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Estimated and Measured Traveltime for the Crow River Watershed, Minnesota

Scientific Investigations Report 2007–5138

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

Cover. Photograph showing injected dye in the Crow River downstream from Rockford, Minn., July 11, 2006. View looking downstream from left bank.

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Conversion Factors and Abbreviations

Inch/Pound to SI

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)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
	Volume	
liter (L)	2.113	pint (pt)

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).

Abbreviations

ppb – parts per billion

USACE – U.S. Army Corps of Engineers

USGS – U.S. Geological Survey

WWTP – wastewater-treatment plant

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Abstract

A time-of-travel study involving a luminescent dye was done on the Crow River in Minnesota from Rockford to the confluence with the Mississippi River at Dayton on July 11, 2006, at a streamflow of 293 cubic feet per second at Rockford. Dye was injected in the Crow River at Rockford, and traveltime and concentrations were measured at three sampling locations downstream: at the Hanover historic bridge in Hanover, at County Road 116 near St. Michael, and at County Road 12 in Dayton. The results of the measured traveltimes were compared to estimated traveltimes from a previous study of the Crow River and six other rivers in the Upper Mississippi River basin in 2003. Regression equations based on watershed characteristics of drainage area, river slope, mean-annual streamflow, and instantaneous streamflow at the time of measurement from more than 900 stream segments across the Nation were used to estimate traveltimes. Traveltimes were estimated and measured for the leading edge, peak concentration, and trailing edge of tracer-response curves. Estimated traveltimes for the leading edge, peak concentration, and trailing edge at Dayton were 25.3, 28.4, and 35.6 hours, respectively. Measured traveltimes for the leading edge, peak concentration, and trailing edge at Dayton were 33.2, 38.2, and 49.2 hours, respectively, for the 22.4-mile reach. Although traveltimes for the Crow and the Sauk Rivers were underestimated by use of the regression equations, the regression estimates were close enough to measured values to be considered satisfactory; hence, this estimating technique should be applicable in other source-water planning efforts in and near the study area.

Introduction

The cities of St. Cloud, Minneapolis, and St. Paul 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 traveltime of the contaminant from a spill to water intakes and an estimate of the dispersion of the contaminant in the river.

The time required for a contaminant to reach a specific point in a river is the primary factor in determining the concentrations that may occur at a given point. Traveltime depends on many factors, among which are the general morphology of the river and, particularly, the amount of ponding caused by dams or other structures. Stream velocity and traveltime commonly vary with streamflow.

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 leading edge of the contaminant plume. The arrival time of the leading edge of the plume serves as an indication of when a problem first may exist and helps to define the overall shape of the concentration response function.

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

To address the need for reliable estimates of traveltime, the U.S. Geological Survey (USGS)—in cooperation with the Upper Mississippi River Source Water Protection Project—did a study on the Crow River to aid in implementation of source-water protection efforts in the Upper Mississippi River Basin. The dye injection part of the time-of-travel study defined time-concentration curves for cross-section locations in the delineated source-water protection area of the Crow River for the cities of Minneapolis and St. Paul (Minnesota Pollution Control Agency, 2001).

Purpose and Scope

The purpose of this report is to present the results of the cooperative study, which include (1) the measurement of traveltimes in the Crow River, at median flow conditions, by use of a dye tracer and (2) a comparison of measured and estimated traveltimes in the Crow River to evaluate the regression-equation based estimation technique. The report also discusses and compares the results of a similar study on the Sauk River at St. Cloud (Arntson and others, 2004).

Previous Studies

Previous studies of traveltimes were done on the Mississippi River by the U.S. Army Corps of Engineers (USACE) (1997) and the USGS.

The USACE determined traveltimes as part of the River Defense Network Program. The traveltimes 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 water supplies in times of low flow.

The USGS measured traveltimes on the Mississippi River from Anoka to Hastings during the low-flow years of 1976–77. The study, using dye-trace methods, was done in cooperation with the Metropolitan Waste Control Commission to understand wastewater-treatment-effluent flow and dispersion at times of low flow (U.S. Geological Survey, written commun., 1978). Traveltimes along tributary streams were not measured or calculated for the 1976–77 study.

In response for the need for reliable estimates of traveltime on streams tributary to the Mississippi River, the USGS did a study to aid in the implementation of source-water protection efforts in the Upper Mississippi River Basin in cooperation with the Upper Mississippi River Source Water Protection Project. Traveltimes for seven streams tributary to the Mississippi River from St. Cloud to Minneapolis were estimated for three flow conditions; low, median, and high. The streams were the Sauk, Elk, Crow, and Rum Rivers, and Elm, Coon, and Rice Creeks (fig. 1). Regression equations based on watershed characteristics of drainage area, river slope, mean annual streamflow, and instantaneous streamflow at the time of measurement from more than 900 stream segments across the Nation were used to estimate traveltimes (Jobson, 1996). Traveltimes were estimated for the leading edge, peak concentration, and trailing edge of tracer-response curves. As part of the seven-watershed study a time-of-travel study involving a water-soluble-tracer dye was done on the Sauk River from Rockville to the confluence with the Mississippi River (Arntson and others, 2004) (fig. 1). The study defined tracer-response curves and evaluated estimated and measured traveltimes of the Sauk River for the city of St. Cloud.

Hydrologic Setting

The Crow River watershed is in the east-central part of Minnesota (fig. 1). It covers an area of 2,760 mi^2 and converges from the southwest with the Mississippi River at Dayton. The topography of the Crow River watershed consists of gently rolling hills. Land use in the Crow River watershed is primarily agricultural with some scattered urban development, mostly in the lower part. The watershed receives about 29 in. of precipitation a year with about 25 in. as rainfall. The average temperatures are 69°F in the summer months and 13°F in the winter months (Baker and others, 1985).

Methods

The methods used to estimate traveltimes from equations and the methods used to measure traveltimes by use of a tracer dye are discussed in the following sections.

Estimates of Traveltimes from Equations

Estimated traveltimes for the Crow River were based on work from the previous Upper Mississippi River study (Arntson and others, 2004) in which regression equations were used to estimate traveltimes for low, median, and high flows at three locations in the lower reach of the river. The set of equations were subsequently revised to include traveltime estimates at two additional locations where dye concentration samples were collected (fig. 2). Traveltimes, peak velocities, and unit peak concentrations from selected locations to the mouth for the Crow River were determined using the revised set of equations.

The previous and current studies used the method developed by Jobson (1996) to estimate traveltimes in rivers. Jobson's method (1996) is based on a compilation of dye-tracer studies from more than 900 stream segments nationwide that represent a range in river size, slope, and geomorphic type, and it yields estimates of (1) the rate of movement of a conservative contaminant (hereafter, 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 streamflow, and instantaneous streamflow at the time of the measurement. (All mentions of Jobson hereafter refer to his 1996 report.)

Figure 1. Location of seven watersheds tributary to the Upper Mississippi River.

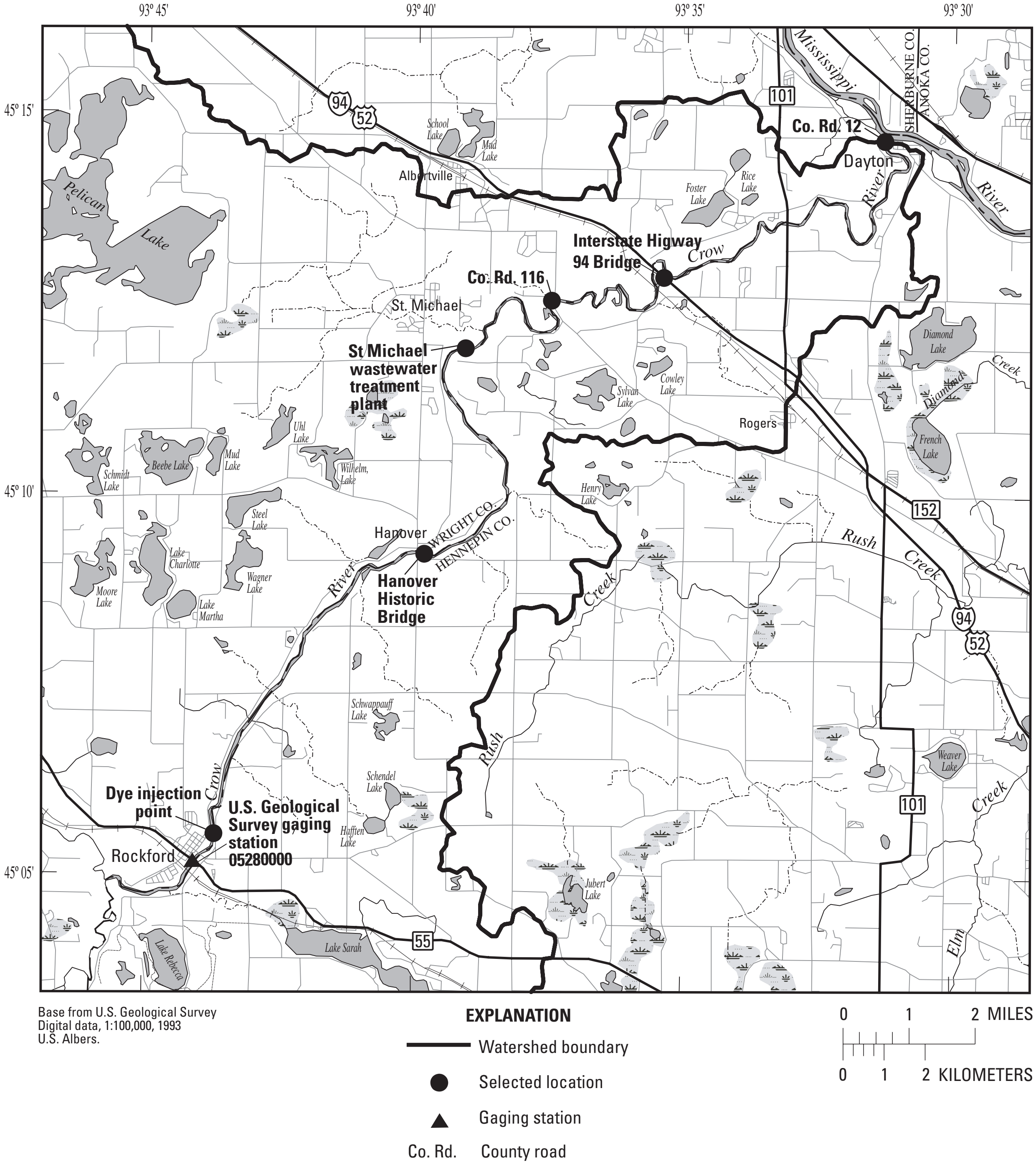


Figure 2. Downstream reach of Crow River showing selected locations of estimated and measured traveltime points.

Traveltime estimates were determined using the following equations.

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

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

where

- V_p is the peak velocity [m/s],
- D'_a is the dimensionless drainage area defined as $(D_a^{1.25} \text{ x } g^{0.5})/Q_a$,
- D_a is the drainage area of the river at the point of measurement [m^2],
- g is gravitational acceleration [9.86 m/s^2],
- Q_a is the mean annual streamflow at the section [m^3/s],
- Q'_a is the dimensionless relative streamflow defined as Q/Q_a,
- S is the slope of the reach [m/m], and
- Q is the streamflow at the section of the time of measurement [m^3/s].

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

$$V_{mp} = 0.25 + \left(0.02 \text{ x } (D'_a)^{0.919} \text{ x } (Q'_a)^{-0.469} \text{ x } S^{0.159} \text{ x } (Q/D_a)\right) \quad (2)$$

The equation for the traveltime of the leading edge of a contaminant plume is

$$T_l = 0.890 \text{ x } T_p \quad (3)$$

where

- T_l is the traveltime of the leading edge
- T_p is the traveltime of the peak concentration and is equal to the reach distance, in meters, divided by peak velocity, V_p

and where

- T_l and T_p have the same units.

Unit peak concentration is a relative term used to define a contaminant concentration independent of the magnitude of streamflow. The unit peak concentration can then be used for simulating the concentrations expected from various contaminants for different streamflows. The unit peak concentration is defined as 1,000,000 times the concentration produced in a unit streamflow 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.

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}):

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

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

$$C_{up} = 857 \times T_p^{-0.760\left(\frac{Q}{Q_a}\right)^{-0.079}} \quad (5)$$

Estimates for the traveltime of the leading edge, the traveltime of the peak concentration, and the magnitude of the unit peak concentration 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 10 percent of 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

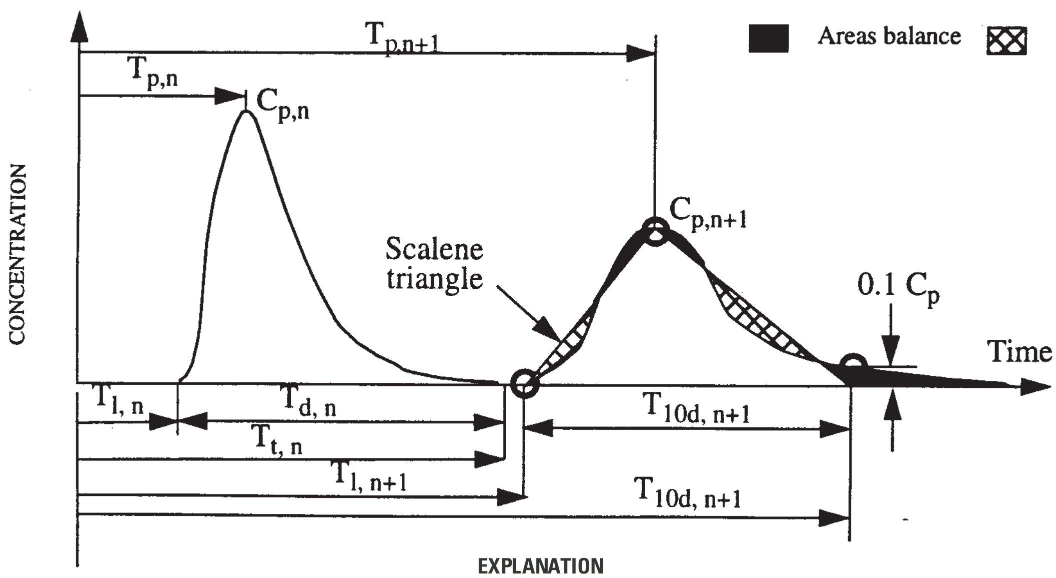
$$T_{10d} = 2{,}000{,}000/C_{up} \quad (6)$$

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 traveltime of the leading edge gives the traveltime of the trailing edge of the contaminant plume.

Watershed drainage area, channel slope, mean annual streamflow, and instantaneous streamflow were used to compute the traveltime variables from Jobson's equations. Watershed drainage area and channel slope were determined from 1:24,000-scale topographic maps. Mean annual streamflow was determined at the USGS gaging station at Rockford (USGS station 05280000) for the period of record (Mitton and others, 2002). The mean annual streamflow was adjusted for each sampling location on the Crow River on the basis of a simple linear relation with drainage area.



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 trailing 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 tracer-response curves (modified from Kilpatrick and Wilson, 1989, p. 3).

Time-of-Travel Study

Time-of-travel studies are done to quantify traveltime and dispersion for rivers. A known quantity of a water-soluble tracer dye is injected into a stream, and concentrations are measured as the dye moves downstream. The theoretical distribution of tracer concentrations resulting from an instantaneous injection of dye is shown in figure 4. The tracer-response curves shown in figure 4 are a function of longitudinal distance, not a function of time. For midstream injections, tracer plumes move faster than the mean stream velocity because the bulk of the tracer is transported in the high-velocity part of the stream. Preferably, measurements at locations for time-of-travel studies are far enough downstream that longitudinal dispersion is the dominant process; therefore the tracer moves downstream at the mean stream velocity.

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 traveltimes in streams when referenced to injection or spill times.

Tracer-response curves were determined using the methods developed by Wilson and others (1986) by instantaneously injecting a measured amount of water-soluble tracer upstream from the sampling locations and by measuring dye concentrations over time downstream at each sampling section. Results were used to compare measured traveltimes to estimated traveltimes from mathematical solutions at the same reaches on the river.

The study reach, 22.4 mi in length, was divided into areas of similar channel slope. Sample locations were established at three road crossings on the Crow River: at the Hanover historic bridge in Hanover, at County Road 116 near St. Michael, and at County Road 12 in Dayton (fig. 2).

Rhodamine WT concentrated dye, in the amount of 2.75 L, was injected in the Crow River just downstream from Rockford (fig. 2). The dye was injected at the center of flow at the water surface in about 2 ft of water. The location was approximately 6 mi upstream from the first sampling location (thus allowing sufficient time for the dye to mix laterally) and was within 1 mi of the USGS gaging station at Rockford. The dye was premeasured before it arrived at the site. A streamflow measurement was made at the injection site downstream from Rockford. The measured streamflow, 293 ft^3/s, was used in a longitudinal dispersion equation (Kilpatrick and Wilson, 1989) to compute the required amount of dye necessary to result in an observed concentration of 2 µg/L at the mouth. The units of parts per billion (ppb), which are equivalent to micrograms per liter, will be used in this report because the fluorometer used to measure dye concentration displays concentration directly in parts per billion.

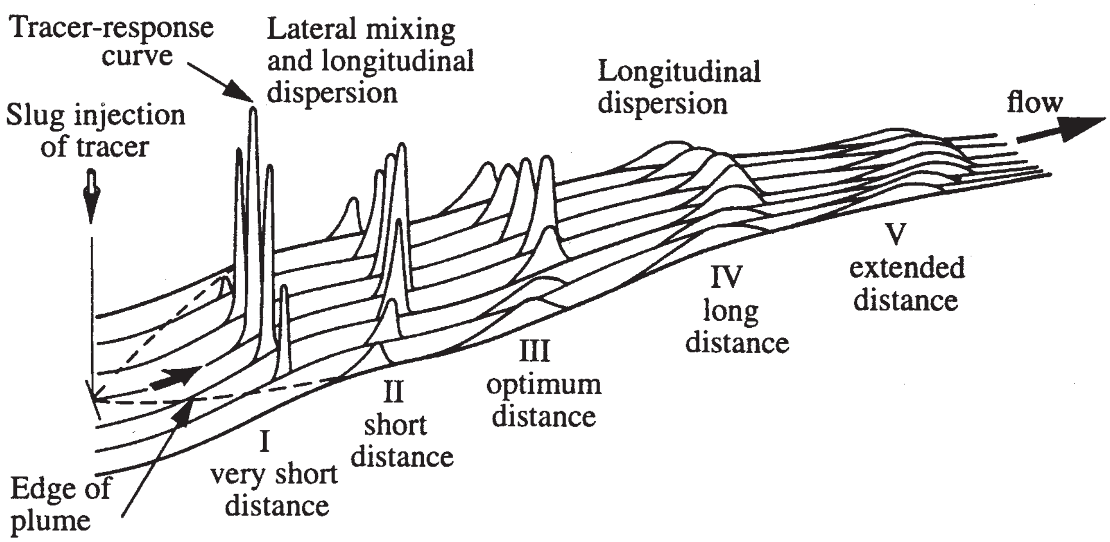


Figure 4. Lateral mixing and longitudinal dispersion of concentration of a water-soluble tracer downstream from a single, center, slug injection (modified from Kilpatrick, 1993, p. 2).

Although the rhodamine WT dye appeared bright pink when it was injected near Rockford, it was indistinguishable to the naked eye at all sampling locations downstream. An estimate of traveltime to each sampling location was determined on the basis of measured stream velocity. Sampling commenced at 5-minute intervals at an estimated time of arrival, each sample being analyzed at the site by use of a portable fluorometer. Three samples were collected within each sample cross section at left, center, and right positions across the channel. Samples were collected by lowering a weighted sample bottle to just below the water surface. Three samples were collected 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 locations.

The fluorometer used to measure the fluorescence of the water samples was calibrated with pre-mixed standards prior to use and in accordance with USGS (Wilson and others, 1986) and manufacturer's (Turner Designs, 1999) procedures. Fluorescence was measured in the field immediately after sampling and again in the USGS Minnesota Water Science Center laboratory under a controlled environment to verify initial field measurements. Water samples were collected in standardized glass vials, each one etched with a unique identification number. Sample measurements were logged by use of assigned unique numbers.

Estimated Traveltimes of the Crow River

Time-of-travel equations used in the 2003 study (Arntson and others, 2004) were used as a starting point for this study. The original set of equations was modified to include two additional locations at bridges at Hanover (Hanover historic bridge) and St. Michael (County Road 116). The new locations were used as sampling points rather than the original locations at Interstate Highway 94 and the St. Michael wastewater-treatment plant (WWTP) because of the inherent dangers and inaccessibility of those sites for sampling (fig. 2).

The revised set of equations was used to estimate traveltimes for the leading edge, peak concentration, and trailing edge of the solute from the dye injection point on the Crow River below Rockford to the mouth. A measured streamflow of 293 ft^3/s on July 11, 2006, was used to estimate traveltimes. The measured streamflow was very near to the median flow of 270 ft^3/s as represented by the 50 percent exceedance streamflow for the Crow River at Rockford (USGS gaging station 05280000).

Jobson's equations were used to compute velocities in meters per second and converted to feet per second for each reach by use of the associated watershed characteristics. Velocities of the peak concentrations ranged from 0.91 ft/s at Hanover historic bridge to 1.15 ft/s at County Road 12 at Dayton for the Crow River. The computed maximum probable velocity was about 1.75 times the computed velocities for peak concentration at the given streamflow.

Traveltimes were estimated for each reach of the study area by use of the computed velocity and the reach length (table 1). The minimum traveltime of peak concentration is based on the maximum probable velocity. Total traveltime of the trailing edge to the mouth of the Crow River is given from selected points for the given streamflow.

Table 1. Estimated and measured traveltimes for reaches in the Crow River.

[ft³/s, cubic feet per second; Co Rd, County Road; WWTP, wastewater-treatment plant; a, not estimated; USGS, U.S. Geological Survey; b, not measured]

Sampling section (fig. 3)	Distance upstream from mouth (feet)	Measured or planned flow (ft³/s)	Traveltime of peak concentration (hours)	Traveltime of leading edge to mouth (hours)	Duration of solute (hours)	Total traveltime to trailing edge (hours)
Crow River — Estimated traveltimes from slug injected at Rockford using regression equations						
Mouth	0	293	28.5	25.4	10.4	35.8
Co Rd 12 (Dayton bridge)	623	293	28.4	25.3	10.3	35.6
Interstate Highway 94 Bridge	34,900	293	20.5	18.2	7.9	26.1
Co Rd 116 (St. Michael bridge)	48,900	293	17.4	15.5	6.9	22.4
St. Michael WWTP	63,700	293	14.2	12.6	5.8	18.4
Hanover historic bridge	86,800	293	9.6	8.6	4.2	12.8
Dye injection point (Rockford)	118,000	293	a	a	a	a
USGS gaging station 05280000 (Rockford)	121,000	293	a	a	a	a
Crow River — Measured traveltimes from dye injection at Rockford, July 11, 2006						
Mouth	0	293				
Co Rd 12 (Dayton bridge)	623	293	38.2	33.2	16.0	49.2
Interstate Highway 94 Bridge	34,900	293	b	b	b	b
Co Rd 116 (St. Michael bridge)	48,900	293	23.2	19.2	13.5	32.7
St. Michael WWTP	63,700	293	b	b	b	b
Hanover historic bridge	86,800	293	12.2	10.2	9.7	19.9
Dye injection point (Rockford)	118,000	293	b	b	b	b
USGS gaging station 05280000 (Rockford)	121,000	293	b	b	b	b

The equations discussed in this report are used to estimate traveltimes to the mouth from an upstream point, representing an injection point. As such, the difference in estimated traveltimes to the mouth between locations does not represent the time traveled between those locations due to the effects of attenuation of the response curve over longer channel reaches. Jobson's equations were based on studies where a soluble dye tracer was used; therefore, the traveltime estimates in table 1 are only valid for soluble conservative contaminants.

Measured Traveltimes from the Crow River Time-of-Travel Study

The Crow River time-of-travel study defined tracer-response curves for sampling locations in the source-water assessment area of the Crow River (fig. 2) for the cities of Minneapolis and St. Paul and allowed for evaluation of estimated and measured traveltime information in one of the seven tributaries described in an earlier report (Arntson and others, 2004). The Crow River was chosen for the study because it is near the Minneapolis and St. Paul water utilities' 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.

Measurements of dye concentration at the three sampling points within each sampling cross-section showed that lateral mixing of the dye occurred at all sampling locations. The dye plume traveled slightly faster at the center of the channel than at the sides. The individual traveltimes of the left, center, and right sampling points within a sampling cross-section were close enough to each other to average together in determining traveltimes at all sampling locations. Travel times are listed in table 1.

Peak concentrations attenuated from the first sample location to the last as a result of longitudinal dispersion. Plots of average concentrations for the three sample locations are shown in figure 5. The first sample location shows a higher peak concentration and a shorter duration than the last sample location near the mouth.

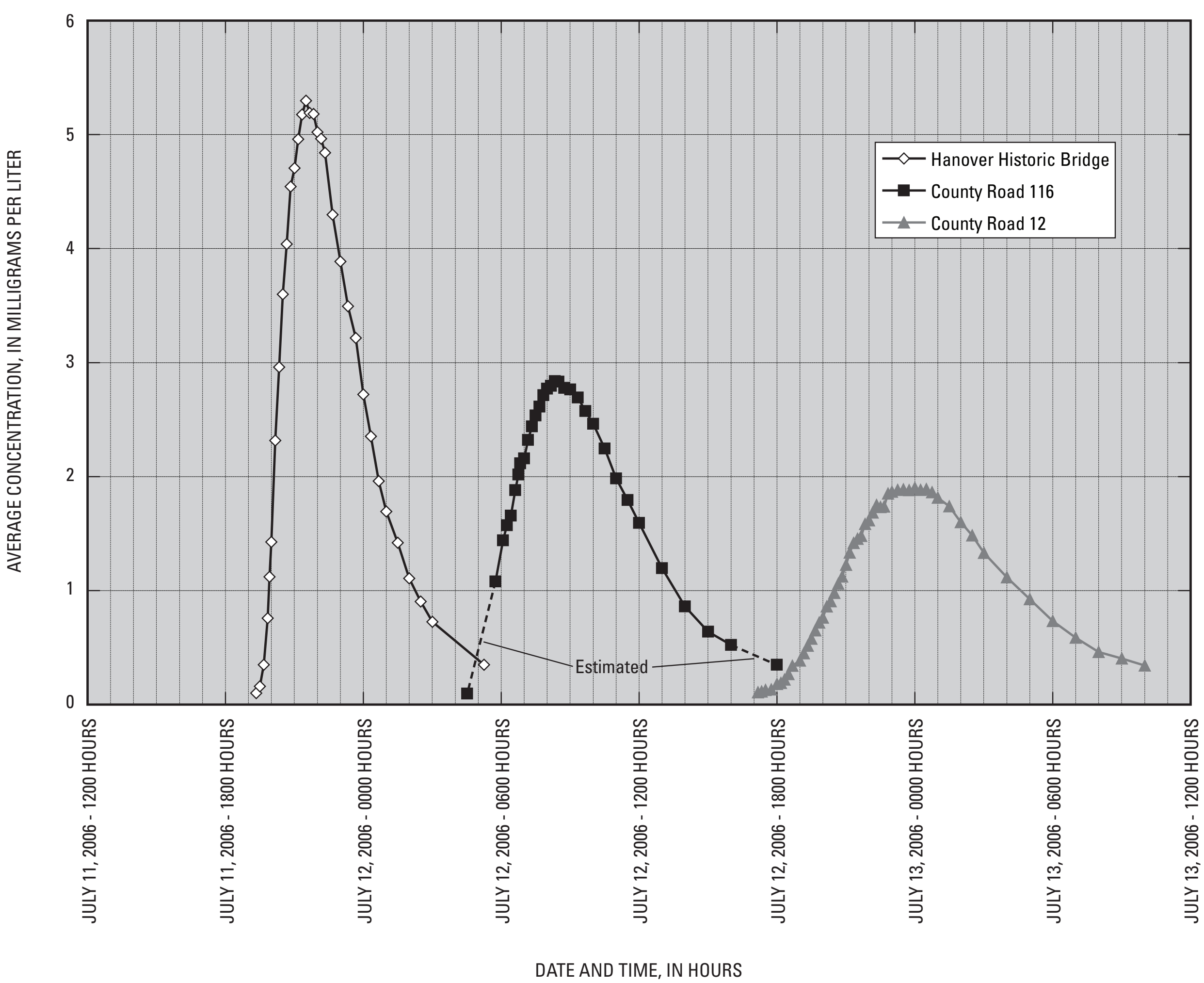


Figure 5. Tracer-response curves for three Crow River locations.

The traveltime for the leading edge of the dye plume for the 22.4-mi reach from Rockford to County Road 12 near the mouth of the Crow River at Dayton was 33.2 hours (table 1). The duration of the dye plume at Dayton was 16.0 hours.

The estimated traveltimes were less than the measured traveltimes (table 1). At the measured streamflow of 293 ft^3/s, the estimated traveltimes for the leading edge were 76 percent of the measured traveltimes at County Road 12, 81 percent at County Road 116, and 84 percent at Hanover. The estimated traveltimes for the trailing edge, or total traveltime in table 1, were 72 percent of the measured traveltimes at County Road 12, 69 percent at County Road 116, and 64 percent at Hanover.

Comparisons Between the Crow and Sauk Time-of-Travel Studies

The successful completion of the Crow River time-of-travel study created an opportunity to compare the results of the study with the results of the study done in 2003 on the Sauk River, from Rockville to the confluence with the Mississippi River at St. Cloud (fig. 1). The Sauk River dye study defined tracer-response curves for sampling locations in the source-water assessment area of the Sauk River for the city of St. Cloud and allowed for evaluation of estimated and measured traveltime information in one of the seven tributaries described by Arntson and others (2004).

The methods used in the Sauk River study were the same as in the Crow River study. Tracer-response curves were determined by instantaneously injecting a measured amount of water-soluble dye upstream from the sampling locations and measuring dye concentrations over time downstream at each sampling location. Results were used to compare measured traveltime to estimates of traveltime from mathematical solutions at the same reaches on the river. The mathematical methods used were the same for both studies.

The estimated traveltimes for the Sauk River were less than the measured traveltimes. At the measured streamflow of 457 ft^3/s, the estimated times for the leading edge ranged from 79 to 88 percent of the measured times, with the lower percentage at the mouth of the river. The estimated traveltimes for the trailing edge, or total traveltime, ranged from 71 to 78 percent of the measured times, with the lower percentage again at the mouth.

The magnitude and skew of estimated traveltimes and other watershed characteristics of both studies can be seen by comparing values between the two studies. A variety of characteristics for the Crow and Sauk River studies ranging from watershed size to traveltimes are listed in table 2.

Table 2. Watershed and dye-study characteristics for the Crow and Sauk Rivers time-of-travel studies.

[ft^3/s, cubic feet per second; ppb, parts per billion; ft/s, feet per second; mi^2, square miles]

Characteristic	Crow River	Sauk River
Drainage area, in mi^2	2,760	1,043
Study-reach length, in miles	22.4	15.7
Elevation at injection point, in feet	896	1,063
Elevation at mouth, in feet	843	989
Slope of study reach	.000448	.000891
Mean annual streamflow, in ft^3/s	815	308
Median streamflow[1], in ft^3/s	270	142
Study streamflow, in ft^3/s	293	457
Distance to first location from dye-injection point, in miles	5.97	5.98
Slope of first reach	.000185	.000404
Stream velocity of first reach, in ft/s	.86	1.75
Volume of injected dye, in liters	2.75	2.00
Peak dye concentration at first location, in ppb	5.30	5.36
Peak dye concentration at mouth, in ppb	1.89	2.68
Measured traveltimes at first location downstream from injection point		
Time to leading edge, in hours	10.2	5.0
Time to peak concentration, in hours	12.2	5.9
Solute duration, in hours	9.7	3.6

[1]From Mitton and others (2002).

The estimated traveltimes were less than the measured traveltimes for both the Crow River (table 1) and the Sauk River. Estimated traveltimes ranged from 64 to 84 percent of the measured traveltimes at the most upstream location and from 72 to 76 percent at the most downstream location on the Crow River, indicating that the equations better estimated traveltimes for shorter reaches where watershed characteristics were fairly consistent. The results were similar for the Sauk River, where estimated traveltimes ranged from 78 to 88 percent of the measured traveltimes for the most upstream location and from 71 to 79 percent for the most downstream location. The greater disparity between estimated and measured traveltimes at the most downstream location of the Crow River compared to the most downstream location of the Sauk River can be attributed to its longer reach; 22.4 mi compared to 15.7 mi, respectively.

Both studies were planned to measure the traveltimes at median streamflow (also known as the 50-percent exceedance flow). The Crow River study was done at 293 ft^3/s, very close to the median streamflow of 270 ft^3/s. The Sauk River study, on the other hand, was done during a year of higher sustained streamflows, and the streamflow of 457 ft^3/s during the study (about 20 percent exceedance) considerably exceeded the median streamflow of 142 ft^3/s.

The Crow River watershed is almost three times the area of the adjacent Sauk River watershed; drainage areas are 2,760 and 1,043 mi^2, respectively. The channel slope of the Crow River study reach is about one-half the channel slope of the Sauk River study reach, resulting in lower stream velocities and greater traveltimes for the Crow River for any given streamflow.

The first sampling location downstream from the dye injection point was about 6.0 mi for both the Crow and Sauk Rivers. Although less dye was injected for the Sauk River study, 2.00 L, than the Crow River study, 2.75 L, the measured peak dye concentrations at the first sampling locations were about equal; 5.36 and 5.30 ppb, respectively. Lower velocities and longer durations on the Crow River required more dye to achieve the same concentration.

The 22.4-mi study reach of the Crow River was about 50 percent longer than the 15.7-mi study reach of the Sauk River. Natural attenuation of the dye-response curve with lower peak dye concentrations at the mouth of the river appears to be related to the length of the stream reach, as evidenced by peaks of 1.89 ppb on the Crow River compared to 2.68 ppb on the Sauk River. Longer durations between leading edge and trailing edge of the dye plume also were noted at the first sampling section downstream from the injection point of each watershed (9.7 hours on the Crow River and 3.6 hours on the Sauk River).

Implications

This study has resulted in additional understanding of river hydraulics and estimates of traveltime that should benefit water managers in the Upper Mississippi River Basin—specifically those of the Minnesota Department of Health, and the cities of Minneapolis and St. Paul—in their efforts to protect drinking-water supplies. The study tested the feasibility of traveltime-estimation techniques in streams in Minnesota and increased the accuracy of the estimation technique when applied to the Crow River watershed. The study also has added to the accuracy of information previously obtained from the earlier Sauk River time-of-travel study. Although traveltimes for the Crow and the Sauk Rivers were underestimated by use of the regression equations, the regression estimates were close enough to measured values to be considered satisfactory; hence, this estimating technique should be applicable in other source-water planning efforts in and near the study area.

Summary

A time-of-travel study, involving a luminescent dye was done in cooperation with the Upper Mississippi River Source Water Protection Project on the Crow River in Minnesota from Rockford to the confluence with the Mississippi River at Dayton on July 11, 2006, at a streamflow of 293 cubic feet per second at Rockford. Dye was injected in the Crow River at Rockford, and traveltime and concentrations were measured at three sampling locations downstream: at the Hanover historic bridge in Hanover, at County Road 116 near St. Michael, and at County Road 12 in Dayton. The results of the measured traveltimes were compared to estimated traveltimes from a previous study of the Crow River and six other rivers in the Upper Mississippi River basin in 2003 and also to the measured traveltimes of a study done on the Sauk River in 2003. Regression equations based on watershed characteristics of drainage area, river slope, mean-annual streamflow, and instantaneous streamflow at the time of measurement from more than 900 stream segments across the Nation were used to estimate traveltimes. Traveltimes were estimated and measured for the leading edge, peak concentration, and trailing edge of tracer-response curves. Estimated traveltimes for the leading edge, peak concentration, and trailing edge at Dayton were 25.3, 28.4, and 35.6 hours, respectively. Measured traveltimes for the leading edge, peak concentration, and trailing edge at Dayton were 33.2, 38.2, and 49.2 hours, respectively, for the 22.4-mile reach.

The successful completion of the Crow River time-of-travel study provided an opportunity to compare the results with those from the earlier study on the Sauk River. Estimated traveltimes were less than measured traveltimes for both the Crow River and the Sauk River. Estimated traveltimes ranged from 64 to 84 percent of measured traveltimes at the most upstream location and from 72 to 76 percent at the most downstream location on the Crow River, indicating that the equations better estimated traveltimes for the shorter reaches. The results were similar for the Sauk River, where estimated traveltimes ranged from 78 to 88 percent of measured traveltimes for the most upstream location and from 71 to 79 percent for the most downstream location.

The 22.4-mile study reach of the Crow River was about 50 percent longer than the 15.7-mile study reach of the Sauk River. Natural attenuation of the dye-response curve with lower peak dye concentrations at the mouth of the river appears to be related to the length of the stream reach, as evidenced by peaks of 1.89 parts per billion on the Crow River compared to 2.68 parts per billion on the Sauk River. Longer durations between leading edge and trailing edge of the dye plume also were noted at the first sampling section downstream from the injection point of each watershed (9.7 hours on the Crow River and 3.6 hours on the Sauk River).

This study has resulted in additional understanding of river hydraulics and estimates of traveltime that should benefit water managers in the Upper Mississippi River Basin—specifically those of the Minnesota Department of Health, and the cities of Minneapolis and St. Paul—in their efforts to protect drinking-water supplies. The study tested the feasibility of traveltime-estimation techniques in streams in Minnesota and increased the accuracy of the estimation technique when applied to the Crow River watershed.

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