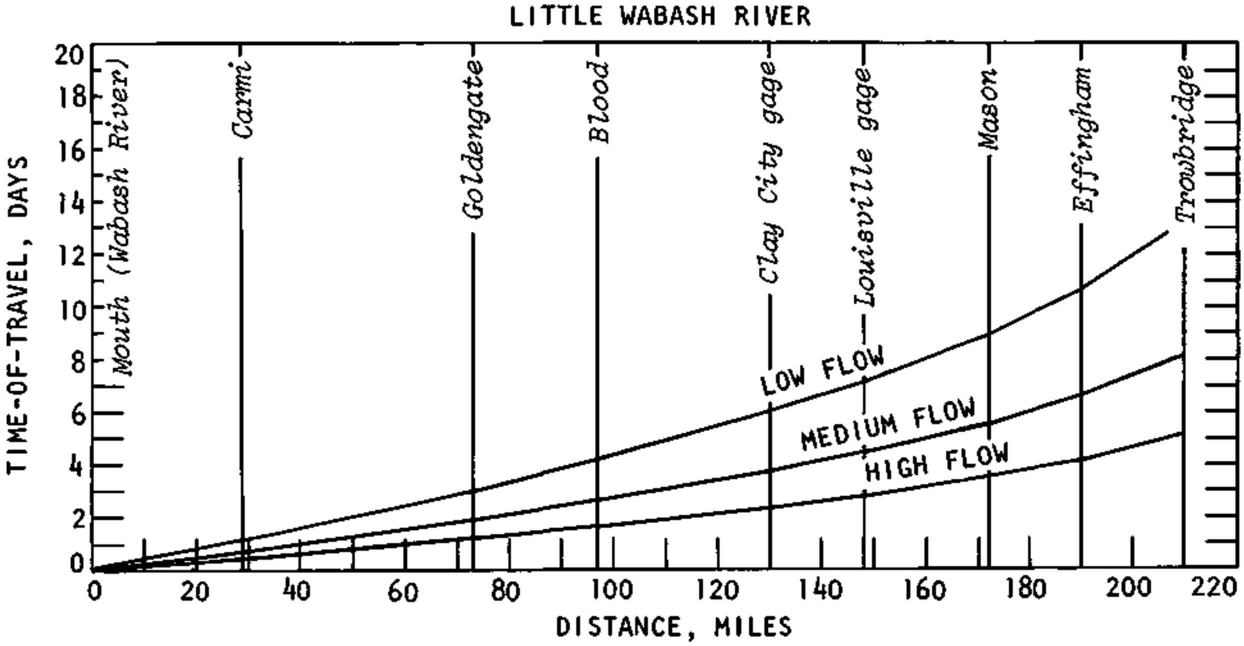


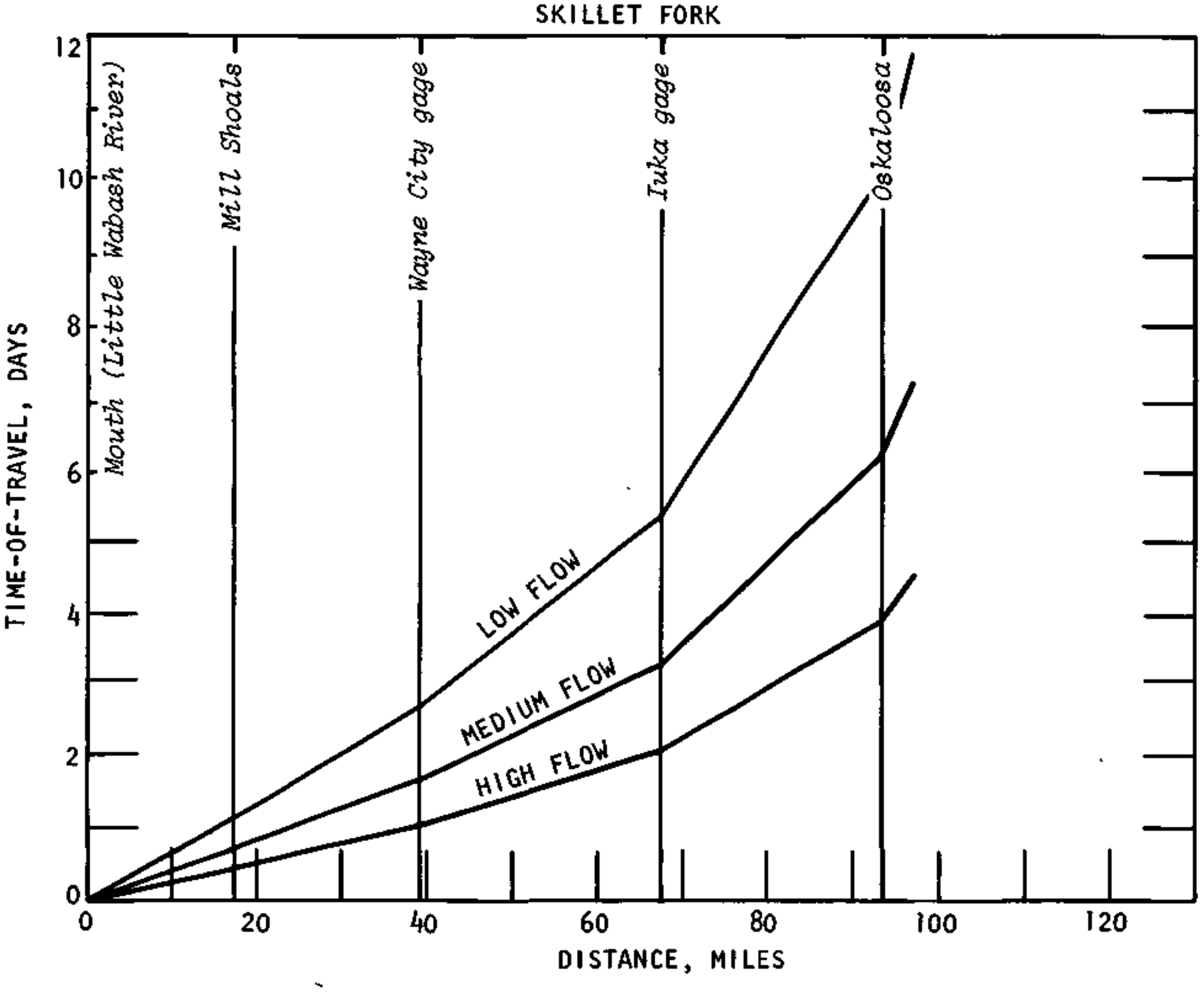
EMBARRAS RIVER,
ORIGIN TO LAKE CHARLESTON

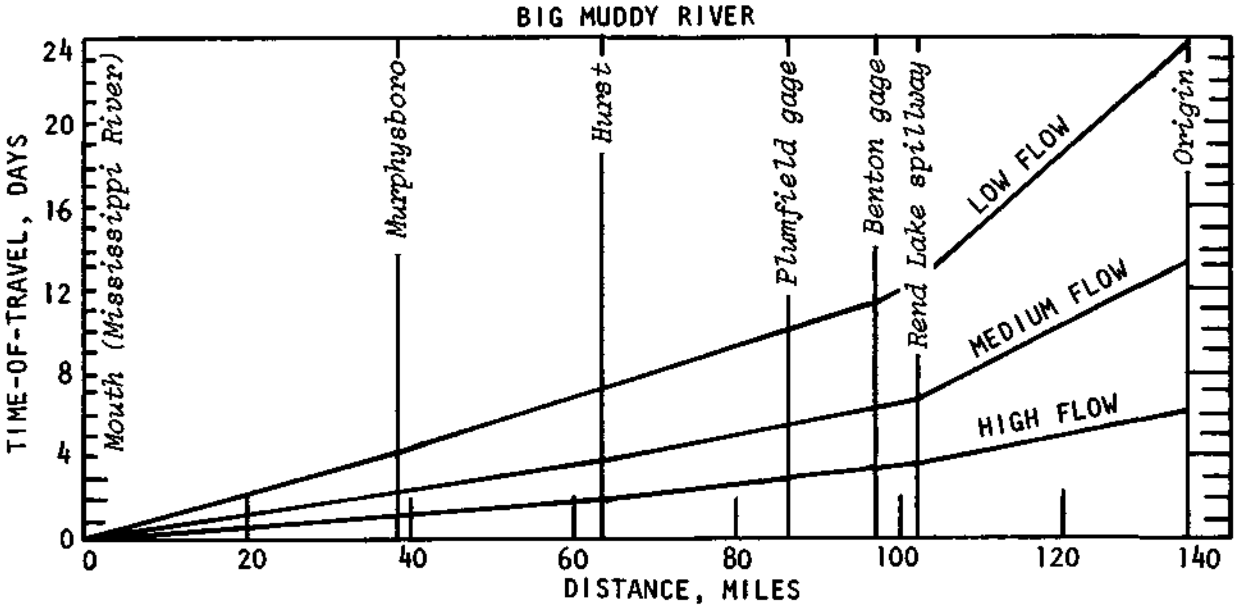


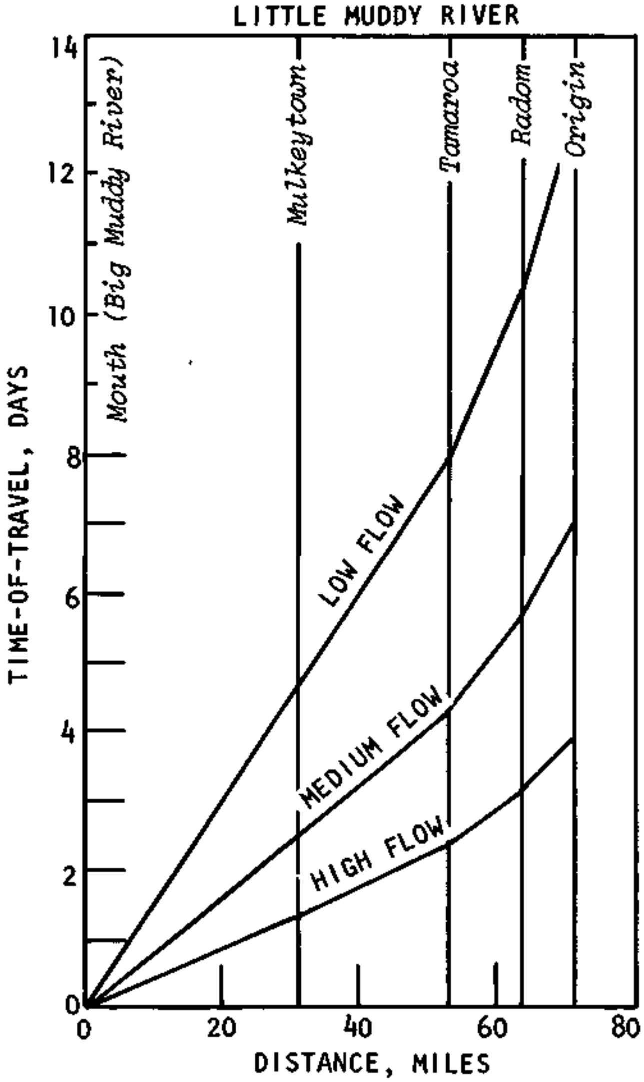
EMBARRAS RIVER, CHARLESTON TO MOUTH

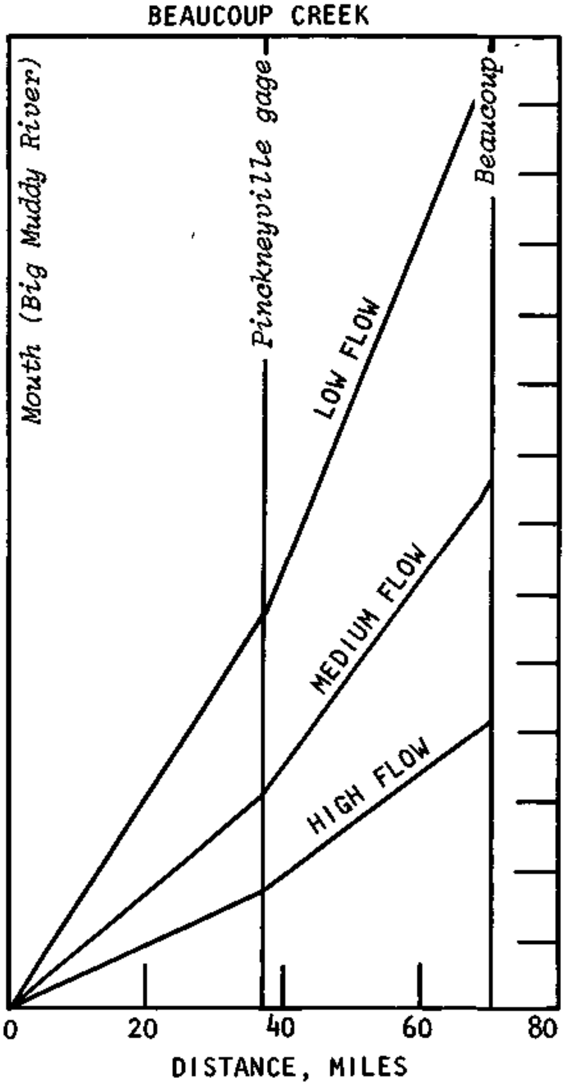


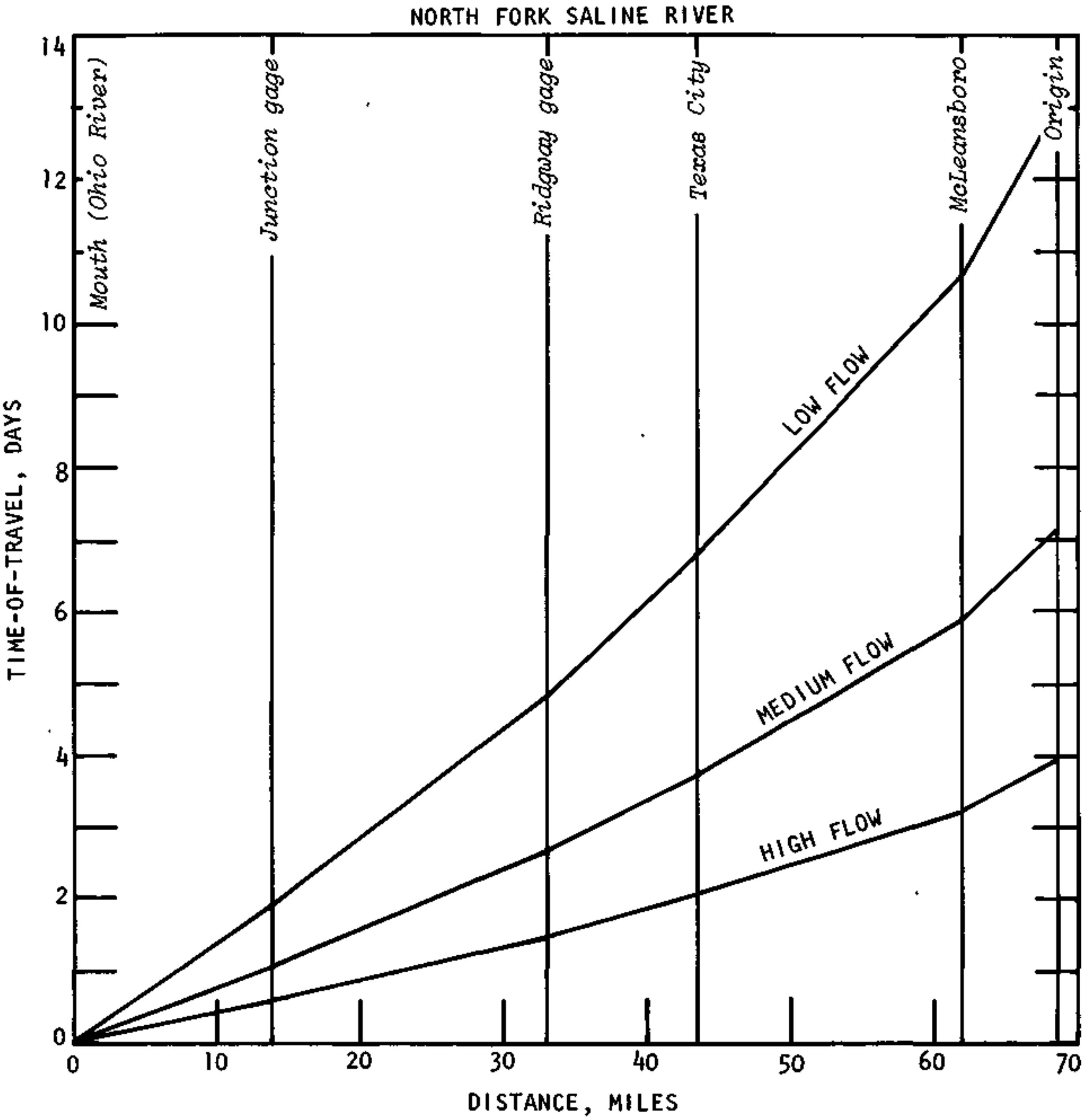

LITTLE WABASH RIVER
TIME-OF-TRAVEL, DAYS
DISTANCE, MILES
0
2
4
6
8
10
12
14
16
18
20
0
20
40
60
80
100
120
140
160
180
200
220
Mouth (Wabash River)
Carmi
Goldengate
Blood
Clay City gage
Louisville gage
Mason
Effingham
Trowbridge
LOW FLOW
MEDIUM FLOW
HIGH FLOW


SKILLET FORK
TIME-OF-TRAVEL, DAYS
DISTANCE, MILES
0
2
4
6
8
10
12
0
20
40
60
80
100
120
Mouth (Little Wabash River)
Mill Shoals
Wayne City gage
Iuka gage
Oskaloosa
LOW FLOW
MEDIUM FLOW
HIGH FLOW

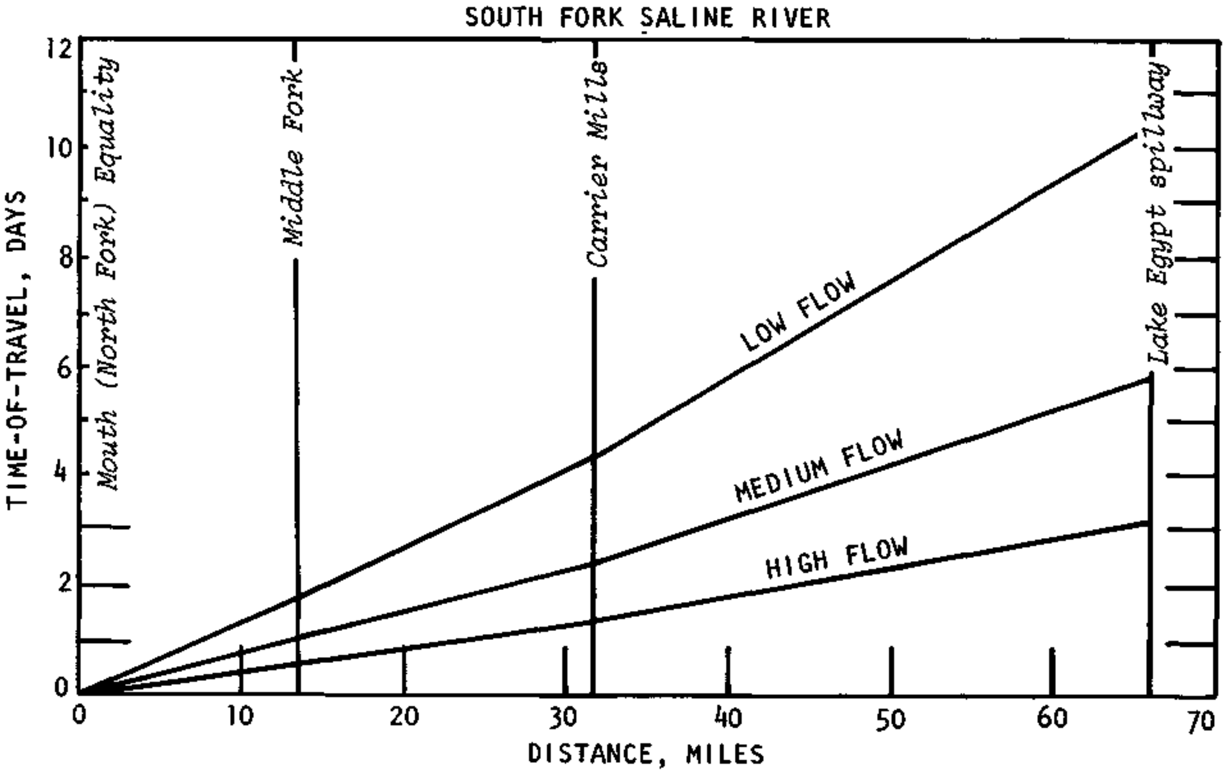

BIG MUDDY RIVER
TIME-OF-TRAVEL, DAYS
0
4
8
12
16
20
24
Mouth (Mississippi River)
Murphysboro
Hurst
Plumfield gage
Benton gage
Rend Lake spillway
Origin
LOW FLOW
MEDIUM FLOW
HIGH FLOW
0
20
40
60
80
100
120
140
DISTANCE, MILES

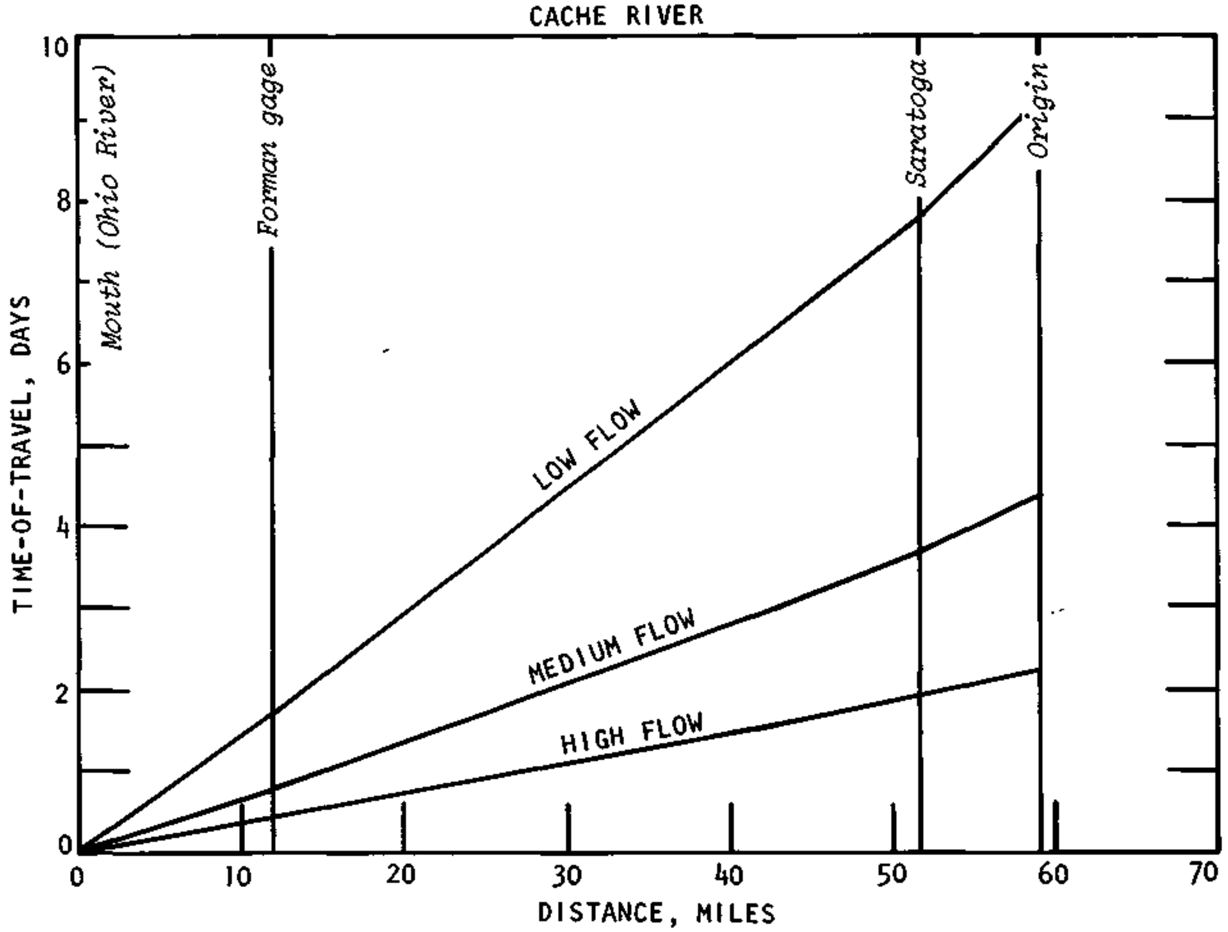

LITTLE MUDDY RIVER
TIME-OF-TRAVEL, DAYS
0
2
4
6
8
10
12
14
Mouth (Big Muddy River)
Mulkeytown
Tamaroa
Radom
Origin
LOW FLOW
MEDIUM FLOW
HIGH FLOW
0
20
40
60
80
DISTANCE, MILES


BEAUCOUP CREEK
Mouth (Big Muddy River)
Pinckneyville gage
Beaucoup
LOW FLOW
MEDIUM FLOW
HIGH FLOW
0
20
40
60
80
DISTANCE, MILES



NORTH FORK SALINE RIVER
TIME-OF-TRAVEL, DAYS
DISTANCE, MILES
0
2
4
6
8
10
12
14
0
10
20
30
40
50
60
70
Mouth (Ohio River)
Junction gage
Ridgway gage
Texas City
McLeansboro
Origin
LOW FLOW
MEDIUM FLOW
HIGH FLOW


SOUTH FORK SALINE RIVER
TIME-OF-TRAVEL, DAYS
DISTANCE, MILES
0
2
4
6
8
10
12
0
10
20
30
40
50
60
70
Mouth (North Fork) Equality
Middle Fork
Carrier Mills
Lake Egypt spillway
LOW FLOW
MEDIUM FLOW
HIGH FLOW


CACHE RIVER
TIME-OF-TRAVEL, DAYS
DISTANCE, MILES
0
2
4
6
8
10
0
10
20
30
40
50
60
70
Mouth (Ohio River)
Forman gage
Saratoga
Origin
LOW FLOW
MEDIUM FLOW
HIGH FLOW