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Estimation of Travel Times for Seven Tributaries of the Mississippi River, St. Cloud to Minneapolis, Minnesota, 2003

Scientific Investigation Report 2004-5192

U.S. Department of the Interior
U.S. Geological Survey

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Conversion Factors, and Water-Quality Unit

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Estimation of Travel Times for Seven Tributaries of the Mississippi River, St. Cloud to Minneapolis, Minnesota, 2003

By A.D. Arntson, D.L. Lorenz, and J.R. Stark

Abstract

Travel times for seven streams tributary to the Mississippi River from St. Cloud to Minneapolis, Minnesota, were estimated for three flow conditions; low, median, and high. Travel times were estimated for Sauk, Elk, Crow, and Rum Rivers, and Elm, Coon, and Rice Creeks. Regression equations based on watershed characteristics of drainage area, river slope, mean annual discharge, and instantaneous discharge at the time of measurement from more than 900 streams across the nation were used to estimate travel times. Travel times were estimated for the leading edge, peak concentration, and trailing edge of tracer-response curves. To test the validity of these equations, a time of travel study, using a luminescent dye, was conducted on the Sauk River, from Rockville, to the confluence with the Mississippi River on June 16, 2003, at a discharge of 457 ft^3/s at Rockville. Dye was injected in the Sauk River at Rockville, and time and concentrations were measured at three sampling sections downstream; at County Road 121, Veterans Drive, and County Road 1 near the mouth. The estimated travel times for the leading edge, peak concentration, and trailing edge at County Road 1 were 10.6 hrs, 11.9 hrs, and 14.6 hrs, respectively. The measured travel times for the leading edge, peak concentration, and trailing edge were 13.4 hrs, 15.5 hrs, and 20.5 hrs, respectively for the 15.7 mile reach.

Introduction

The cities of St. Cloud, Minneapolis, and St. Paul, Minnesota obtain most of their drinking water from the Mississippi River. Spills or discharges of contaminants into the Mississippi River, or its tributaries upstream from the city water intakes could threaten water supplies (Minnesota Pollution Control Agency, 2001). If a contaminant spill or discharge occurs, the managers of the water supplies need to know when to stop pumping water from the river and how long to wait before again pumping water from the river to protect their water supplies. Water managers need a reliable estimate of the travel time of the contaminant from a spill to water intakes and an estimate of the dispersion of the contaminant in the river.

Although many excellent models are available to estimate travel time and dispersion of contaminants, none can be used with confidence without the calibration and verification along a particular river reach (Jobson, 1996). The availability of measured field data is usually the most difficult and expensive kind of data needed to predict the rate of movement, dilution, and mixing of contaminants in rivers and streams.

Previous studies of travel times on the Mississippi River were conducted by the U.S. Army Corps of Engineers (USACOE) (1997) and the U.S. Geological Survey (USGS). The USACOE determined travel times as part of the River Defense Network Program. The travel times from reservoir pools to the Twin Cities (Minneapolis and St. Paul) were needed to adequately plan for water for use in river navigation and for providing water supplies in times of low flow. The USGS measured travel times on the Mississippi River from Anoka to Hastings during the low-flow years of 1976–77. The study, using dye trace methods, was done for the Metropolitan Waste Control Commission to understand wastewater treatment effluent flow and dispersion in time of low flow (U.S. Geological Survey, written commun., 1978). Travel times along tributary streams were not measured or calculated.

To address the need for reliable estimates of travel time, the USGS, in cooperation with the cities of St. Cloud, Minneapolis, and St. Paul, the Minnesota Pollution Control Agency, the Minnesota Department of Health, and the Metropolitan Council conducted a study to aid in implementation of source-water protection efforts in the Upper Mississippi River Basin.

Purpose and Scope

The purpose of this report is to present the results of the cooperative study, which includes: (1) estimates of travel times in seven tributaries of the Upper Mississippi River in Minnesota: (2) measurements of travel times in the Sauk River, at median flow conditions, using a dye tracer; and (3) comparison of estimated and measured travel times in the Sauk River to evaluate the estimation technique. Results are based on conservative, water-soluble materials.

Hydrologic Setting

The Mississippi River and confluence points for seven of its tributaries are located in the east-central part of the state (fig. 1). The Mississippi River drainage area at St. Cloud, downstream from the confluence with the Sauk River, is 13,300 mi^2, and at Minneapolis is 19,100 mi^2. The distance from St. Cloud to Minneapolis along the Mississippi River is approximately 75 miles. The topography of the seven tributary watersheds consists of gently rolling hills west of the Mississippi River and generally flat to the east. The watersheds receive about 29 inches of precipitation a year with about 25 inches as rainfall. The average temperatures are 68^{o}F in the summer months and 12^{o}F in the winter months.

The Sauk River watershed covers an area of 1,043 mi^2. The topography generally is gently rolling hills with a predominately agricultural land use. The St. Cloud metropolitan area, with a population of 66,000 (U.S. Department of Commerce, 2000), is located at the confluence of the Sauk River with the Mississippi River. The upper watershed is an area of

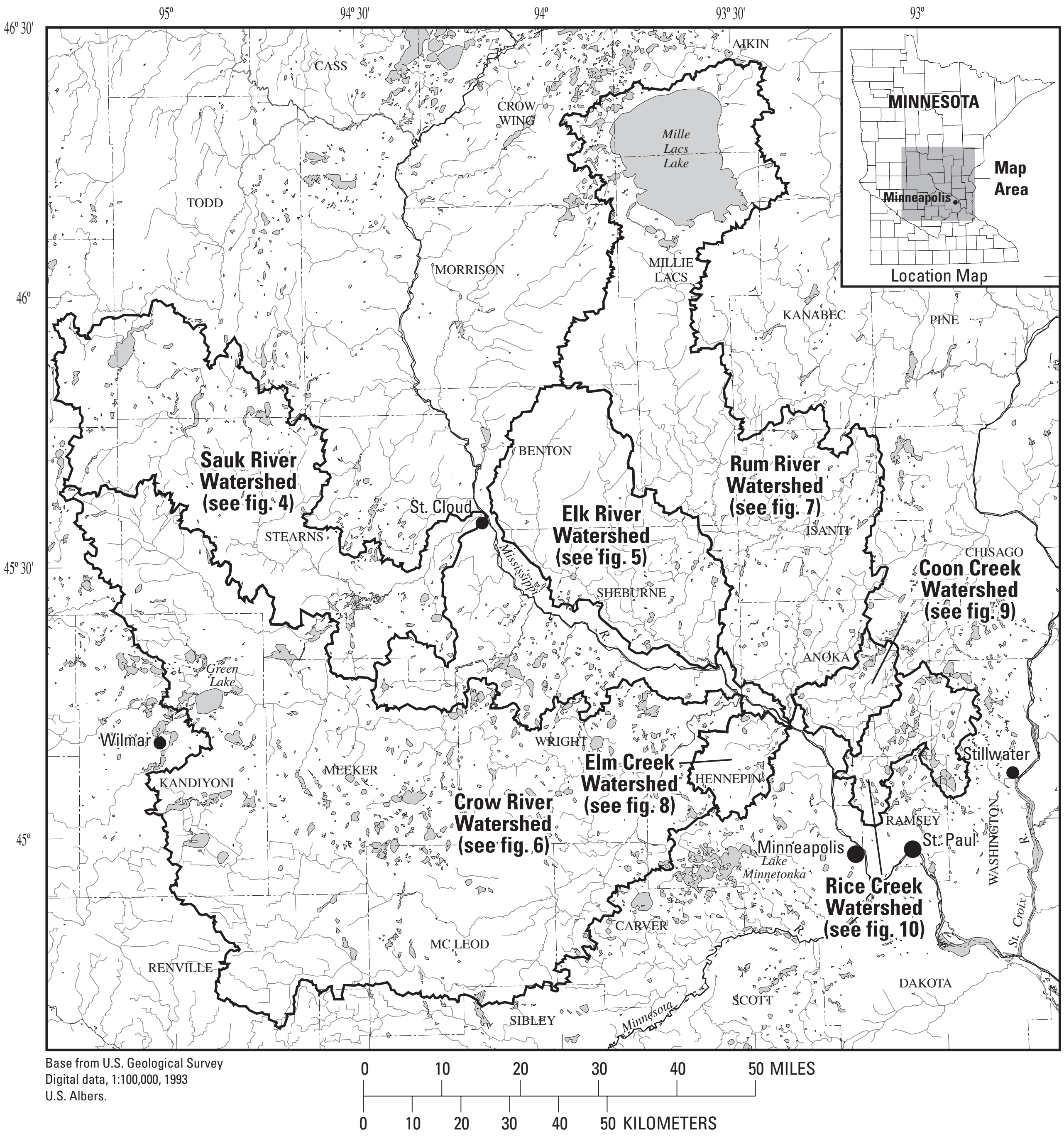


Figure 1. Locations of seven river watersheds tributary to the Upper Mississsippi River

many lakes that retain precipitation from snowmelt and rainfall. Lakes, ponds, and wetlands (storage) in the Sauk River watershed covers about 18 percent of the watershed, with about 4 percent as lakes. Discharge and stage increase more rapidly in the St. Cloud area following rainfall and snowmelt events primarily from urban runoff and shorter overland and tributary travel distances. Stage can be sustained for extended periods of time due to the slower release of runoff amounts from lake and wetland storage in the upper watershed.

The Elk River watershed covers an area of 611 mi^2 and converges from the north with the Mississippi River at the city of Elk River, Minnesota. Elk River flows through Orono Lake, a backwater formed from the power generating dam near the mouth at Elk River. Land use in the Elk River watershed is primarily agricultural with urban development increasing near the mouth.

The Crow River watershed covers an area of 2,760 mi^2 and converges from the southwest with the Mississippi River at Dayton, Minnesota. Land use in the Crow River watershed is primarily agricultural with some scattered urban development.

The Rum River watershed covers an area of 1,560 mi^2 and converges from the north with the Mississippi River at Anoka, Minnesota. Lake Mille Lacs forms the headwaters of the Rum River. Land use in the Rum River watershed in primarily agricultural with urbanization occurring in the lower reach of the watershed. A power generating dam is located on the Rum River in Anoka.

The Elm Creek watershed covers an area of 106 mi^2 and converges from the southwest with the Mississippi River in Champlin, Minnesota. Elm Creek flows through Hayden Lake a short distance upstream from the confluence with the Mississippi River. Land use in the Elm Creek watershed has steadily changed from agricultural to urban in recent years. A wier-crested dam at East River Road provides storage for Mill Pond.

The Coon Creek watershed covers an area of 109 mi^2 and converges from the northeast with the Mississippi River and downstream from the Coon Rapids Dam in Coon Rapids, Minnesota. The upper reaches of the Coon Creek watershed contain wetlands while the lower reaches continue to become more urbanized.

The Rice Creek watershed covers an area of 180 mi^2 and converges from the east with the Mississippi River in Fridley, Minnesota. The upper reaches of the Rice Creek watershed form a chain of lakes while the lower reaches are fully urbanized.

Methods

The U.S. Geological Survey (Jobson, 1996) developed a method to estimate travel times in rivers based on extensive sets of readily available stream and watershed-characteristic data collected from rivers throughout the nation. The method, based on measured dye trace studies, provides estimates of (1) the rate of movement of a conservative contaminant (hereinafter, contaminant) through a river reach, (2) the rate of attenuation of the peak concentration of a contaminant with time, and (3) the length of time required for the contaminant to pass a point in the river. Data used to develop these regression equations include information about drainage area, river slope, mean annual discharge, and instantaneous discharge at the time of the measurement. All additional references to Jobson in this report are from Jobson (1996).

The accuracy of the estimated time of travel for the Sauk River was tested by measuring the time of travel for the river with an injected water-soluble tracer dye. The river reach was divided into three reaches of similar channel slope, and sampling locations were established near the points where the channel slope changed. Rhodamine WT 20 tracer dye was injected into the Sauk River just downstream from County Road 139 in Rockville, Minnesota. Water samples were collected at three sample locations along the study reach. Dye concentrations were measured and tracer-response curves were developed at these sampling locations to determine times of peak concentrations and travel times between the sampling locations.

Time-of-travel studies are conducted to quantify travel time and dispersion for rivers. A known quantity of a water-soluble tracer dye is instantaneously injected into a stream and concentrations are measured as it moves downstream. The theoretical distribution of tracer concentrations resulting from the injection is shown in figure 2. The tracer-response curves shown in figure 2 are a function of longitudinal distance, and not as a function of time. The results of a water soluble tracer injection are plotted as concentration varies with time (tracer response curve) at one or more cross sections along the study reach downstream from the injection point, as shown in figure 3. The tracer-response curve is the basis for determining time of travel in streams when referenced to injection or spill times.

Travel times, peak velocities, and unit-concentrations from selected locations to the mouth for seven tributaries were determined using Jobson's equations. The tributaries are the Sauk (fig. 4), Elk (fig. 5), Crow (fig. 6), and Rum (fig. 7) Rivers; and Elm (fig. 8), Coon (fig. 9), and Rice Creeks (fig. 10).

Drainage area, stream slope, annual mean discharge, and instantaneous discharge were compiled from existing data available from the U.S. Geological Survey, or from local watershed organizations that maintain stream gages on Coon Creek and Rice Creek. Time-of-travel estimates were determined for three flow conditions: low, median, and high for each of the seven tributaries using Jobson's equations.

The equation to estimate velocity of peak concentration (also known as peak velocity) is:

$$V_p = 0.094 + 0.0143 \text{ x } (D'_a)^{0.919} \text{ x } (Q'_a)^{-0.469} \text{ x } S^{0.159} \text{ x } (Q/D_a) \quad (1)$$

where

V_p is the peak velocity, [m/s]

g is the gravitational constant, [9.86 m/s^2]

Da is the drainage area of the river at the point of measurement, [m^2],

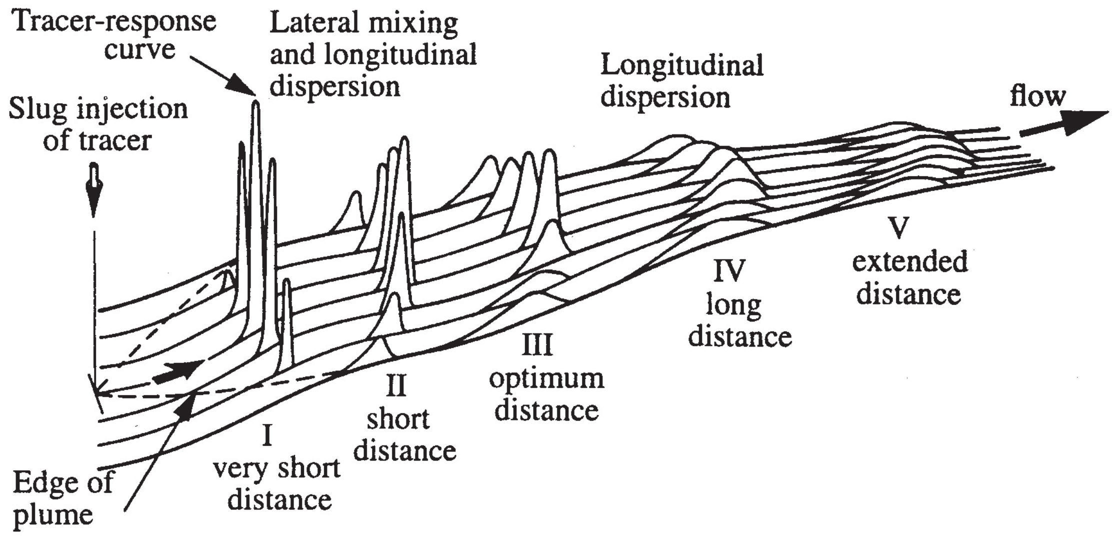
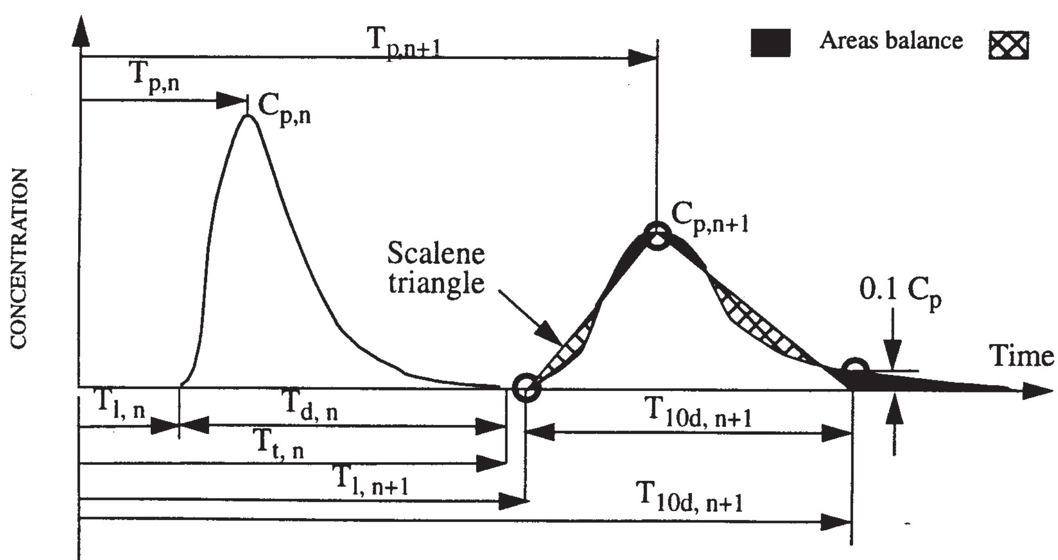


Figure 2. Lateral mixing and longitudinal dispersion of concentration of a water-soluble tracer downstream from a single, center, slug injection (modified from Kilpatrick, 1993, p. 2).



EXPLANATION

C_p - peak concentration of the tracer plume
T_l - time it takes for the arrival of the leading edge of a tracer plume at a sampling location
T_p - time it takes for the arrival of the peak concentration of the tracer plume
T_t - time it takes for the arrival of the tailing edge of the tracer plume
T_d - duration of the tracer plume (Tt - T1)
T_{10d} - duration from leading edge of the plume until tracer concentration has been reduced to within 10 percent of the peak concentration
n - is the number of sampling site downstream from the injection

Figure 3. Definition sketch for trace-response curves (modified from Kilpatrick and Wilson, 1989, p. 3).

D'_a is the dimensionless drainage area defined as $D_a^{1.25}$ x $g^{0.5}$ /Q_a,

Q is the discharge at the section of the time of measurement, [m^3/s],

Q_a is the mean annual flow at the section, [m^3/s],

Q'_a is the dimensionless relative discharge defined as Q/Q_a,

S is the slope of the reach [m/m].

To help estimate a “worst case” scenario, Jobson also developed an equation to estimate a maximum probable velocity (V_{mp}). The equation for the V_{mp} is:

$$V_{mp} = 0.25 + 0.02 \times (D'_a)^{0.919} \times (Q'_a)^{-0.469} \times S^{0.159} \times (Q/D_a) \qquad (2)$$

In addition to knowing when the peak concentration will arrive at a site, it is important to understand the timing of the arrival of the first part of the contaminant plume. The time of arrival of the leading edge of the plume serves as an indication of when a problem first may exist. The equation for the travel time of the leading edge is:

$$T_l = 0.890 \times T_p \qquad (3)$$

where

T_l is the travel time of the leading edge(s)

T_p is the travel time of the peak concentration(s) and is equal to the reach distance divided by peak velocity, V_p.

Unit peak concentration is a relative term used to define a contaminant concentration independent of the magnitude of discharge. The unit peak concentration can then be used for simulating the concentrations expected from various contaminants for different stream discharges. The unit peak concentration is defined as 1,000,000 times the concentration produced in a unit discharge due to the injection of a mass of conservative soluble substance (Jobson, 1996). The unit peak concentration fits one unit of mass of tracer into one unit of flow.

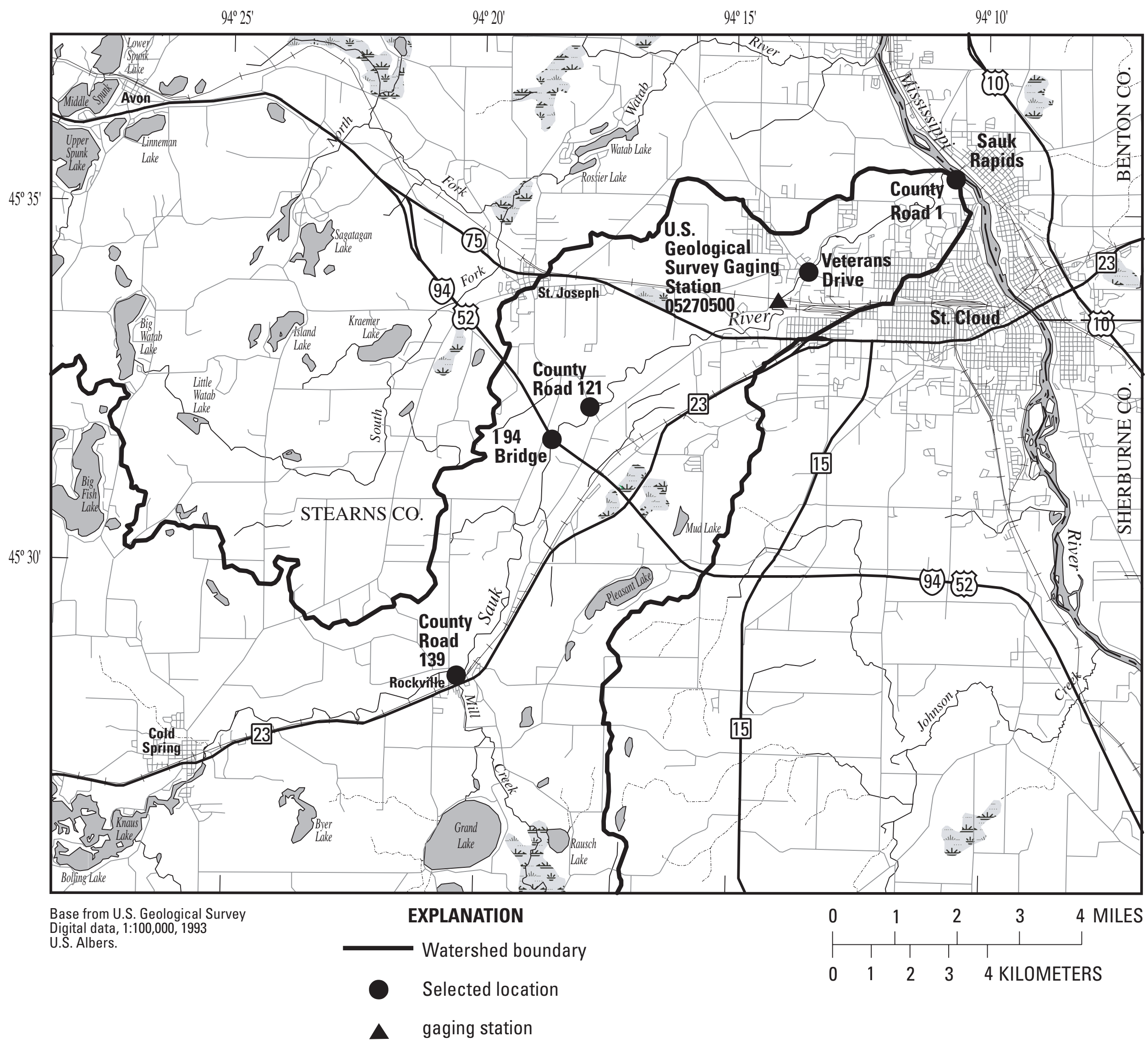


Figure 4. Downstream reach of Sauk River showing selected locations of estimated time of travel points.

The presence of pools, riffles, bends and other channel characteristics increase the rate of longitudinal mixing and, therefore, affect the unit peak concentration. Jobson developed a regression equation that produced a reasonable estimate of the unit peak concentration:

$$C_{up}=1{,}025 \text{ x } T_p^{-0.887} \quad (4)$$

Jobson also used other river characteristics to define the unit peak concentration relations including drainage area (D_a), reach slope (S), mean annual river discharge (Q_a), and discharge at the time of the measurement (Q). Another equation for unit peak concentration that accounts for some of the other characteristics is:

$$C_{up} = 857T_p^{A} \quad (5)$$

where

$$A = -0.760(Q/Q_a)^{-0.079} \quad (6)$$

Estimates for the travel time of the leading edge, the travel time of the peak concentrations, and the magnitude of the unit peak concentrations define two points on a tracer-response curve. Kilpatrick and Taylor (1986) found that the area of a normal slug-produced tracer-response curve is nearly equal to the area of a scalene triangle (fig. 3), with a height equal to the peak concentration and the base extending from the leading edge to a point where the trailing edge concentration is equal to 0.1 times the unit peak concentration, with the area under the unit peak concentration curve equal to 1,000,000 units. The equation for time-of-passage is:

$$T_{10d} = 2{,}000{,}000/C_{up} \quad (7)$$

Where T_{10d} is the time of passage from the leading edge of a tracer response curve to a point where the concentration has been reduced to 10 percent of the peak concentration. Adding the time-of-passage, or duration of a solute, to the travel time of leading edge gives the travel time of the trailing edge of the contaminant plume.

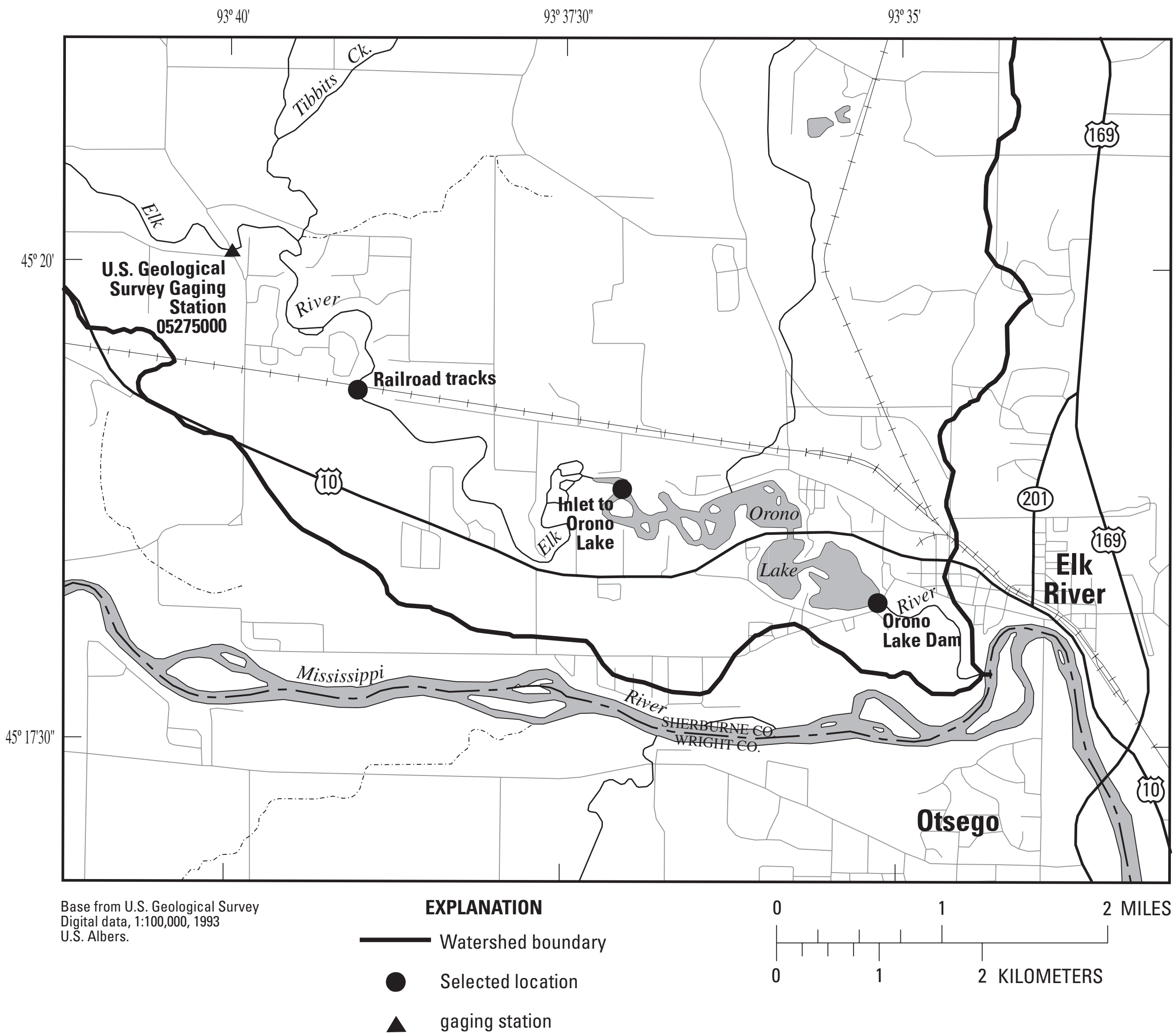


Figure 5. Downstream reach of Elk River showing selected locations of estimated time of travel points.

Estimated Travel Times of Seven Mississippi River Tributaries

Watershed drainage area, channel slope, mean annual discharge, and instantaneous discharge were used to compute the time of travel variables from Jobson's equations. Watershed drainage area and channel slope were determined from 1:24,000 scale topographic maps.

Mean annual discharge was determined at USGS gaging stations for the period of record (Mitton and others, 2002). The mean annual discharge was adjusted for each sampling section based on a simple linear relation with drainage area.

For the Coon Creek and Rice Creek watersheds, where there were not sufficient long term (greater than 10 years) USGS discharge records, intermittent shorter term (1- 2 years) daily discharges were obtained from local watershed managers. The shorter term daily discharges at Coon Creek and Rice Creek were related to daily discharges from nearby long term USGS records at Elm Creek and Elk River, respectively. A linear regression analysis was used to determine mean annual discharge for the Coon and Rice Creek watersheds. About

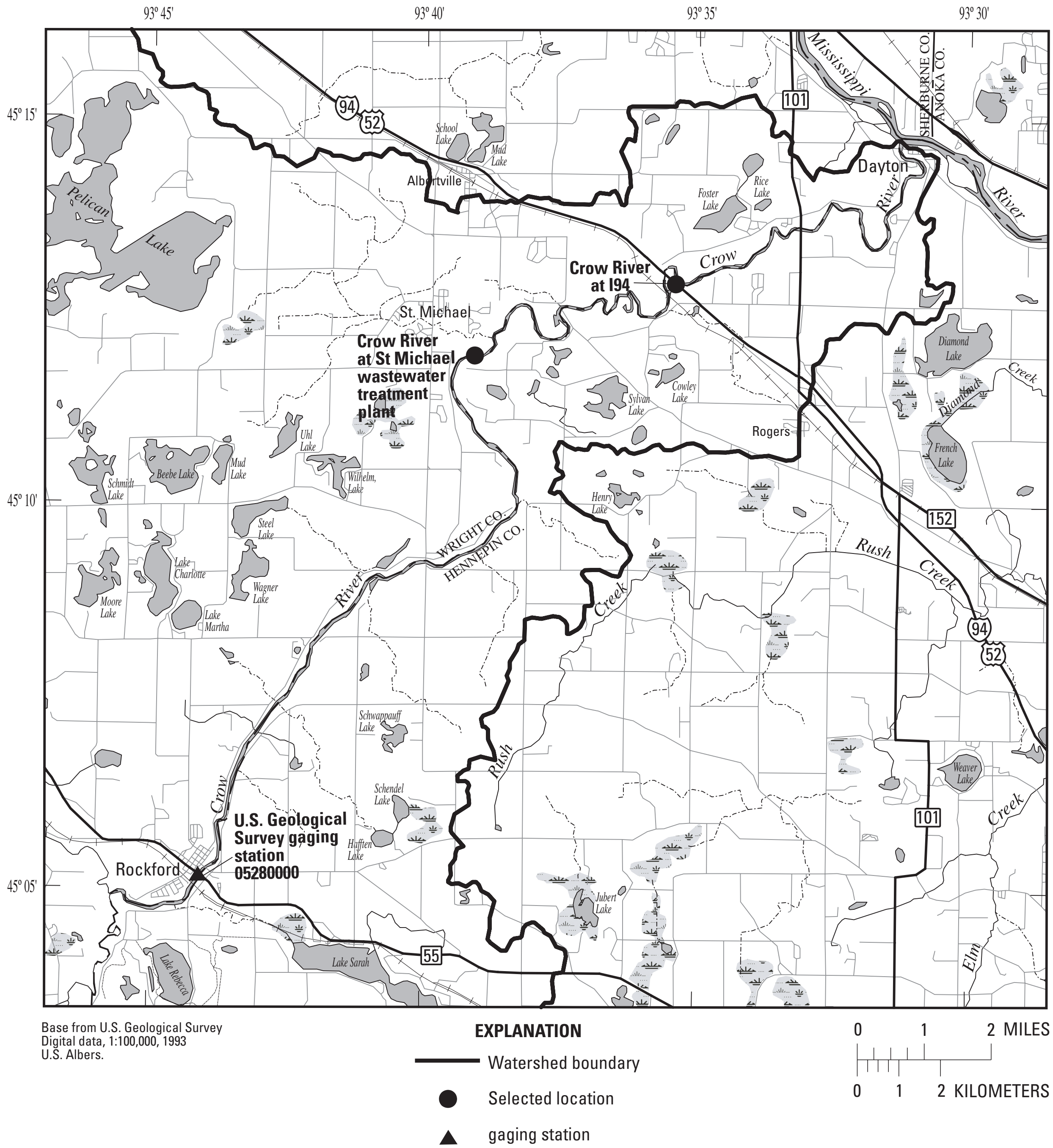


Figure 6. Downstream reach of Crow River showing selected locations of estimated time of travel points.

770 daily discharges for Coon Creek were related to Elm Creek daily discharges. The resultant mean annual discharge for Coon Creek was adjusted for coefficient bias and back transformation (Helsel and Hirsch, 1992). The adjusted mean annual discharge for Coon Creek was 62 ft^3/s. About 2,470 daily discharges for Rice Creek were related to Elk River daily discharges. The resultant mean annual discharge for Rice Creek was adjusted for back transformation. The adjusted mean annual discharge for Rice Creek was 84 ft^3/s.

Coefficient bias results when one stream has greater variability than the other stream. Elm Creek has much greater variability than Coon Creek. The mean discharge of Elm

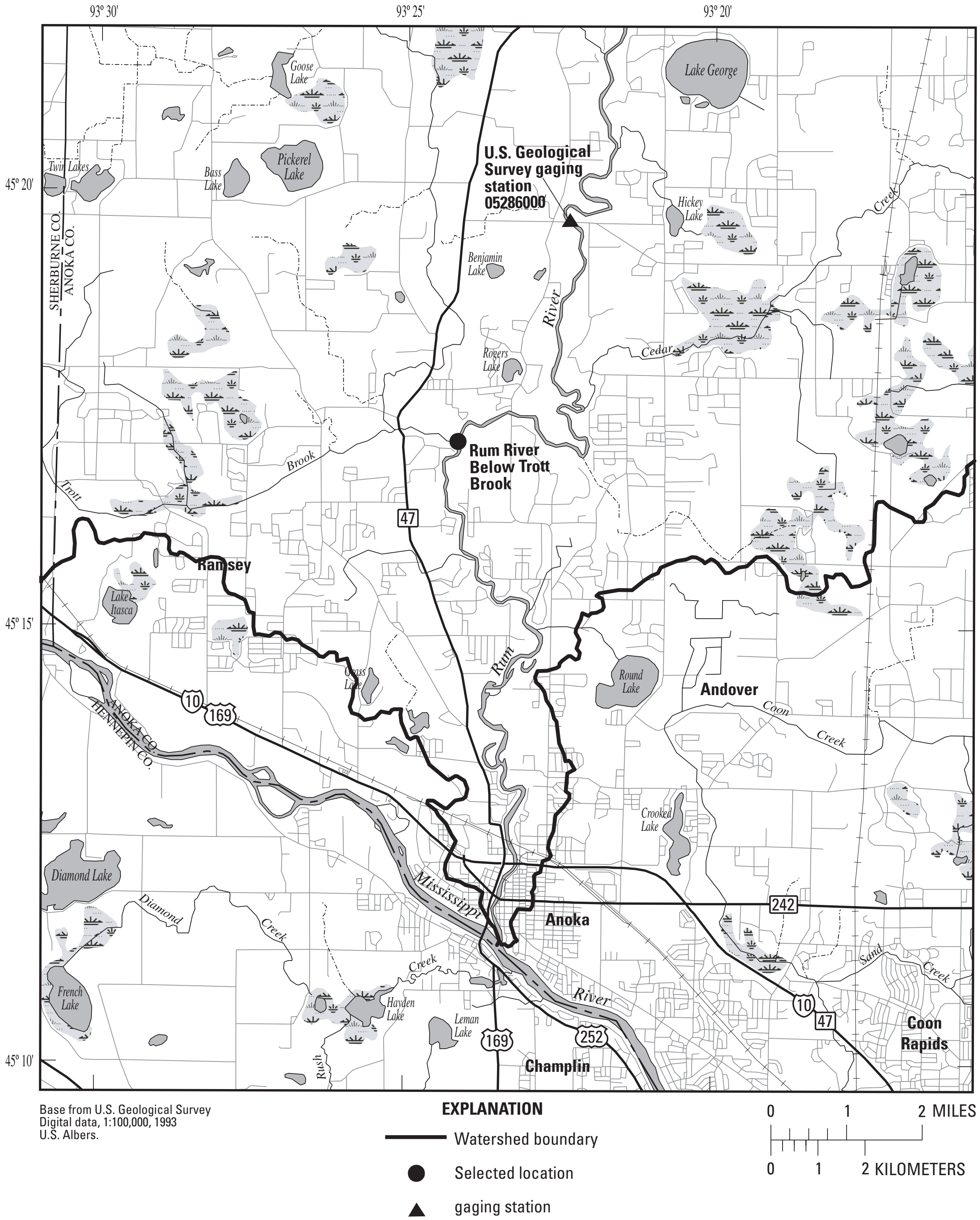


Figure 7. Downstream reach of Rum river showing selected locations of estimated time of travel points.

Creek does not correspond to the mean discharge of Coon Creek when log-transforms are used in regressions because the distributions of daily discharges between the two streams do not match. The daily discharges of Elm and Coon Creeks were used to estimate the coefficient bias. Back-transformation bias results when converting estimates in log-space to flow-space. The antilog of the estimate underestimates the mean of the actual data. The maximum likelihood estimate correction factor, defined as the antilog of ½ the residual variance, was used to determine the back transformation correction for Coon and Rice Creeks (Helsel and Hirsch, 1992).

The estimated times of travel for the leading edge, peak concentration, and trailing edge of the solute are listed in tables 1-3 for each of the seven Mississippi River tributaries for each of the flow conditions; low (table 1), median (table 2), and high (table 3). Each tributary was divided into reaches with uniform channel slopes. Velocities of the peak concentrations were computed in meters per second and converted

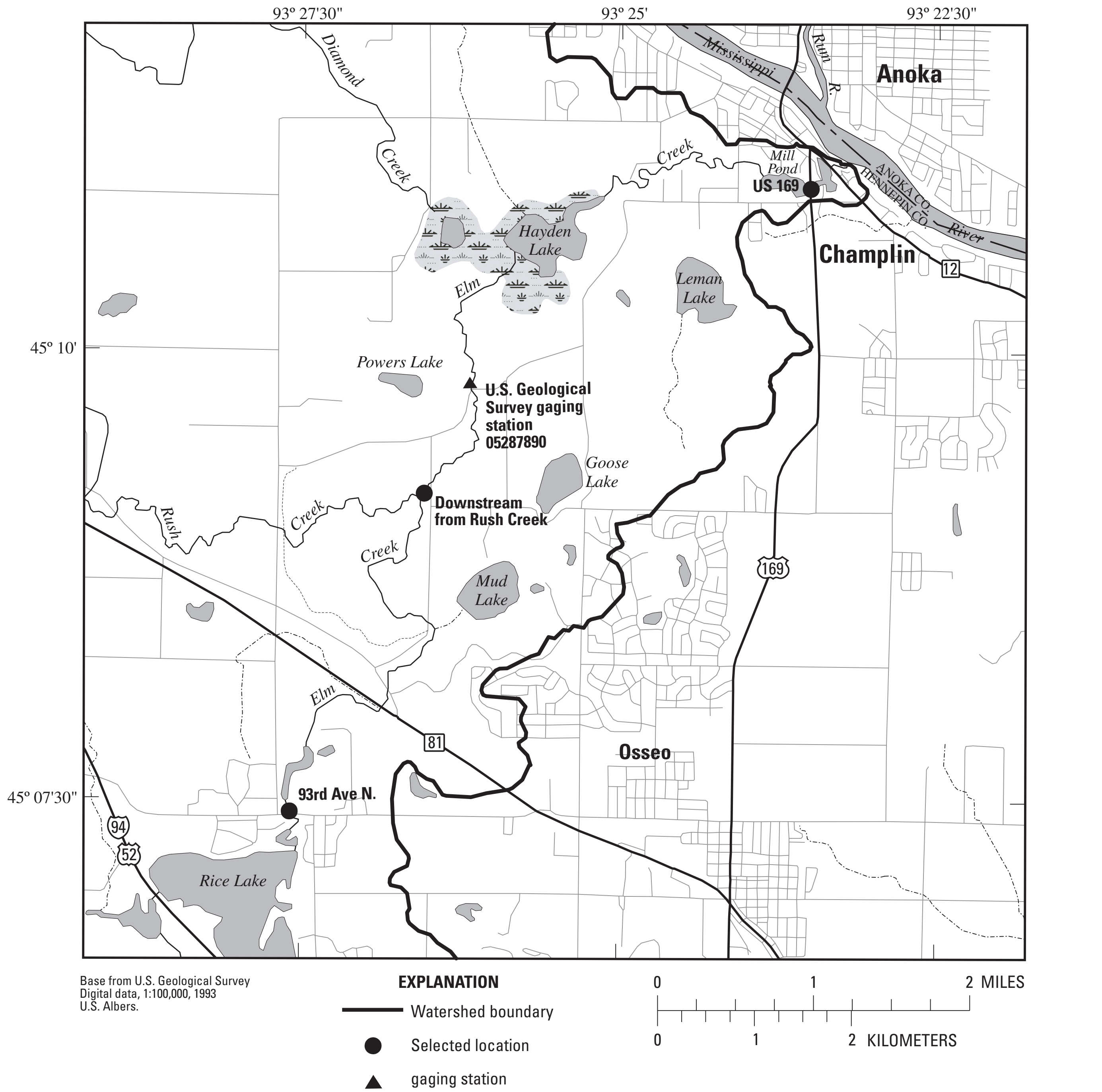


Figure 8. Downstream reach of Elm Creek showing selected locations of estimated time of travel points.

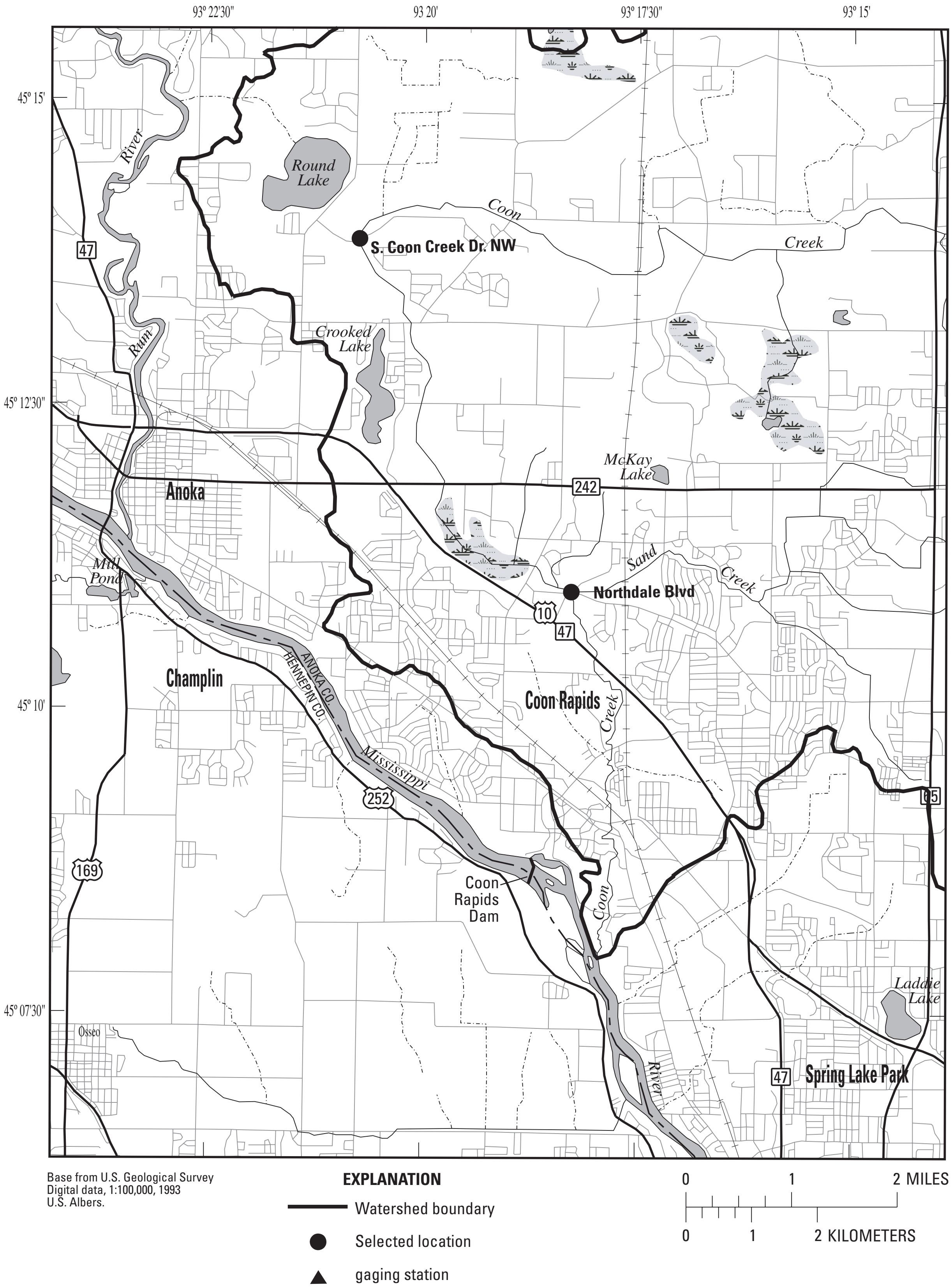


Figure 9. Downstream reach of Coon Creek showing selected locaitons of estimated time of travel points.

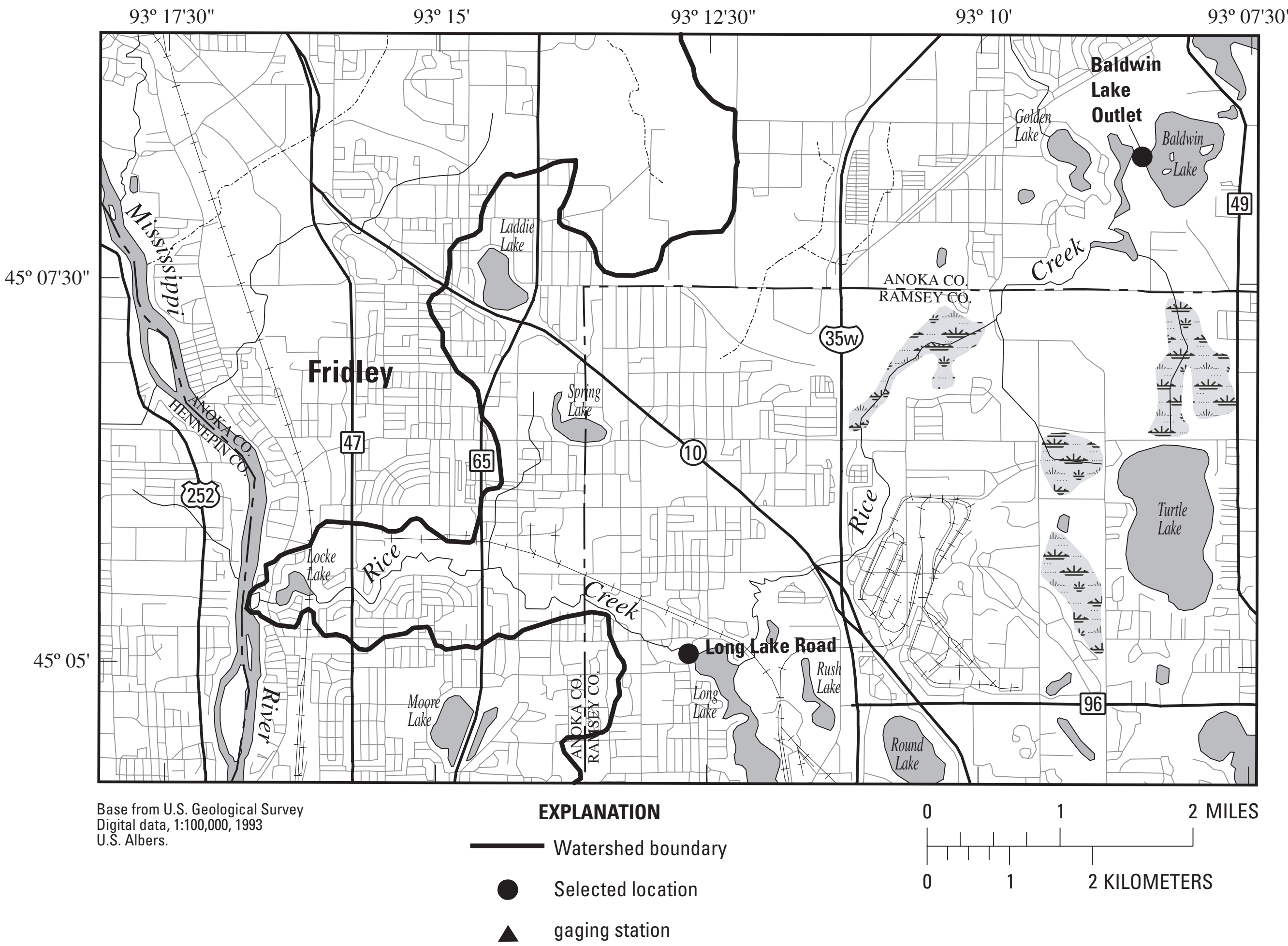


Figure 10. Downstream reach of Rice Creek showing selected locations of estimated time of travel points.

to feet per second for each reach using Jobson's equations and the associated watershed characteristics. Computed peak velocities ranged from 0.48 ft/s for Elm Creek to 0.92 ft/s for the Elk River at low flows, and from 1.6 ft/s for Coon Creek to 2.7 ft/s for the Crow River at high flows. Computed maximum probable velocities typically were about 2 times greater at lower flows and about 1.5 times greater at higher flows than the computed peak velocities. Corresponding travel times were estimated for each reach using the computed peak velocities and the reach length. The minimum travel time of peak concentration is based on the maximum probable velocity. Total travel times of the trailing edge to the mouth of each tributary are given at selected points for each of three flow conditions. The low flow values are represented by the 90 percent exceedance discharges (table 1), the median flow values are represented by the 50 percent exceedance discharges (table 2), and the high flow values are represented by the 10 percent exceedance discharges (table 3) for all tributaries except Coon and Rice Creeks where low and high flow discharges were assumed due to lack of available data, and the mean annual discharge was used for the median flow value.

On tributaries where the main channel passes through storage areas of lakes, marshes, and backwater from dams, the computed reach velocities do not reflect or incorporate the inherent retention times and delays caused by these features. Jobson's equations are based on stream reaches where storage was not a major factor. Storage effects were ignored in this study so that the minimum travel times could be estimated, as would be the case if a dam were breeched and the water stored behind it were totally drained. Estimation of retention times for these areas of storage was beyond the scope of this study. Users of these data must make the appropriate adjustments based on flow volumes and area of effective flow for storage areas (Mays, 2000). Jobson's equations were based on studies where a soluble dye tracer was used; therefore, the time of travel estimates in tables 1-3 are only valid for soluble conservative contaminants.

Sauk River Time of Travel Study

A time-of-travel study, using a water-soluble-tracer dye, was conducted on the Sauk River, from Rockville to the confluence with the Mississippi River (fig. 4). This tracer study defines tracer-response curves for sampling sections in the

Table 1. Estimated low-flow travel times represented by 90 percent exceedance discharge

[ft³/s, cubic feet per second; USGS, U.S. Geological Survey; WWTP, wastewater treatment plant]

Location	Distance upstream from mouth, in feet	Discharge, in ft³/s	Minimum travel time of peak concentration to mouth, in hours	Travel time of peak concentration to mouth, in hours	Travel time of leading edge to mouth, in hours	Duration of solute at mouth, in hours	Total travel time of trailing edge to mouth, in hours
Sauk River							
County Road 1	328	37	0.1	0.1	0.1	0.1	0.2
Veterans Drive	21,800	37	4.0	7.6	6.8	4.0	10.8
USGS gage 05270500	27,800	37	5.2	9.9	8.8	5.1	13.9
County Road 121	51,500	37	9.9	18.9	16.8	9.1	26.0
Interstate 94 Bridge	57,000	37	11.0	21.1	18.8	10.0	28.8
County Road 139 (Rockville)	83,000	37	16.3	31.3	27.9	14.4	42.2
Rum River							
Downstream from Trott Brook	48,500	111	9.1	17.4	15.4	8.0	23.4
County Road 22, USGS gage 05286000	84,200	111	15.7	29.7	26.4	12.8	39.2
Elk River							
Orono Lake Dam	5,800	67	0.9	1.7	1.5	1.0	2.5
Inlet to Orono Lake	18,300	67	3.2	5.9	5.2	3.0	8.2
Railroad tracks	35,800	67	6.2	11.5	10.2	5.2	15.4
USGS gage 05275000	48,300	67	8.4	15.6	13.8	6.8	20.6
Crow River							
Interstate 94 Bridge	34,900	39	8.2	17.1	15.2	10.2	25.4
St. Michael WWTP	63,700	39	14.5	29.8	26.5	17.4	43.9
USGS gage 05280000 (Rockford)	122,600	39	27.8	57.1	50.8	32.8	83.6
Elm Creek							
US Hwy 169	2,400	2.0	0.6	1.3	1.2	0.8	2.0
USGS gage 05287890	26,400	2.0	7.1	16.0	14.2	9.6	23.8
Downstream from Rush Creek	33,500	2.0	9.0	20.4	18.1	12.1	30.3
93rd Avenue North	55,900	2.0	15.0	33.6	29.9	19.8	49.7
Coon Creek[1]							
Northdale Boulevard	32,700	15	6.7	13.0	11.6	5.8	17.4
South Coon Creek Drive NW	57,100	15	11.7	23.0	20.5	9.4	29.9
Rice Creek[1]							
Long Lake Road	34,500	20	6.6	12.6	11.2	5.7	16.9
Baldwin Lake outlet	72,700	20	14.4	27.8	24.8	11.3	36.0

[1] Assumed low-flow discharge

source-water assessment area of the Sauk River for the city of St. Cloud, and allows for evaluation of estimated and measured time-of-travel information in one of the seven tributaries described in this report. The Sauk River was chosen for the tracer study because of its proximity to the St. Cloud Water Utility intakes, and because it does not contain complicated hydrologic reaches involving reservoirs, lakes, or wetlands, thus making the comparison of estimated and measured results much easier.

Tracer-response curves were determined by instantaneously injecting a measured amount of water-soluble tracer upstream from the sampling sections and by measuring dye

Table 2. Estimated median-flow travel times represented by 50 percent exceedence discharge

[ft^3/s, cubic feet per second; USGS, U.S. Geological Survey; WWTP, wastewater treatment plant]

	Distance upstream from mouth, in feet	Discharge, in ft^3/s	Minimum travel time of peak concentration to mouth, in hours	Travel time of peak concentration to mouth, in hours	Travel time of leading edge to mouth, in hours	Duration of solute at mouth, in hours	Total travel time ot trailing edge to mouth, in hours
			Sauk River				
County Road 1	328	457	0.03	0.04	0.04	0.06	0.10
Veterans Drive	21,750	457	1.78	2.82	2.51	1.39	3.90
USGS gage 05270500	27,764	457	2.32	3.67	3.27	1.69	4.96
County Road 121	51,499	457	4.47	7.12	6.33	2.75	9.09
Interstate 94 Bridge	57,007	457	4.99	7.95	7.07	2.99	10.06
County Road 139 (Rockville)	83,055	457	7.46	11.93	10.62	4.03	14.65
			Rum River				
Downstream from Trott Brook	48,516	360	6.59	11.39	10.14	4.56	14.69
County Road 22, USGS gage 05286000	84,184	360	11.28	19.42	17.28	6.99	24.27
			Elk River				
Orono Lake Dam	5,827	163	0.70	1.17	1.05	0.74	1.78
Inlet to Orono Lake	18,305	163	2.46	4.24	3.77	2.05	5.82
Railroad tracks	35,848	163	4.80	8.26	7.35	3.49	10.85
USGS gage 05275000	48,349	163	6.50	11.21	9.98	4.46	14.43
			Crow River				
Interstate 94 Bridge	34,949	270	5.31	9.42	8.39	4.19	12.58
St. Michael WWTP	63,737	270	9.12	15.96	14.20	6.50	20.70
USGS gage 05280000 (Rockford)	122,578	270	17.51	30.62	27.25	11.18	38.43
			Elm Creek				
US Hwy 169	2,408	11.0	0.45	0.84	0.75	0.56	1.31
USGS gage 05287890	26,366	11.0	5.47	10.79	9.60	4.90	14.50
Dwonstream from Rush Creek	33,542	11.0	6.97	13.75	12.24	6.01	18.25
93rd Avenue North	55,944	11.0	11.50	22.57	20.09	9.17	29.25
			Coon Creek[1]				
Northdale Boulevard	32,738	65.0	4.53	7.85	6.98	3.10	10.09
South Coon Creek Drive NW	57,129	65.0	8.01	13.94	12.41	4.80	17.21
			Rice Creek[1]				
Long Lake Road	34,529	93.0	4.25	7.18	6.39	2.90	9.30
Baldwin Lake outlet	72,727	93.0	9.44	16.14	14.37	5.37	19.74

[1] Mean annual discharge

concentrations over time downstream at each sampling section (Wilson, 1986). Results were used to compare measured travel time to estimates of travel time from mathematical solutions at the same reaches on the river.

The study reach was divided into areas of similar channel slope, and sampling sections were established near the points where the channel slope changed. Sample sections were established at road crossings at County Road 121, Veterans Drive, and County Road 1 (fig. 4).

Two liters of Rhodamine WT 20 percent concentration dye were injected in the Sauk River just downstream from County Road 139 in Rockville, Minnesota (fig. 4). The loca-

Table 3. Estimated high-flow travel times represented by 10 percent exceedence discharge

[ft^3/s, cubic feet per second; USGS, U.S. Geological Survey; WWTP, wastewater treatment plant]

	Distance upstream from mouth, in feet	Discharge, in ft^3/s	Minimum travel time of peak concentration to mouth, in hours	Travel time of peak concentration to mouth, in hours	Travel time of leading edge to mouth, in hours	Duration of solute at mouth, in hours	Total travel time of trailing edge to mouth, in hours
			Sauk River				
County Road 1	328	735	0.02	0.04	0.03	0.06	0.09
Veterans Drive	21,750	735	1.47	2.26	2.01	1.16	3.17
USGS gage 05270500	27,764	735	1.91	2.95	2.63	1.40	4.02
County Road 121	51,499	735	3.68	5.73	5.10	2.24	7.33
Interstate 94 Bridge	57,007	735	4.11	6.40	5.69	2.42	8.11
County Road 139 (Rockville)	83,055	735	6.16	9.61	8.56	3.23	11.79
			Rum River				
Downstream from Trott Brook	48,516	1350	4.10	6.50	5.78	2.51	8.29
County Road 22, USGS gage 05286000	84,184	1350	6.98	11.05	9.84	3.68	13.51
			Elk River				
Orono Lake Dam	5,827	553	0.44	0.69	0.61	0.49	1.11
Inlet to Orono Lake	18,305	553	1.59	2.52	2.25	1.27	3.51
Railroad tracks	35,848	553	3.09	4.92	4.38	2.06	6.43
USGS gage 05275000	48,349	553	4.20	6.68	5.95	2.57	8.51
			Crow River				
Interstate 94 Bridge	34,949	2240	2.47	3.84	3.42	1.67	5.09
St. Michael WWTP	63,737	2240	4.15	6.39	5.68	2.39	8.08
USGS gage 05280000 (Rockford)	122,578	2240	7.96	12.25	10.90	3.78	14.68
			Elm Creek				
U.S. Hwy 169	2,408	103	0.22	0.35	0.31	0.31	0.62
USGS gage 05287890	26,366	103	2.91	4.81	4.28	1.98	6.26
Downstream from Rush Creek	33,542	103	3.71	6.13	5.46	2.36	7.82
93rd Avenue North	55,944	103	6.06	9.99	8.89	3.34	12.24
			Coon Creek[1]				
Northdale Boulevard	32,738	150	3.40	5.57	4.95	2.20	7.15
South Coon Creek Drive NW	57,129	150	6.03	9.90	8.82	3.31	12.13
			Rice Creek[1]				
Long Lake Road	34,529	200	3.22	5.18	4.61	2.10	6.72
Baldwin Lake outlet	72,727	200	7.21	11.71	10.43	3.77	14.20

[1] Assumed high-flow discharge

tion was chosen because it was 6 miles upstream from the first sampling section, thus allowing sufficient time for the dye to laterally mix. It also was a good location for making an accurate stream-discharge measurement. The dye was premeasured before arriving at the site. A stream discharge measurement was made at the mouth of the Sauk River prior to the injection of the dye at Rockville. The measured discharge, 478 ft^3/s, was used in a longitudinal dispersion equation (Kilpatrick, 1989) to compute the required amount of dye necessary to result in an observed concentration of 2 μg/L at the mouth. The dye was injected at the center of flow at the water surface in about 4 feet of water. A stream discharge measurement of

457 ft^3/s was made at the site immediately following the dye release.

While the Rhodamine WT dye appeared bright pink when it was injected at County Road 139, it was indistinguishable to the naked eye at all sampling sections downstream. An estimate of travel time to each sampling section was determined based on measured stream velocity and sampling commenced at 5-minute intervals at an estimated time of arrival with each sample being analyzed at the site using a portable fluorometer. Samples were collected within each sample section at left, center, and right portions of the river. Samples were collected by lowering a weighted sample bottle to just below the water surface. Three samples were taken every 5 minutes until after the measured peak concentrations and the dye trace indicated a recession, at which time the sampling interval was lengthened to 10 minutes or more. Sampling ceased when the measured concentrations were 10 percent of the peak concentration or less. This method was used at all three sampling sections.

Measurements showed that lateral mixing was fairly well completed at all sampling sections. There was a slight time difference in the tracer-response curves as is shown in figure 11 for the sampling section at County Road 121. The dye plume traveled faster at the center of the channel than at the sides. The times were close enough to average together in determining travel times at all sampling sections. The travel times are listed in table 4.

Peak concentrations attenuated from the first sample section to the last as a result of longitudinal dispersion. Plots of average concentrations for three sample sections are shown in figure 12. The first sample section shows a higher peak concentration and a shorter duration than the last sample section near the mouth.

The travel time for the leading edge of the dye plume from Rockville, Minnesota, to County Road 1 near the mouth of the Sauk River, on June 16, 2003, at a discharge of 457 ft^3/s for the 15.7-mile reach was 13.42 hours (table 4). The duration of the dye plume was 7.08 hours.

The estimated travel times were less than the measured travel times (table 4). The estimated times for the leading edge were 79 percent of the measured times at County Road 1, 85 percent at Veterans Drive, and 90 percent at County Road 121 for the measured flow of 457 ft^3/s at the time of the study. The estimated times for the trailing edge, or total travel time in table 4, were 71 percent of the measured times at County Road 1, 76 percent at Veterans Drive, and 77 percent at County Road 121.

Jobson's equations give reasonable estimates of travel time for streams where storage is not a factor. An alternate system or an adjustment is needed for those streams where

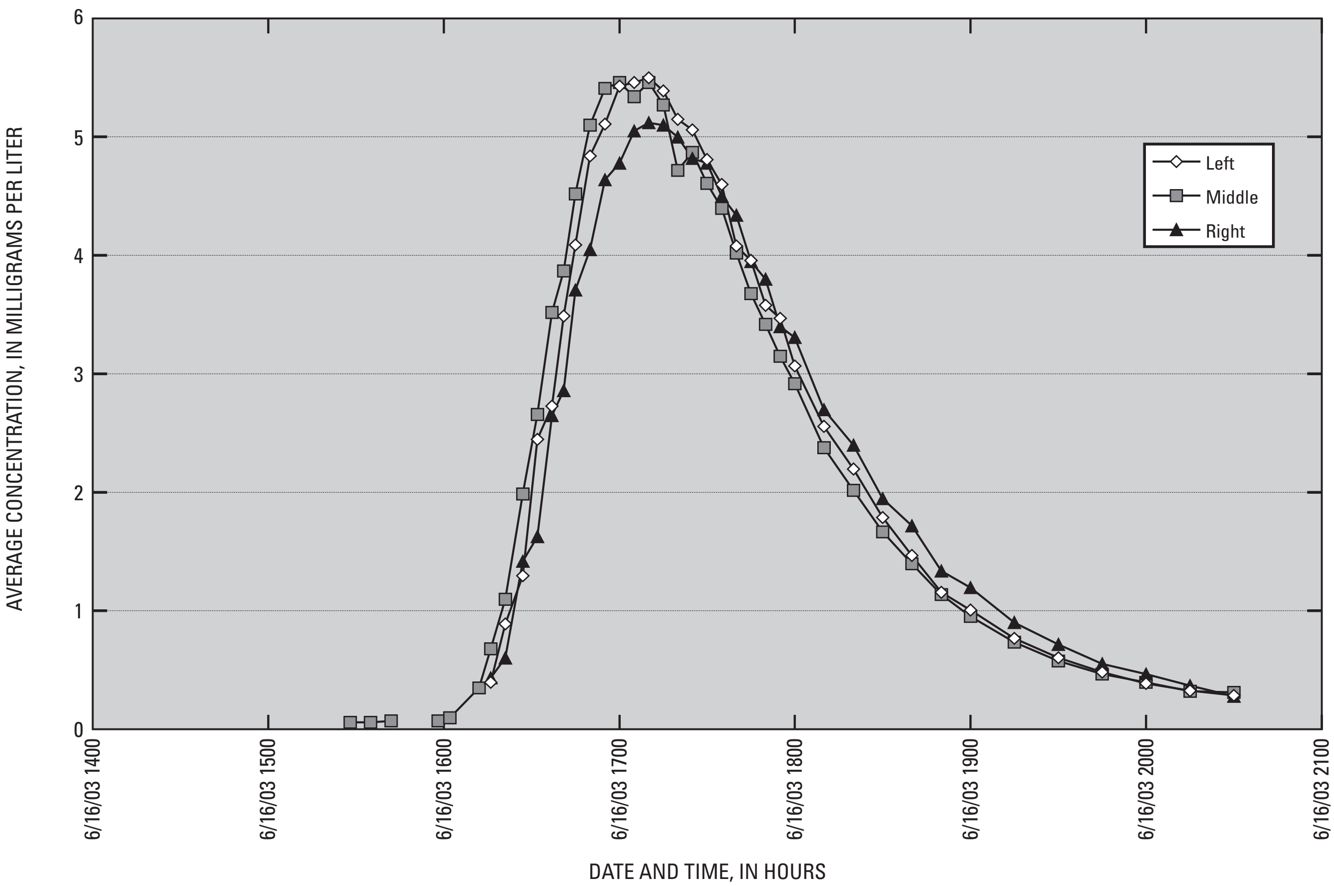


Figure 11. Tracer-response curves at left, center, and right sampling sections on the Sauk River at County Road 121.

Table 4. Comparison of estimated and measured travel times for reaches in the Sauk River

[ft^3/s, cubic feet per second; USGS, U.S. Geological Survey; WWTP, wastewater treatment plant]

Sampling section (fig. 4)	Distance upstream from mouth, in feet	Measured or planned flow, in ft^3/s	Travel time of peak concentration, in hours	Travel time to leading edge, in hours	Duration of solute, in hours	Total travel time to trailing edge, in hours
Sauk River - Estimated travel times from slug at Rockville						
County Road 1	328	457	11.9	10.6	4.0	14.6
Veterans Drive	21,800	457	9.4	8.4	3.4	11.8
County Road 121	51,000	457	5.0	4.4	2.1	6.6
County Road 139 (Rockville)	83,000	457	0.0	0.0	0.0	0.0
Sauk River - Measured travel times from dye injection at Rockville, June 16, 2003 at 11:15 hrs						
County Road 1	328	457	15.5	13.4	7.1	20.5
Veterans Drive	21,800	457	11.8	9.9	5.6	15.5
County Road 121	51,000	457	5.9	5.0	3.6	8.5
County Road 139 (Rockville)	83,000	457	0.0	0.0	0.0	0.0

storage is a significant factor. Time-of-travel estimates could be improved with additional study of storage effects on Elk River, due to the effects of Lake Orono; Rum River, due to the dam in Anoka; Elm Creek, due the effects of Hayden Lake; and Rice Creek, due to the effects of Baldwin and Long Lakes. Other numerical solutions also could be utilized to evalu-

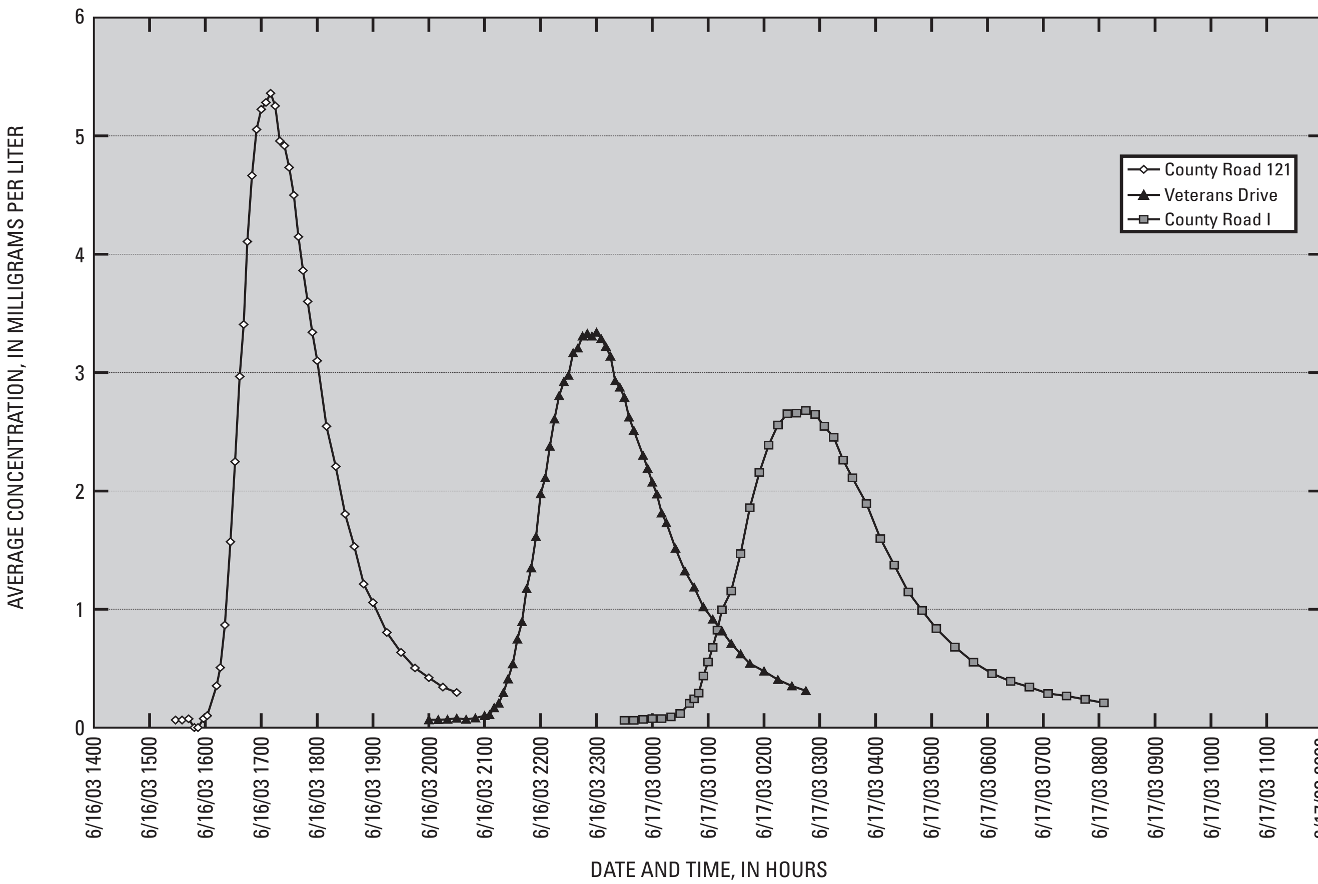


Figure 12. Tracer-response curves for three Sauk River sections.

ate storage areas with regard to volume, slope, and effective conveyance areas to determine estimates of travel time (Mays, 2000).

The study described in this report only involved the estimate of travel times within each of seven tributaries. Results from a tracer-response study also can provide useful information concerning flow dispersion and loss of mass of a contaminant.

Acknowledgments

The Coon Creek Watershed District and the Rice Creek Watershed District provided discharge records that were used to determine annual mean discharges for the respective tributaries. The St. Cloud Water Utility helped collect and analyze water samples from its water intakes. Appreciation also goes to Gregory A. Payne, a U.S. Geological Survey "Volunteer for Science," for his expertise and assistance in dye trace methods.

Summary

The cities of St. Cloud, Minneapolis and St. Paul, Minnesota obtain most of their drinking water from the Mississippi River. It is important that this source of water be protected from contamination caused by accidental spills or discharges. Water managers need a reliable estimate of the travel time of a contaminant from a spill to water intakes, and an estimate of the dispersion of the contaminant in the river. Travel times for seven streams tributary to the Mississippi River from St. Cloud to Minneapolis, Minnesota, were estimated for three flow conditions; low, median, and high. Travel times were estimated for Sauk, Elk, Crow, and Rum Rivers, and Elm, Coon, and Rice Creeks. A method, developed by the U.S. Geological Survey based on drainage area, slope, mean annual discharge, and instantaneous discharge at the time of measurement from more than 900 streams across the nation, was used to estimate travel times in a set of regression equations. Travel times were estimated for the leading edge, peak concentration, and trailing edge of a tracer-response curve.

To test the validity of these equations, a time of travel study, using a luminescent dye, was conducted on the Sauk River, from Rockville, Minnesota, to the confluence with the Mississippi River on June 16, 2003, at a discharge of 457 ft^3/s at Rockville. The time of travel study defined tracer-response curves for sample sections in the source-water protection area of the Sauk River for the city of St Cloud, and allowed for the comparison of estimated and measured time of travel information in one of the seven tributaries. Tracer-response curves were used to determine times of travel between sample sections at County Road 121, Veterans Drive, and County Road 1 along the Sauk River. The comparison of measured travel times to estimated travel times of the leading edge of the dye plume on the Sauk River shows that the estimated travel times were less than measured times. The estimated travel times for the leading edge, peak concentration, and trailing edge at County Road 1 were 10.6 hrs, 11.9 hrs, and 14.6 hrs respectively. The measured travel times for the leading edge, peak concentration, and trailing edge were 13.4 hrs, 15.5 hrs, and 20.5 hrs respectively for the 15.7 mile reach.

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