PREPARED IN COOPERATION WITH
FEDERAL, STATE, AND MUNICIPAL AGENCIES



# TRAVEL OF SOLUTES IN LOWER MISSOURI RIVER

## INTRODUCTION

The Missouri River has been transformed in recent years from an uncontrolled floodway to a regulated and highly complex artery that serves the people of its basin in many ways. The river and the reservoirs constructed on it provide water for municipal and industrial supplies, sewage disposal, power generation, navigation, irrigation, recreation, and some commercial fishing. This stream is one of the country's great natural resources and, as any resource, must be understood if it is to be managed efficiently.

Little is known about how fast water and water-borne contaminants move from one location in the river to another; even less is known about how these contaminants disperse and become diluted. On occasions large amounts of sewage have seriously interfered with treatment processes of downstream users. Also, chemicals spilled accidentally into the river or its tributaries have at times seriously degraded the quality of the water for use. To protect the downstream user, reliable predictions must be made of the arrival time, concentration, average rate of movement, and passage time of contaminants in the stream. These predictions can be made from the results of this dye-tracer study.

This study was confined to the 806-mile reach of river from Yankton, S. Dak., to St. Louis, Mo. Meaningful measurements of traveltime cannot be made for much of the river upstream from Yankton because the mainstem reservoirs form an almost continuous chain of lakes from Central Montana to Yankton, S. Dak.

Conditions of the channel differ within the study reach. From Yankton to the vicinity of Ponca State Park, Nebr., the channel is in its natural, braided condition. From the vicinity of the park to Sioux City, Iowa, some bank stabilization structures have been installed. From Sioux City downstream, extensive levees, revetments, and jetties have been constructed, and much channel alinement and dredging has been done by the U.S. Army Corps of Engineers to maintain an adequate navigational channel and to provide protection from floods.

Flow in the river is regulated by releases of water from Lewis and Clark Lake near Yankton, S. Dak., and from reservoirs on some of the principal tributaries. The river flow is fairly uniform for long periods, but heavy precipitation in tributary basins without large reservoirs or in parts of the basins downstream from the reservoirs still cause the river to flood. During the ice-free period of the year sufficient water to provide adequate depth for barge traffic is released from the reservoirs. During the ice period the amount of water release is decreased to the amounts needed for water supplies for about 2 1/2 million people who depend upon the river for water.

Many Federal, State, and Municipal agencies cooperated in this study by providing financial assistance and manpower. The Federal agencies were the Iowa, Kansas, Missouri, Nebraska, and South Dakota districts of the Water Resources Division of the U.S. Geological Survey; the Omaha and Kansas City districts of the U.S. Army Corps of Engineers; the Missouri Basin Regional office of the Federal Water Pollution Control Administration; and the U.S. Weather Bureau. The State and Municipal agencies were:

Iowa Natural Resources Council
Iowa Department of Health
Iowa State Conservation Commission
Iowa Geological Survey
Council Bluffs, Iowa Water Department
Kansas State Department of Health
Missouri Water Resources Board
Missouri Division of Geological Survey and Water Resources
Missouri Water Pollution Board
Missouri Conservation Commission
Nebraska Game, Forestation and Parks Commission
Nebraska Department of Water Resources
Nebraska Department of Health
Omaha, Nebraska Metropolitan Utilities District
South Dakota Geological Survey
South Dakota Water Resources Commission

Coordination for this study was provided by Anthony Homyk, district chief, Water Resources Division, U.S. Geological Survey, Rolla, Mo., and his counterpart in other States.

## METHOD OF STUDY

The dye-tracing technique is a widely accepted method of measuring time of travel of solutes in streams. Refined methods developed principally in this study (written communication, F. A. Kilpatrick) will show that dye may be used to simulate not only the time of travel of solutes but also dispersion and dilution. The technique involves the addition of a known amount of fluorescent dye which disperses in the water to form a dye cloud. Subsequent downstream measurement of the dye cloud determines the rate of travel, dispersion, and dilution. Concentrations of the dye at the sampling site at various times were determined by testing the samples with a fluorometer.

The dye used in this study was Rhodomine BA, a 40-percent solution by weight in a mixture of water and acetic acid. It had a specific gravity of between 1.00 and 1.03 and, therefore, mixed readily with the stream water into which it was poured. The reddish-pink dye is a good tracer because it is (1) water soluble, (2) easily detected, (3) harmless in low concentrations, (4) relatively cheap, and (5) reasonably stable in a normal stream environment (written communication, J. R. Wilson, 1966).

Two sets of field measurements were made—the first between October 4-6, 1966, and the second between December 6-8, 1966. Flow during the October measurements was typical of the normal navigation season. Flow during the December measurements was normal for the winter period in the upper half of the study reach but was somewhat greater than normal in the lower half. Although measurements at the normal winter rate of flow in the lower reach would have been preferred, postponement until the flow was normal throughout the reach would have involved the risks of operating boats and equipment with ice in the river.

The study reach was divided into ten subreaches. This division was necessary so that a minimum amount of dye could be used and the dye concentrations in the vicinity of waterplant intakes would be less than 10 ppb (parts per billion), which is the upper limit generally used by the Geological Survey. The dye was injected in a line laterally across the river so that lateral dispersion would take place in a short distance. The injection was made at the upstream end of each subreach, and sampling was done at two or more locations downstream in each subreach, as shown on the map.

## OBSERVATIONS

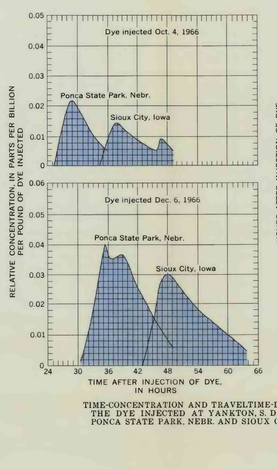
After injection, the dye began to disperse in three directions, vertically, laterally, and longitudinally. Vertical dispersion was accomplished quickly, and because a line injection was used, lateral dispersion was also obtained in a relatively short distance at all injection points. Longitudinal dispersion continued indefinitely; and it is this spread and reduction of the dye cloud along with its rate of movement which provide the most important information. Typically, the dye arrives abruptly with a rapid increase in concentration to that of the peak, and then diminishes gradually into a long trailing edge. The dye cloud takes this shape because the dye is momentarily slowed along the banks before being reflected back into the main flow to form an ever-lengthening "tail." Data in table 1 were computed from the October and December measurements. They indicate the time that lapsed between injection of dye and the detection at the downstream sites of the arrivals of the leading edge, peak concentration, centroid, and trailing edge of the dye mass and the rate at which these components of the dye cloud moved. The dye moved fastest between Omaha and Plattsmouth and slowest between Yankton and Ponca State Park.

Only a fraction of the dye injected was subsequently detected at the downstream sampling sites, and the percentage detected decreased with distance from the injection point. The reason for the losses of dye is not known, but may have been due to adsorption on vegetation (including algae) and suspended sediment in the water, photochemical decay, chemical reactions with substances in the water, dilution to concentration too small to detect, or a combination of these causes. Although losses are not desirable because greater amounts of dye must be used, they do not seriously affect the computations of travel time and rate. However, such losses do prevent accurate assessment of the concentrations of contaminants which might not have the same loss or decay characteristics as the dye. All concentrations shown have been adjusted for dye loss.

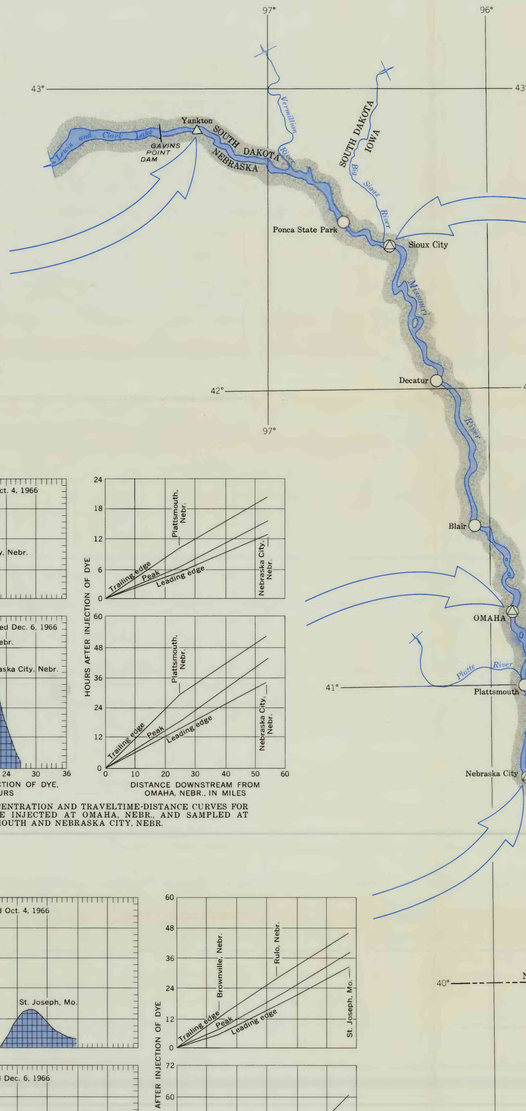
Because the water discharge and the amount of dye used (table 1) differed for each injection site, the concentrations have been converted to the relative concentrations shown in the 10 sets of time-concentration graphs in this report. The graphs show relative concentrations versus time after injection in hours. An average curve was used because the samples taken laterally at 3 to 5 sites in each section indicated good lateral mixing. Arrival times of leading edges, peak concentrations, centroids, and trailing edges are the same whether concentrations used are measured concentrations or relative.

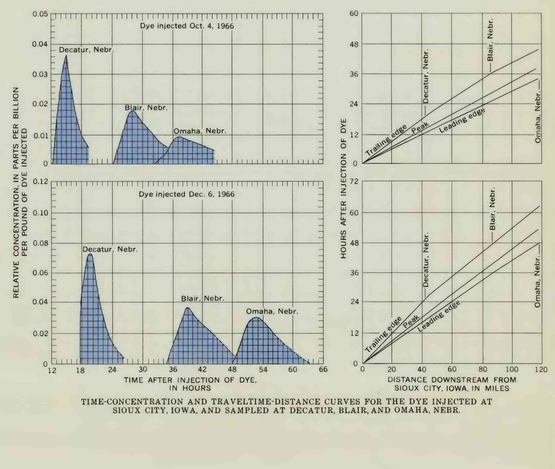
After most of the dye passed the sampling sites, the concentrations decreased at an even slower rate and the time at which the very last dye actually passed could not be determined. For practical purposes all the dye had passed a sampling site as soon as the concentration line of the graph for that site started to become asymptotic to the time line. For most locations this time corresponded approximately to the time when the relative concentration of dye decreased to about 0.005 parts per billion per pound of dye injected. This latter time was considered as the time of arrival of the trailing edge of the dye and the graphs were ended at that time.

The positions of the leading edges, the peak concentrations, and the trailing edges of the dye for any given time following the injection of the dye can be seen from the graphs of time after injection versus distance. The full length of the dye cloud as it passed any given mileage point can be determined by scaling the distance from the leading edge to the trailing edge. The dye cloud lengthened rapidly for about the first 30 miles and more slowly thereafter.

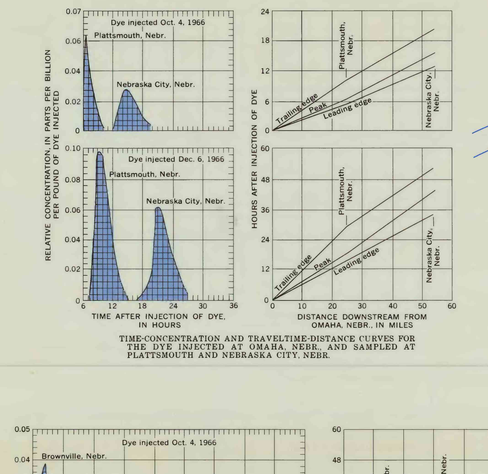



TIME-CONCENTRATION AND TRAVELTIME-DISTANCE CURVES FOR THE DYE INJECTED AT YANKTON, S. DAK. AND SAMPLED AT PONCA STATE PARK, NEBR. AND SIOUX CITY, IOWA

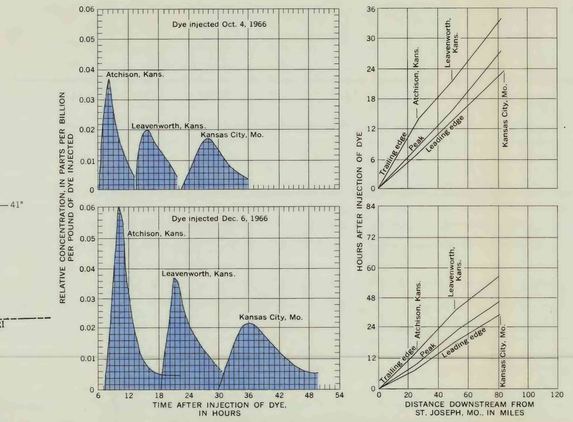


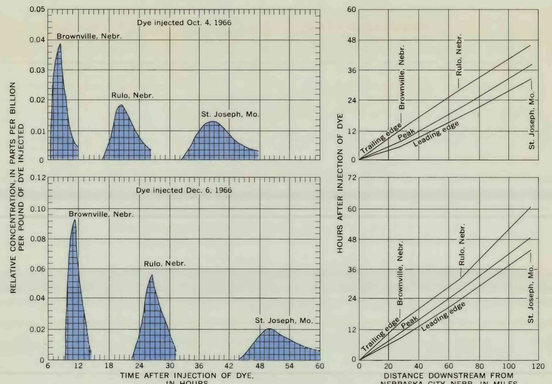

TIME-CONCENTRATION AND TRAVELTIME-DISTANCE CURVES FOR THE DYE INJECTED AT SIOUX CITY, IOWA, AND SAMPLED AT DECATUR, BLAIR, AND OMAHA, NEBR.



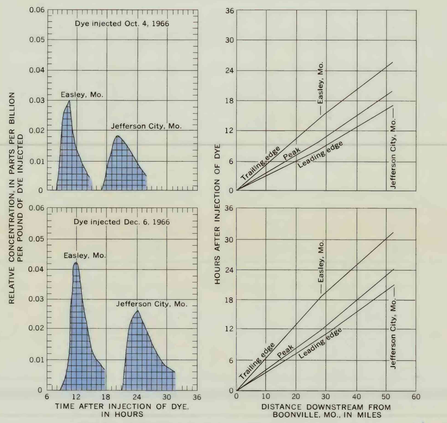

TIME-CONCENTRATION AND TRAVELTIME-DISTANCE CURVES FOR THE DYE INJECTED AT OMAHA, NEBR., AND SAMPLED AT PLATTSMOUTH AND NEBRASKA CITY, NEBR.



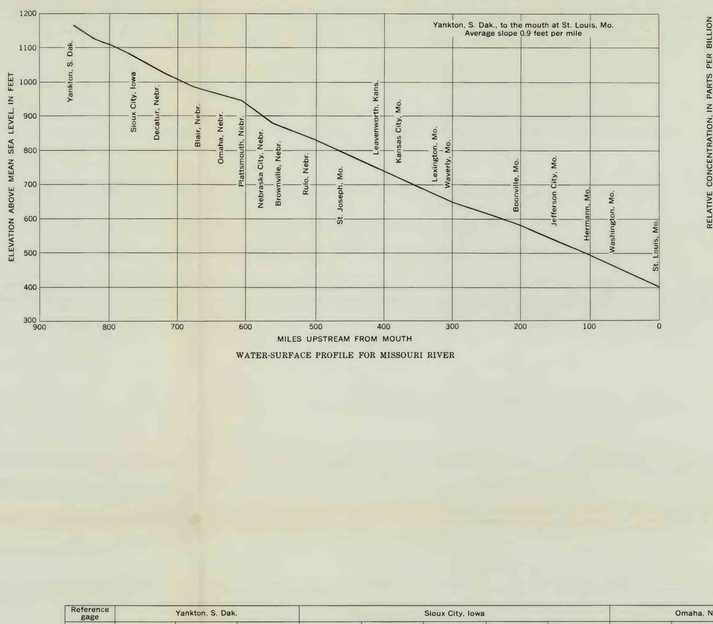

TIME-CONCENTRATION AND TRAVELTIME-DISTANCE CURVES FOR THE DYE INJECTED AT ST. JOSEPH, MO., AND SAMPLED AT ATCHISON, KANS., LEAVENWORTH, KANS., AND KANSAS CITY, MO.



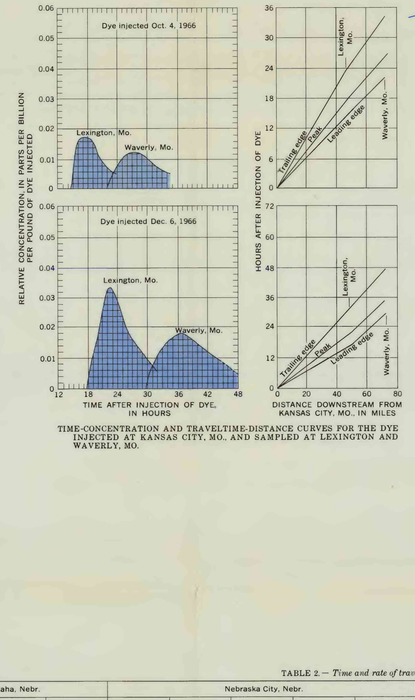

TIME-CONCENTRATION AND TRAVELTIME-DISTANCE CURVES FOR THE DYE INJECTED AT NEBRASKA CITY, NEBR., AND SAMPLED AT BROWNVILLE, NEBR., RULO, NEBR., AND ST. JOSEPH, MO.



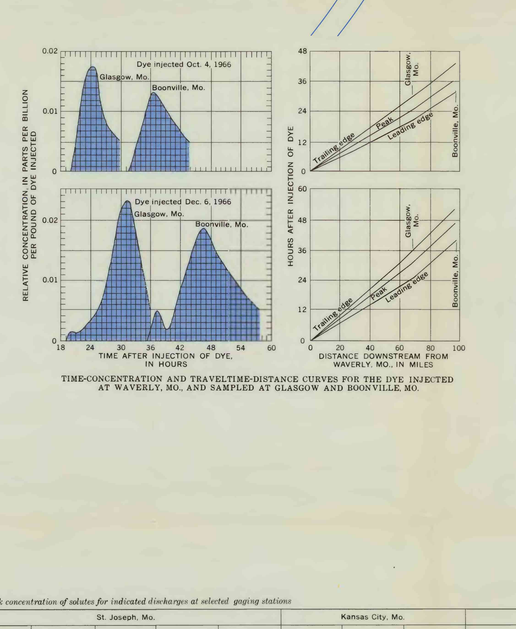

TIME-CONCENTRATION AND TRAVELTIME-DISTANCE CURVES FOR THE DYE INJECTED AT BOONVILLE, MO., AND SAMPLED AT EASLEY AND JEFFERSON CITY, MO.



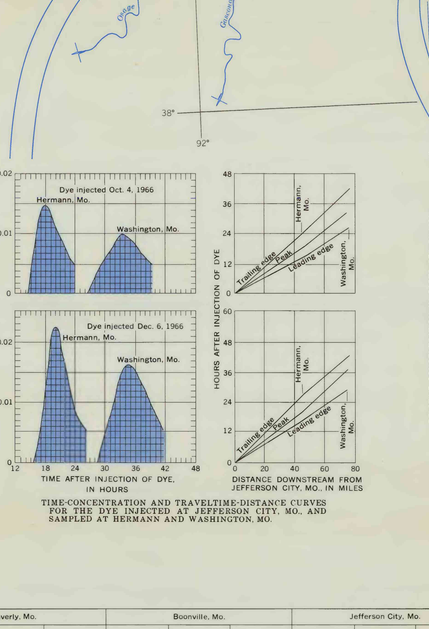

WATER-SURFACE PROFILE FOR MISSOURI RIVER



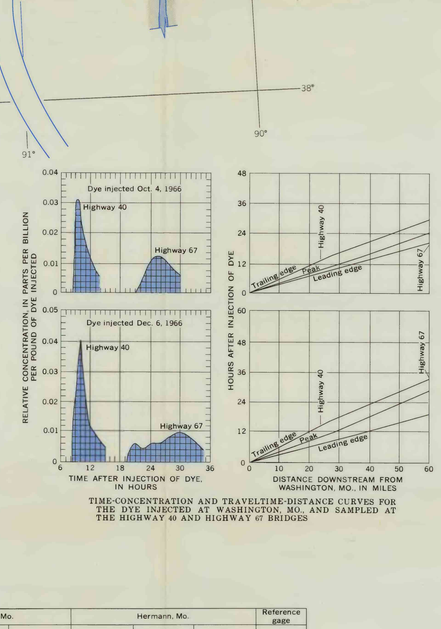

TIME-CONCENTRATION AND TRAVELTIME-DISTANCE CURVES FOR THE DYE INJECTED AT KANSAS CITY, MO., AND SAMPLED AT LEXINGTON AND WAVERLY, MO.




TIME-CONCENTRATION AND TRAVELTIME-DISTANCE CURVES FOR THE DYE INJECTED AT WAVERLY, MO., AND SAMPLED AT GLASGOW AND BOONVILLE, MO.




TIME-CONCENTRATION AND TRAVELTIME-DISTANCE CURVES FOR THE DYE INJECTED AT JEFFERSON CITY, MO., AND SAMPLED AT HERMANN AND WASHINGTON, MO.




TIME-CONCENTRATION AND TRAVELTIME-DISTANCE CURVES FOR THE DYE INJECTED AT WASHINGTON, MO., AND SAMPLED AT THE HIGHWAY 40 AND HIGHWAY 67 BRIDGES

TABLE 1.—*Observed traveltimes and rates of travel for dye injected at 1000 hours on October 4 and December 6, 1966*

| Sampling and injection sites | River-mile location | Distance from injection site (miles) | OCTOBER Reference discharge (cfs) | Amount of dye dumped (pounds) | Percent of dye detected | Leading edge of dye Hours | Leading edge of dye MPH | Peak of dye concentration Hours | Peak of dye concentration MPH | Centroid of dye Hours | Centroid of dye MPH | Trailing edge of dye Hours | Trailing edge of dye MPH | DECEMBER Reference discharge (cfs) | Amount of dye dumped (pounds) | Percent of dye detected | Leading edge of dye Hours | Leading edge of dye MPH | Peak of dye concentration Hours | Peak of dye concentration MPH | Centroid of dye Hours | Centroid of dye MPH | Trailing edge of dye Hours | Trailing edge of dye MPH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Injection at Yankton, S. Dak. | 805.8 | | 31,000 | 175 | | | | | | | | | | 10,500 | 200 | | | | | | | | | |
| 1. Ponca State Park, Nebr. | 753.0 | 52.8 | 31,000 | | 41 | 26 | 2.03 | 29 | 1.82 | 31½ | 1.68 | 36 | 1.47 | 10,500 | | 39 | 31½ | 1.68 | 36½ | 1.46 | 39½ | 1.34 | 49 | 1.08 |
| 2. Sioux City, Iowa | 732.3 | 73.5 | 31,000 | | 35 | 34¼ | 2.15 | 37½ | 1.96 | 42½ | 1.73 | 47 | 1.56 | 14,000 | | 37 | 44 | 1.67 | 49 | 1.50 | 52 | 1.41 | 63 | 1.17 |
| Injection at Sioux City, Iowa | 731.8 | | 31,000 | 313 | | | | | | | | | | 14,000 | 355 | | | | | | | | | |
| 3. Decatur, Nebr. | 691.0 | 40.8 | 31,000 | | 51 | 12¼ | 3.33 | 14¼ | 2.86 | 16 | 2.55 | 19 | 2.15 | 14,000 | | 54 | 17¼ | 2.30 | 19¼ | 2.12 | 22 | 1.86 | 28 | 1.57 |
| 4. Blair, Nebr. | 648.3 | 83.5 | 31,000 | | 26 | 24½ | 3.42 | 27½ | 3.04 | 31½ | 2.65 | 35 | 2.39 | 14,000 | | 34 | 34½ | 2.42 | 38½ | 2.17 | 41¼ | 2.00 | 48 | 1.74 |
| 5. Council Bluffs, Iowa | 626.3 | 105.5 | 31,000 | | 19 | 31 | 3.40 | 35 | 3.01 | 39 | 2.71 | 41 | 2.57 | 14,000 | | 34 | 42½ | 2.48 | 49 | 2.15 | 53¼ | 1.98 | 57 | 1.85 |
| 6. Omaha, Nebr. | 618.9 | 112.9 | 31,000 | | 19 | 33 | 3.42 | 37½ | 3.01 | 42¼ | 2.64 | 45 | 2.51 | 14,000 | | — | — | — | — | — | — | — | — | — |
| 7. Omaha, Nebr. | 615.8 | 116.0 | 32,000 | | 22 | 34 | 3.41 | 38 | 3.05 | 44 | 2.64 | 46 | 2.52 | 13,000 | | — | 46 | 2.46 | 52½ | 2.15 | 56½ | 2.05 | 62 | 1.87 |
| Injection at Omaha, Nebr. | 615.6 | | 32,000 | 175 | | | | | | | | | | 13,000 | 155 | | | | | | | | | |
| 8. Plattsmouth, Nebr. | 590.5 | 25.1 | 32,000 | | 40 | 5¼ | 4.37 | 6½ | 3.86 | 7½ | 3.35 | 10 | 2.51 | 13,000 | | 51 | 8 | 3.14 | 9½ | 2.64 | 11 | 2.28 | 14 | 1.79 |
| 9. Nebraska City, Nebr. | 561.8 | 53.8 | 35,000 | | 40 | 12 | 4.14 | 15¼ | 3.53 | 16½ | 3.26 | 20 | 2.69 | 15,000 | | 28 | 17 | 3.16 | 21¼ | 2.53 | 22¼ | 2.42 | 26 | 2.07 |
| Injection at Nebraska City, Nebr. | 561.8 | | 35,000 | 318 | | | | | | | | | | 15,000 | 300 | | | | | | | | | |
| 10. Brownville, Nebr. | 535.3 | 26.5 | 35,000 | | 57 | 6½ | 4.08 | 8 | 3.31 | 9½ | 2.79 | 12 | 2.21 | 15,000 | | 43 | 9¼ | 2.86 | 11 | 2.41 | 12½ | 2.12 | 15 | 1.77 |
| 11. Rulo, Nebr. | 498.1 | 63.7 | 35,000 | | 41 | 17 | 3.75 | 20½ | 3.11 | 24 | 2.65 | 28 | 2.28 | 16,000 | | 19 | 22½ | 2.83 | 26 | 2.45 | 27½ | 2.32 | 31 | 2.05 |
| 12. St. Joseph, Mo. | 447.9 | 113.9 | 36,000 | | 32 | 32 | 3.56 | 38 | 3.00 | 40 | 2.85 | 46 | 2.48 | 17,500 | | 27 | 43 | 2.65 | 48 | 2.37 | 53 | 2.15 | 60 | 1.90 |
| Injection at St. Joseph, Mo. | 447.9 | | 36,000 | 225 | | | | | | | | | | 17,500 | 200 | | | | | | | | | |
| 13. Atchison, Kans. | 422.5 | 25.4 | 36,000 | | 76 | | 3.63 | 8 | 3.18 | 9¼ | 2.61 | 14 | 1.81 | 16,000 | | 48 | 8 | 3.18 | 11 | 2.31 | 12½ | 2.03 | 17 | 1.49 |
| 14. Leavenworth, Kans. | 396.7 | 51.2 | 36,000 | | 71 | 13 | 3.94 | 16 | 3.20 | 19 | 2.69 | 20 | 2.56 | 16,000 | | 43 | 13 | 3.94 | 23 | 2.23 | 25 | 2.05 | 31 | 1.65 |
| 15. Kansas City, Mo. | 365.7 | 82.2 | 38,000 | | 31 | 23 | 3.57 | 27½ | 2.99 | 29 | 2.83 | 37 | 2.22 | 18,000 | | 30 | 30 | 2.74 | 36 | 2.28 | 39¼ | 2.19 | 45 | 1.83 |
| Injection at Kansas City, Mo. | 365.7 | | 38,000 | 250 | | | | | | | | | | 18,000 | 300 | | | | | | | | | |
| 16. Lexington, Mo. | 317.3 | 48.4 | 38,000 | | 72 | 14 | 3.46 | 17¼ | 2.73 | 19¼ | 2.45 | 26 | 1.86 | 18,000 | | 48 | 18 | 2.69 | 23 | 2.10 | 24¼ | 2.00 | 32 | 1.51 |
| 17. Waverly, Mo. | 293.4 | 72.3 | 38,000 | | 38 | 22 | 3.29 | 27 | 2.68 | 28¼ | 2.51 | 37 | 1.95 | 19,000 | | 46 | 29½ | 2.45 | 35½ | 2.04 | 38¼ | 1.86 | 48 | 1.51 |
| Injection at Waverly, Mo. | 293.4 | | 38,000 | 300 | | | | | | | | | | 19,000 | 300 | | | | | | | | | |
| 18. Glasgow, Mo. | 226.3 | 67.1 | 38,000 | | 54 | 20½ | 3.27 | 24½ | 2.74 | 26½ | 2.53 | 36 | 1.86 | 20,000 | | 43 | 23 | 2.92 | 32 | 2.10 | 33¼ | 2.02 | 46 | 1.46 |
| 19. Boonville, Mo. | 196.6 | 96.8 | 39,000 | | 37 | 31½ | 3.07 | 37 | 2.62 | 39 | 2.48 | 47 | 2.06 | 21,000 | | 27 | 40½ | 2.39 | 47 | 2.06 | 47¼ | 2.03 | 57 | 1.70 |
| Injection at Boonville, Mo. | 196.5 | | 39,000 | 160 | | | | | | | | | | 21,000 | 125 | | | | | | | | | |
| 20. Easley, Mo. | 169.1 | 27.4 | 39,000 | | 82 | 8 | 3.42 | 10 | 2.74 | 11½ | 2.38 | 14 | 1.96 | 24,000 | | 68 | 10 | 2.74 | 11½ | 2.38 | 13½ | 2.03 | 18 | 1.52 |
| 21. Jefferson City, Mo. | 143.9 | 52.6 | 40,000 | | 66 | 17 | 3.09 | 20 | 2.63 | 22¼ | 2.35 | 26 | 2.02 | 25,000 | | 39 | 21 | 2.50 | 24 | 2.19 | 26½ | 1.98 | 31 | 1.70 |
| Injection at Jefferson City, Mo. | 143.5 | | 40,000 | 230 | | | | | | | | | | 25,000 | 340 | | | | | | | | | |
| 22. Hermann, Mo. | 97.9 | 45.6 | 41,000 | | 80 | 14¼ | 3.09 | 18 | 2.53 | 20½ | 2.22 | 24 | 1.90 | 31,000 | | 60 | 17 | 2.68 | 20 | 2.28 | 22¼ | 2.00 | 26 | 1.75 |
| 23. Washington, Mo. | 67.6 | 75.9 | 41,000 | | 47 | 29½ | 2.92 | 32 | 2.37 | 35 | 2.17 | 40 | 1.90 | 31,000 | | 32 | 29 | 2.62 | 36 | 2.11 | 36¼ | 2.09 | 41 | 1.85 |
| Injection at Washington, Mo. | 67.6 | | 41,000 | 160 | | | | | | | | | | 31,000 | 150 | | | | | | | | | |
| 24. U.S. Hwy. 40 bridge | 44.0 | 23.6 | 42,000 | | 100 | 8 | 2.05 | 9 | 2.62 | 10¼ | 2.30 | 13½ | 1.75 | 33,000 | | 95 | 8½ | 2.78 | 10 | 2.36 | 12 | 1.97 | 15 | 1.57 |
| 25. U.S. Hwy. 67 bridge | 8.2 | 59.4 | 42,000 | | 69 | 20½ | 2.90 | 24½ | 2.42 | 26¼ | 2.22 | 30 | 1.98 | 33,000 | | 91 | 19½ | 3.13 | 29 | 2.05 | 30 | 1.98 | 34 | 1.75 |

## APPLICATIONS

The time-concentration graphs may be used to estimate a similar graph for any amount of "conservative contaminant" introduced into the river if the location, water discharge, and amount of the contaminant introduced is known. A "conservative contaminant" as defined here is one that will remain in solution and that will not be diminished or changed significantly through chemical reactions with other substances in the water, photochemical decay, or other processes. Estimates obtained by using the graphs would be valid only for a measured reach and when water discharges are similar to those in effect during the October or December measurements.

The use of time-concentration graphs is illustrated by the following example.

*Example A.*—Problem: Assume that 100 pounds of conservative contaminant was accidentally spilled into the river at Kansas City and that flow at Kansas City at the time was about 38,000 cfs (cubic feet per second). It is desirable to know at Lexington, Mo., when the leading edge and and peak concentrations will arrive; what the maximum concentration will be, and if excessive on basis of health standards, how long such concentrations may be expected to endure.

Solution: Enter the time-concentration graph for Lexington obtained at 38,000 cfs. Tabulate the hours after injection and the relative concentrations picked from the graph. Multiply the relative concentrations (parts per billion per pound) by the pounds of contaminant spilled to give the predicted concentrations shown below:

| Hours after injection | Relative concentration (ppb per lb) | Predicted concentration, ppb (Relative concentration x pounds of contaminant) |
|---|---|---|
| 15 | 0.006 | 0.6 |
| 16 | .016 | 1.6 |
| 17 | .017 | 1.7 |
| 18 | .017 | 1.7 |
| 19 | .016 | 1.6 |
| 20 | .012 | 1.2 |
| 22 | .008 | .8 |
| 24 | .006 | .6 |

From these results it can be seen that the leading edge and peak would arrive about 15 and 17 hours after the spill, respectively. The maximum conservative concentration is seen to be 1.7 ppb, which, depending on the nature of the contaminant, may or may not be excessive. If excessive, the duration of such concentrations could be readily deduced from the data.

The graphs of time after injection versus distance downstream may be used to estimate the time required for a contaminant spilled at one point to pass a given mileage point downstream or where the contaminant would be after a given time. The same limitations apply to estimates made by using these graphs as apply to the estimates made by using the time-concentration graphs.

*Example B.*—Problem: For the same conditions as in example A it is desirable to know how long it would take for the contaminant to pass a point 60 miles downstream.

Solution: On the traveltime-distance graph for Kansas City, find the point representing 60 miles downstream. The corresponding hours for the intersection with the line representing the leading and trailing edges are 19 and 29 hours, respectively. The difference, 10 hours, is the time required for the contaminant to pass the 60-mile point.

*Example C.*—Problem: For the same conditions as in example A it is desirable to know where the contaminant would be 12 hours after it entered the river.

Solution: Locate the 12-hour point on traveltime-distance graph for Kansas City. The corresponding value for the leading edge is 40 miles and for the trailing edge, 24 miles downstream from the point of spillage.

The time of travel usually varies inversely and rate of travel directly with the rate of water discharge. For within-bank stages and for streams having channel control, the time of travel and discharge have been found to have a straight line relation when plotted on logarithmic coordinates (Harris, 1968). By applying this relationship to data obtained in this study, the times of travel and rates of travel for the peak concentration at various rates of water discharge have been computed and are given in table 2. The upper limit of 100,000 cfs discharge is within-bank flow and is greater than any sustained flow likely to occur. Data in the table are applicable when flows are fairly uniform and should not be used for overbank flows.

The hours of traveltime of a peak concentration from any of the specified locations to another in table 2 can be read directly. Those from any unspecified location to another can be computed using the appropriate travel rates.

The variations in water discharge from one place to another are nonlinear; that is, for a given discharge at one site there is not necessarily a corresponding fixed discharge at another site. For this reason, the time of travel must be computed separately for each subreach through which the water passes and the resulting times must then be added. The following example shows how this may be done.

*Example D.*—Problem: For the same conditions as in example A, it is desirable to know how long it would take the peak concentration of the contaminant to reach Boonville.

Solution: The reference gage for the subreach from Kansas City to Waverly is at Kansas City and water discharge there was 38,000 cfs. For a discharge of 30,000 cfs the time required from Kansas City to Waverly would be 29.4 hours and for a discharge of 40,000 cfs, 26.6 hours. By interpolation the time required for a discharge of 38,000 cfs is about 27 hours.

The reference gage for the subreach from Waverly to Boonville is at Waverly. If we assume that the discharge at Waverly was 40,000 cfs, the time of travel from Waverly to Boonville is 36.4 hours. The total travel time would then be 27+36.4 hours, or about 63 hours.

If the river-mile distance between the source of contamination and the downstream location of interest is known and the water discharge applicable to each subreach involved also is known, the problem in example D could be solved simply by dividing the mileage in each subreach by the rate of travel, in miles per hour, and adding the quotients.

The data in this report are for a fully conservative soluble contaminant. Contaminants that do not fall into this category, such as low-density oily wastes, might move at rates considerably different from those of a conservative soluble contaminant. Moreover, some contaminants might enter into chemical reactions with other substances in the water and consequently, the maximum concentrations would be lower than those estimated. If a contaminant is nonconservative, estimates of concentration made by using data in this report are likely to be high and for this reason are on the safe side.

A contaminant may be introduced into the river in many ways. It might be introduced suddenly or gradually, or it might be introduced along the bank or near midstream. The mode of introduction can affect significantly both the traveltime and the maximum concentrations attained.

## SELECTED REFERENCES

Buchanan, T. J., 1964, Time of travel of soluble contaminants in streams: Am. Soc. Civil Engineers Proc., v. 90, no. SA3, Paper 3932, 12 p.

Harris, D. D., 1968, Travel rates of water for selected streams in the Willamette River Basin, Oregon: U.S. Geol. Survey Hydrol. Inv. Atlas HA-273.

Stewart, M. R., 1967, Time of travel of solutes in Mississippi River from Baton Rouge to New Orleans, Louisiana: U.S. Geol. Survey Hydrol. Inv. Atlas HA-260.

Wilson, J. F., Jr., and Forrest, W. E., 1965, Potomac River time of travel measurements: Lamont Geol. Observatory Symposium on Diffusion in Oceans and Fresh Waters, Palisades, N. Y., 1964 Proc., p. 1-21.

Wilson, J. R., Jr., and McAvoy, R. L., 1966, Water movement in the Patuxent River Basin, *in* Crooks, J. W., O'Bryan, D., and others, Water resources of the Patuxent River Basin: U.S. Geol. Survey Hydrol. Inv. Atlas HA-244.

TABLE 2.—*Time and rate of travel of peak concentration of solutes for indicated discharges at selected gaging stations*

| Reference gage | Discharge (cfs) | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Hours | MPH | Reference gage |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Yankton, S. Dak. to Sioux City, Iowa | | Yankton, S. Dak. to Ponca State Park, Nebr. | | Ponca State Park, Nebr. to Sioux City, Iowa | | Sioux City, Iowa to Omaha, Nebr. | | Sioux City, Iowa to Decatur, Nebr. | | Sioux City, Iowa to Blair, Nebr. | | Decatur, Nebr. to Blair, Nebr. | | Blair, Nebr. to Omaha, Nebr. | | Omaha, Nebr. to Nebraska City, Nebr. | | Omaha, Nebr. to Plattsmouth, Nebr. | | Plattsmouth, Nebr. to Nebraska City, Nebr. | | Nebraska City, Nebr. to St. Joseph, Mo. | | Nebraska City, Nebr. to Brownville, Nebr. | | Nebraska City, Nebr. to Rulo, Nebr. | | Brownville, Nebr. to Rulo, Nebr. | | Rulo, Nebr. to St. Joseph, Mo. | | St. Joseph, Mo. to Atchison, Kans. | | St. Joseph, Mo. to Leavenworth, Kans. | | Atchison, Kans. to Leavenworth, Kans. | | Leavenworth, Kans. to Kansas City, Mo. | | Kansas City, Mo. to Waverly, Mo. | | Waverly, Mo. to Boonville, Mo. | | Waverly, Mo. to Glasgow, Mo. | | Glasgow, Mo. to Boonville, Mo. | | Boonville, Mo. to Jefferson City, Mo. | | Boonville, Mo. to Easley, Mo. | | Easley, Mo. to Jefferson City, Mo. | | Jefferson City, Mo. to Washington, Mo. | | Jefferson City, Mo. to Hermann, Mo. | | Hermann, Mo. to Washington