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# Travel Times, Streamflow Velocities, and Dispersion Rates in the Missouri River Upstream from Canyon Ferry Lake, Montana

Scientific Investigations Report 2012–5044

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

**COVER.** Looking downstream from the Missouri River Headwaters State Park over the Missouri River, near Trident, Montana, showing non-toxic red dye used in the dye-tracer study (photograph by Kyle W. Blasch, U.S. Geological Survey, taken September 8, 2010).

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By Aroscott Whiteman

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**U.S. Department of the Interior**
KEN SALAZAR, Secretary

**U.S. Geological Survey**
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2012

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Suggested citation:
Whiteman, Aroscott, 2012, Travel times, streamflow velocities, and dispersion rates in the Missouri River upstream from Canyon Ferry Lake, Montana: U.S. Geological Survey Scientific Investigations Report 2012–5044, 20 p.

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# Conversion Factors, Acronyms, and Abbreviated Units

Inch/Pound to SI

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| | Volume | |
| gallon (gal) | 3.785 | liter (L) |
| acre-foot (acre-ft) | 1,233 | cubic meter ($m^3$) |
| | 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 ($m^3/s$) |
| | Hydraulic gradient | |
| foot per mile (ft/mi) | 0.1894 | meter per kilometer (m/km) |

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8

Horizontal coordinate information is referenced to both the North American Datum of 1927 (NAD 27) and the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

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

Water-year definition:

Water year is the 12–month period from October 1 through September 30 of the following calendar year. The water year is designated by the calendar year in which it ends. For example, water year 2010 is the period from October 1, 2009, through September 30, 2010.

## Acronyms used in this report:

| | |
|---|---|
| ADCP | acoustic Doppler current profiler |
| CD–ROM | Compact Disc-Read-Only Memory |
| NTU | nephelometric turbity units |
| NWIS | National Water Information System |
| RWT | rhodamine WT |
| SCUFA | Self-Contained Underwater Fluorescence Apparatus |
| USGS | U.S. Geological Survey |

## Abbreviated units used in this report:

| | |
|---|---|
| ft/mi | foot (feet) per mile |
| ft/s | foot (feet) per second |
| $ft^3/s$ | cubic foot (feet) per second |
| L | liter |
| mg/L | milligram(s) per liter |
| µg/L | microgram(s) per liter |

# Travel Times, Streamflow Velocities, and Dispersion Rates in the Missouri River Upstream from Canyon Ferry Lake, Montana

By Aroscott Whiteman


## Abstract

In 2010, the U.S. Geological Survey (USGS), in cooperation with the Montana Department of Environmental Quality, initiated a dye-tracer study to determine travel times, streamflow velocities, and longitudinal dispersion rates for the Missouri River upstream from Canyon Ferry Lake. For this study, rhodamine WT (RWT) dye was injected at two locations, Missouri River Headwaters State Park in early September and Broadwater-Missouri Dam (Broadwater Dam) in late August, 2010. Dye concentrations were measured at three sites downstream from each dye-injection location. The study area was a 41.2-mile reach of the Missouri River from Trident, Montana, at the confluence of the Jefferson, Madison, and Gallatin Rivers (Missouri River Headwaters) at river mile 2,319.40 downstream to the U.S. Route 12 Bridge (Townsend Bridge), river mile 2,278.23, near Townsend, Montana. Streamflows were reasonably steady and ranged from 3,070 to 3,700 cubic feet per second.

Mean velocities were calculated for each subreach between measurement sites for the leading edge, peak concentration, centroid, and trailing edge at 10 percent of the peak concentration of the dye plume. Calculated velocities for the centroid of the dye plume ranged from 0.80 to 3.02 feet per second within the study reach from Missouri River Headwaters to Townsend Bridge, near Townsend. The mean velocity of the dye plume for the entire study reach, excluding the subreach between the abandoned Milwaukee Railroad bridge at Lombard, Montana (Milwaukee Bridge) and Broadwater-Missouri Dam (Broadwater Dam), was 2.87 feet per second. The velocity of the centroid of the dye plume for the subreach between Milwaukee Bridge and Broadwater Dam (Toston Reservoir) was 0.80 feet per second. The residence time for Toston Reservoir was 8.2 hours during this study.

Estimated longitudinal dispersion rates of the dye plume for this study ranged from 0.72 feet per second for the subreach from Milwaukee Bridge to Broadwater Dam to 2.26 feet per second for the subreach from the U.S. Route 287 Bypass Bridge over the Missouri River north of Toston, Montana to Yorks Islands. A relation was determined between travel time of the peak concentration and the time for the dye plume to pass a site (duration of the dye plume). This relation can be used to estimate when the decreasing concentration of a potential contaminant is reduced to 10 percent of its peak concentration for accidental (contaminant or chemical) spills into the upper Missouri River.


## Introduction

The Missouri River originates near Three Forks, Montana, at the confluence of the Gallatin, Jefferson, and Madison Rivers and flows about 733 river miles (mi) northeastward across Montana (fig. 1). It is a source of drinking water for several municipalities including Helena and Great Falls, Montana. Additionally, the Missouri River is important to the economy of this region serving as a primary water source for irrigation and providing recreational opportunities.

The Missouri River valley serves as a primary railway and highway transportation corridor through Montana. Transportation infrastructure within this corridor includes Interstate Highway 15, Montana Rail Link Railroad, state highways, and county roads. Many of these highways, railroads, and roads cross or come within 500 feet (ft) of the Missouri River. This complex infrastructure makes the Missouri River especially vulnerable to accidental (contaminant or chemical) spills from various sources such as tanker cars and trucks. Knowledge of instream travel times, streamflow velocities, dispersion rates, and dilution of contaminant concentrations is required for effective emergency response to a contaminant spill and can be used to calibrate hydraulic and water-quality models of the Missouri River. In 2010, the U.S. Geological Survey (USGS), in cooperation with the Montana Department of Environmental Quality, initiated a dye-tracer study to determine travel times, streamflow velocities, and longitudinal dispersion rates along the Missouri River upstream from Canyon Ferry Lake. The portion of the Missouri River upstream from Canyon Ferry Lake (fig. 1), hereinafter is referred to as the upper Missouri River.

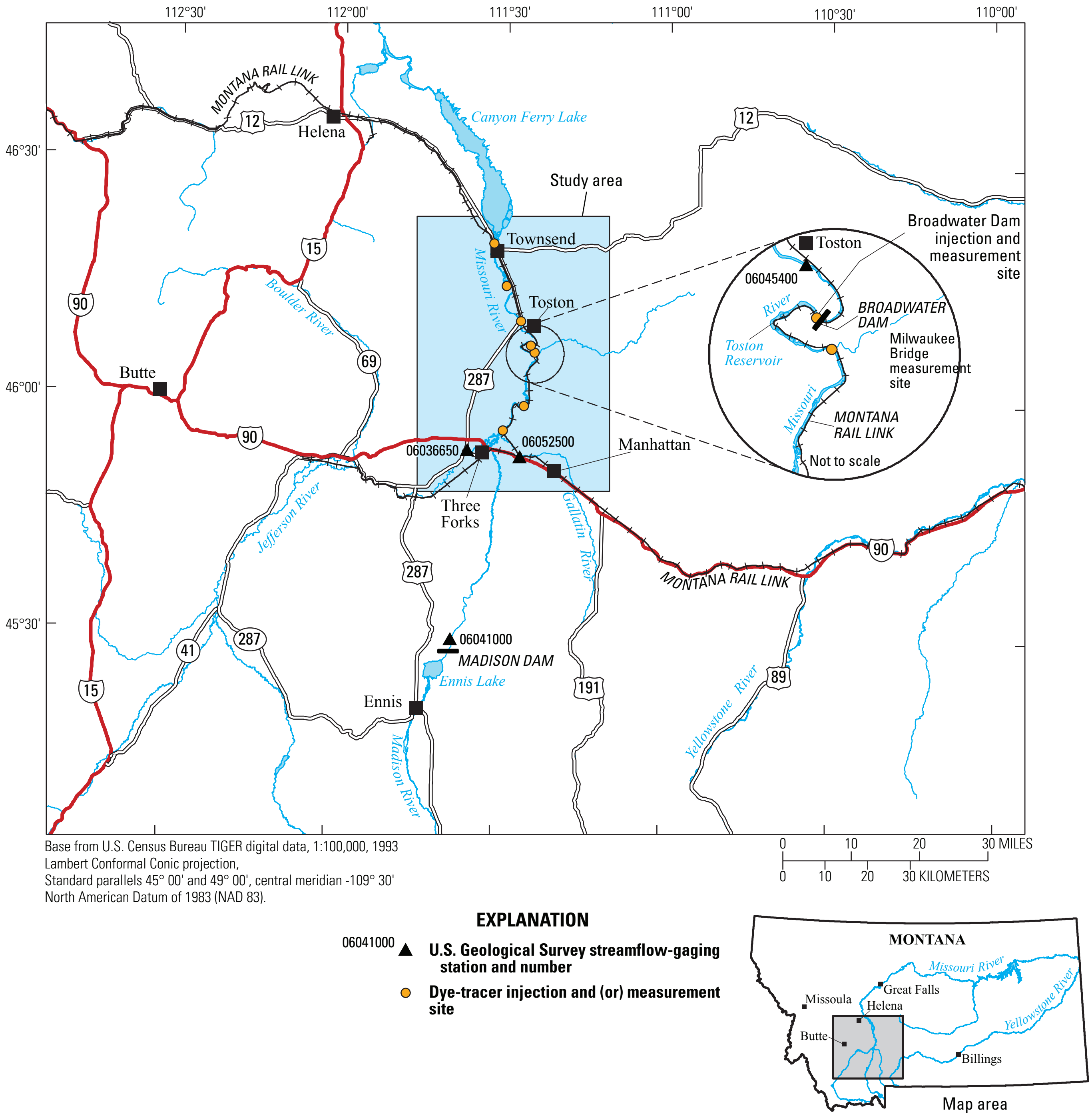



**Figure 1.** Location of the study area, upper Missouri River, Montana.

## Purpose and Scope

The purpose of this report is to describe the results of a study that determined travel times, streamflow velocities, and longitudinal dispersion rates for a 41.2-mile reach of the upper Missouri River from the Missouri River Headwaters State Park downstream to the U.S. Route 12 bridge over the Missouri River near Townsend (Townsend Bridge). For this study, rhodamine WT (RWT) dye was injected at two locations in late August and early September 2010, when measured streamflows during the August and September injections averaged 3,180 cubic feet per second ($ft^3/s$) and 3,600 $ft^3/s$, respectively. Dye concentrations were measured at three sites downstream from each dye-injection location. These data were used to determine travel times, streamflow velocities, and longitudinal dispersion rates for the study reach. Included in this report are the time-of-travel data collected during the dye-tracer study and the analyses used to determine streamflow velocities and longitudinal dispersion rates. Time-of-travel data collected during this study are in appendixes 1–4 [Compact Disc-Read Only Memory (CD–ROM) located in the inside back cover of the printed report].

## Description of Study Area

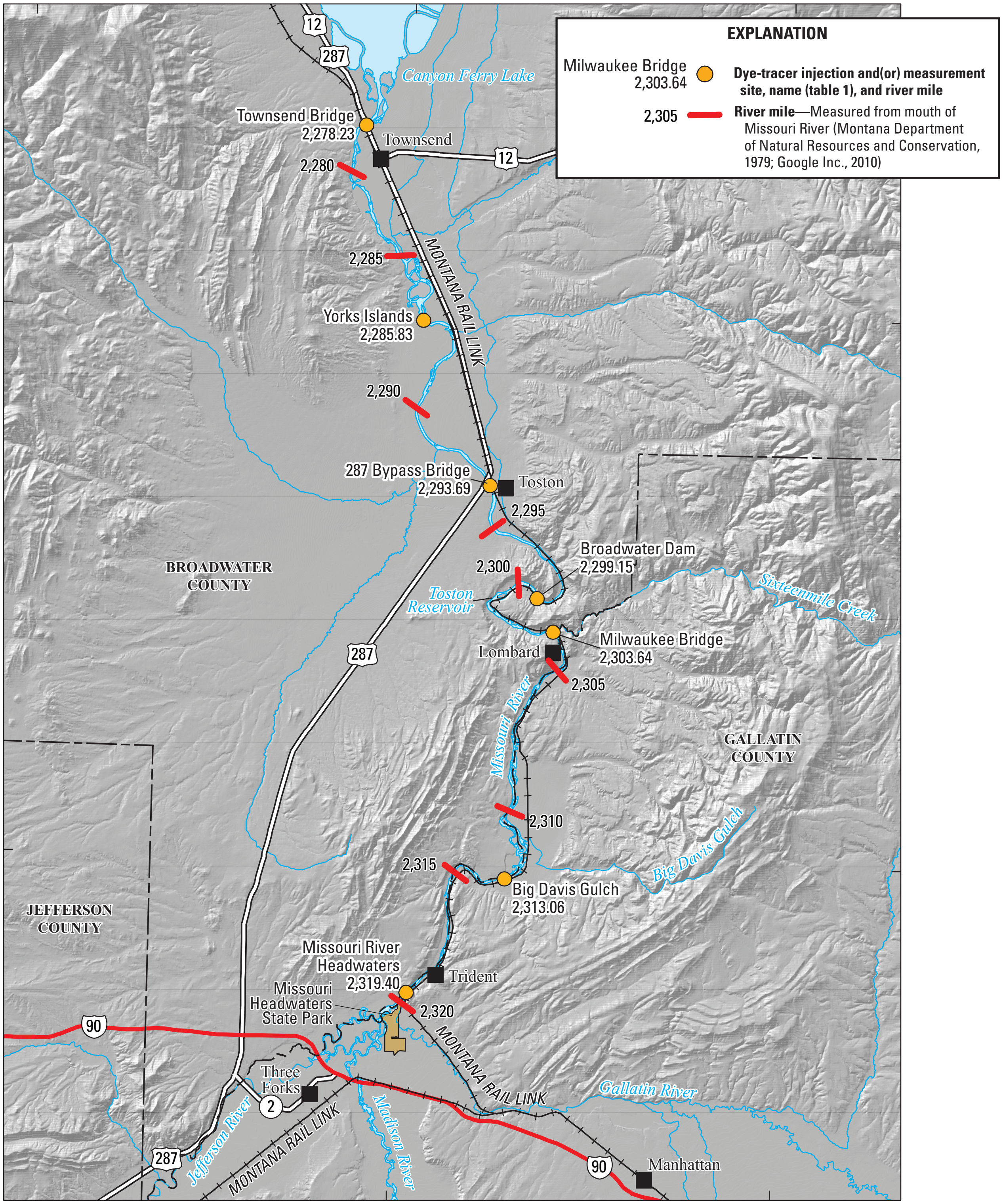
The upstream end of the study reach is near Trident, Montana, at the confluence of the Jefferson, Madison, and Gallatin Rivers in Missouri River Headwaters State Park (Missouri River Headwaters) at river mile 2,319.40 (table 1, fig. 2). The study reach extends 41.2 river miles downstream to Townsend Bridge at river mile 2,278.23 (fig. 2) [river miles derived from the Montana Department of Natural Resources and Conservation (1979) and Google, Inc. (2010)]. The contributions of water from tributaries that flow into the upper Missouri River within the study reach were estimated to be less than 1 percent of the total streamflow at the time of the dye-tracer injection, based on field observations.

Based on 75 years of record from water years 1910–1916, and 1941–2009, mean and median annual streamflows for Missouri River at Toston, Montana (USGS streamflow-gaging station number, 06054500, fig. 1), are 5,093 $ft^3/s$ and 4,000 $ft^3/s$, respectively (U.S. Geological Survey, 2010). Mean daily streamflow ranged from 700 to 33,400 $ft^3/s$. Maximum peak streamflow was 34,000 $ft^3/s$, which occurred on June 12, 1997. The channel slope of the Missouri River within the study reach ranged from 4.2 feet per mile (ft/mi) at Yorks Islands to 5.8 ft/mi at Townsend. The channel substrate ranged from mostly small cobbles and medium gravel at Trident to mostly gravel and sand at Townsend, based on field observations. The channel substrate is mostly medium gravel and sand throughout the small reservoir created by Broadwater-Missouri Dam (hereinafter is referred to as Broadwater Dam), a low-head dam that forms Toston Reservoir (fig. 1).

**Table 1.** Injection and measurement sites along the upper Missouri River, Montana.

[River mileages from Montana Department of Natural Resources and Conservation (1979) and Google Earth (2010). NAD 83, North American Datum of 1983; mi, miles]

| Site name | Site location (NAD 83) | | Site description | River mileage (mi) | Used for dye injection | Used for dye measuring |
|---|---|---|---|---|---|---|
| | Latitude degrees, minutes, seconds | Longitude degrees, minutes, seconds | | | | |
| Missouri River Headwaters | N 45° 56' 25.0" | W 111° 29' 27.6" | Missouri River Headwaters State Park boat access near Trident | 2,319.40 | Yes | No |
| Big Davis Gulch | N 45° 59' 34.9" | W 111° 25' 41.5" | 1.44 miles upstream from Big Davis Gulch, near Trident | 2,313.06 | No | Yes |
| Milwaukee Bridge | N 46° 06' 20.7" | W 111° 24' 00.9" | Milwaukee Bridge near Lombard | 2,303.64 | No | Yes |
| Broadwater Dam | N 46° 07' 13.8" | W 111° 24' 26.6" | Broadwater-Missouri Dam near Toston | 2,299.15 | Yes | Yes |
| 287 Bypass Bridge | N 46° 10' 18.6" | W 111° 26' 37.7" | U.S. Route 287 Bypass Bridge at Toston | 2,293.69 | No | Yes |
| Yorks Islands | N 46° 15' 03.0" | W 111° 29' 28.7" | 0.28 miles upstream from Yorks Islands, near Townsend | 2,285.83 | No | Yes |
| Townsend Bridge | N 46° 20' 07.2" | W 111° 31' 54.1" | U.S. Route 12 bridge near Townsend | 2,278.23 | No | Yes |




Base from U.S. Geological Survey National Elevation Dataset (NED), 1999, 1:24,000,
U.S. Census Bureau TIGER digital data, 1:100,000, 1993
Lambert Conformal Conic projection,
Standard parallels 45° 00' and 49° 00', central meridian -109° 30'
North American Datum of 1983 (NAD 83).



**Figure 2.** Location of sites used for dye injection and dye measurement along the study area, upper Missouri River, Montana.

Throughout the study reach, the upper Missouri River is used only for irrigation and recreation. Water used for irrigation is diverted either by Broadwater Dam or individual pumps at other locations along the river [(Montana) State Engineer's Office, 1956)]. For most of the study reach, the river supports a riparian corridor utilized by numerous wildlife species. Recreationalists commonly use the study reach for fishing, hunting, and paddling.

# Methods for Determining Travel Times, Streamflow Velocities, and Dispersion Rates

Dye tracers are commonly used for time-of-travel studies because the dyes are water soluble and behave similarly to water particles. A measure of the movement of the dye tracer will, in effect, be a measure of the movement of the fluid in the stream and its dispersion characteristics (Kilpatrick and Wilson, 1989). Dispersion and mixing of the injected dye tracer occurs in all three dimensions of the channel: vertical, lateral, and longitudinal. The rate at which mixing of the dye occurs depends on hydraulic characteristics of the stream, velocity variations, and how the dye is injected into the stream. In general, vertical mixing throughout the water column requires the shortest distance from the point of injection. Lateral mixing across the width of the channel requires a greater distance than vertical mixing and until the dye is mixed laterally, its movement does not represent the total flow. Lateral mixing of the dye will occur at a more rapid rate if the dye is injected at multiple points across the channel or from a single point at which the flow is concentrated, such as the face of a low-head dam. Channel characteristics such as sinuosity and channel roughness create variability in the streamflow velocity both laterally and vertically in the water column. Longitudinal mixing or dispersion, the dispersion component of primary interest, occurs continually as the dye moves downstream (Kilpatrick and Wilson, 1989).

## General Description of Dye Tracing

Dye-tracer concentrations measured continuously at points downstream from an instantaneous dye injection can be plotted as a function of time to create a time-concentration curve (fig. 3). Time-concentration curves can be used to determine the time-of-travel and dispersion characteristics of streams. Theoretical characteristics of a time-concentration curve for a stream are shown in figure 3. This time-concentration curve can be used to describe dye movement past a fixed measurement point located downstream from a dye injection (Kilpatrick and Wilson, 1989). The dye concentration and movement characteristics pertinent to time-of-travel measurements include:

$T_l$, travel time of leading edge of dye plume;

$T_p$, travel time of peak concentration of dye plume;

$T_c$, travel time of centroid of dye plume;

$T_{10p}$, travel time of trailing edge of dye plume where dye concentration is reduced to 10 percent of the peak concentration; and

$T_t$, travel time of trailing edge of dye plume.

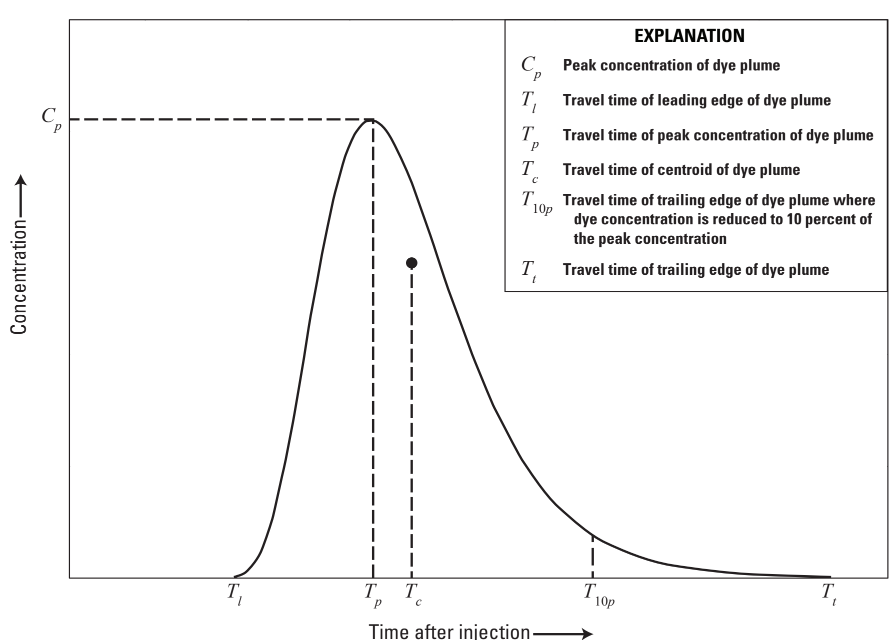



**Figure 3.** A typical time-concentration curve for the movement of dye past a fixed measurement point downstream from a dye injection (modified from Kilpatrick and Wilson, 1989).

The mean travel time ($t_c$) for the flow along the streamline is the difference in elapsed time of the centroids of the time-concentration curves defined upstream and downstream on the same streamline:

$$t_c = T_{c(n+1)} - T_{c(n)}, \quad (1)$$

where

$n$ is the number of the sampling site, and all other terms are as previously defined. The time required for the centroid of a dye plume to travel through a river reach ($t_c$) is used to calculate the mean velocity of the centroid of the dye plume, which represents the mean streamflow velocity for the reach.

The mean travel times of the leading edge ($t_l$), peak concentration ($t_p$), 10 percent of the peak concentration ($t_{10p}$), and trailing edge ($t_t$) along a given streamline are:

$$t_l = T_{l(n+1)} - T_{l(n)}, \quad (2)$$

$$t_p = T_{p(n+1)} - T_{p(n)}, \quad (3)$$

$$t_{10p} = T_{10p(n+1)} - T_{10p(n)}; \text{ and} \quad (4)$$

$$t_t = T_{t(n+1)} - T_{t(n)}, \quad (5)$$

where all terms are as previously defined. These travel times are used to calculate the mean velocity of these portions of the dye plume through a river reach. These mean velocities are then used to estimate longitudinal dispersion rates and also are used to estimate when a contaminant introduced into the stream at a certain point might reach a point downstream, at a concentration great enough to cause concern.

The time, $T_d$, necessary for the dye plume to completely pass a measurement site in a section is:

$$T_d = T_{t(n)} - T_{l(n)}. \quad (6)$$

The time, $T_{10d}$, necessary for the dye plume to pass a measurement site until the concentration of the dye plume on the trailing edge is 10 percent of the peak concentration (duration) is:

$$T_{10d} = T_{10p(n)} - T_{l(n)}. \quad (7)$$

## Dye Injections

For this study, RWT dye was injected into the upper Missouri River from a boat at Missouri River Headwaters and from an inlet structure at Broadwater Dam (table 1, fig. 2). For the injection at Missouri River Headwaters, dye concentrations were measured downstream from a boat at a site a few river miles upstream from the confluence of Big Davis Gulch (Big Davis Gulch), from the abandoned Milwaukee Railroad bridge over the Missouri River at Lombard, Montana (Milwaukee Bridge) and from Broadwater Dam (table 1, fig. 2). For the injection at Broadwater Dam, dye concentrations were measured downstream from the U.S. Route 287 Bypass bridge over the Missouri River north of Toston, Montana (287 Bypass Bridge), from a boat at Yorks Islands, and from Townsend Bridge (table 1, fig. 2). Where possible, bridges were used for measuring sites because they provided the safest access to the centroid of the river.

RWT dye at 20-percent stock solution was used as the dye tracer because it is a nearly conservative, water-soluble, nontoxic dye that can be detected at low concentrations using a fluorometer. The volume of RWT dye injected at Missouri River Headwaters and Broadwater Dam was 45.4 and 23.0 liters (L), respectively. With streamflows of 3,620 and 3,070 $ft^3/s$ at the injection sites (table 2), the resulting instantaneous concentration of the dye in the upper Missouri River was 100 milligrams per liter (mg/L) at the Missouri River Headwaters injection site and 59.8 mg/L at the Broadwater Dam injection site. Three lateral-injection points were used at the Missouri River Headwaters injection site to accelerate lateral mixing, with a third of the dye injected at points representing 25, 50, and 75 percent of total streamflow measured from the left streambank to the right streambank. At Broadwater Dam, all of the dye was injected into the hydraulic vortex created by water passing through the bell-mouthed inlet spillway.

Travel-time data represent the mean travel time of streamflow in a river reach only when the dye is uniformly mixed throughout the entire cross section. The dye is considered completely mixed when lateral and vertical dye concentrations are equivalent throughout a cross section. The distance required for complete lateral mixing (optimal mixing length) for each injection site was estimated using flow and channel characteristics just downstream from each injection site using equation 7 from Kilpatrick and Wilson (1989). The optimal mixing length for the injection at Missouri River Headwaters was estimated to be 0.81 mi. Because of complete mixing from the turbines within the dam structure, the optimal mixing length for the injection at Broadwater Dam was considered to be negligible.

On September 8, 2010, travel times that were calculated from the Missouri River Headwaters injection site to the first measurement site downstream (Big Davis Gulch, fig. 2) did not accurately represent the mean travel time of that subreach because cross-sectional measurements of dye concentrations indicated that the dye was not completely mixed. However, for all other subreaches, the dye was considered to be completely laterally mixed for both the injections at Missouri River Headwaters and Broadwater Dam. Thus, calculated travel times (table 2) did accurately represent the mean travel times between measurement sites.

## Fluorometric Measurements

At each measurement site downstream from a dye-injection site, a Self-Contained Underwater Fluorescence Apparatus (SCUFA) was used to measure the fluorescence of the dye (Turner Designs, 2001; 2004). The SCUFA fluorometer converts the measured fluorescence of the dye to a dye concentration when it is calibrated to known concentrations. Prior to each of the dye injections, the SCUFAs were calibrated with known dye concentrations of 0 µg/L, 10 µg/L, and 25 µg/L depending on the peak dye concentration expected at the measurement site. The SCUFAs were deployed from bridges or an anchor attached to a buoy at each measurement site and were suspended in the water column in the centroid of flow. The centroid of flow was determined by making an instantaneous streamflow measurement with an acoustic Doppler current profiler (ADCP) at the measurement site. Instantaneous streamflow measurements were made in accordance with U.S. Geological Survey procedures (Mueller and Wagner, 2009; Turnipseed and Sauer, 2010). At measurement sites where streamflow measurements could not be obtained, streamflow was estimated by interpolation from upstream and downstream streamflow discharge measurements (table 2). Streamflow at 287 Bypass Bridge was estimated assuming the streamflow increased linearly with distance between streamflow measurements upstream and downstream from the site (about 13.5 $ft^3/s$ per river mile). Streamflow at Townsend Bridge was estimated by assuming no inflow occurred between Yorks Islands and the site, and thus was the same streamflow that was measured at Yorks Islands.

SCUFAs were deployed at each measurement site to record the dye concentrations for the leading edge to the trailing edge of the dye plume where concentration is 10 percent of the peak concentration of the dye plume ($t_{10p}$). For the Broadwater Dam dye injection, the SCUFA at the 287 Bypass Bridge was programmed to collect a reading every 30 seconds to provide a comprehensive dataset; however, the SCUFA at Yorks Islands was programmed to collect a reading every 10 seconds in an attempt to record more data before algae accumulation affected the measurements. The SCUFA at the most downstream measurement site (Townsend Bridge), was programmed to collect a reading every 60 seconds because of the slower passage of dye.

For the dye injection at Missouri River Headwaters, the SCUFAs at Big Davis Gulch and Broadwater Dam were programmed to collect a reading every 30 seconds (table 1, fig. 2). The SCUFA at Milwaukee Bridge (table 1, fig. 2), was programmed to collect a reading every 10 seconds in an attempt to record more data before algae accumulation affected the measurements.

Fluorescence measurements are commonly affected by temperature and turbidity, but SCUFA fluorometers are temperature compensated and also measure turbidity to evaluate and mitigate these effects. Temperature compensation eliminates substantial errors that result from fluctuating water temperatures. Although SCUFA fluorometers limit interference from turbidity, highly turbid water may still affect fluorescence measurements in direct proportion to the turbity of the water. Turbidity and fluorescence were recorded simultaneously at all measurement sites to evaluate turbidity interference (Turner Designs, 2001; 2004). During this study, as algae accumulated on the SCUFAs, turbulence increased, which caused spikes in turbidity and fluorescence. To reduce the effects of turbulence from algae on the fluorescence readings, the SCUFAs were cleaned hourly.

In addition to deploying the SCUFAs, discrete grab samples also were collected at measurement sites at 5-, 10-, 15-, 20-, or 60-minute intervals depending on the expected time-of-passage of the dye plume. These grab samples were collected using a pint glass open-mouthed bottle at a single point adjacent to the SCUFA near the centroid of flow.

## Development of Time-Concentration Curves

Fluorescence and turbidity data collected by the SCUFAs (appendix 1, raw SCUFA data) at each site were reviewed, and outliers from the time-concentration curve were removed from the dataset (fig. 4). Outliers were defined as data values with an associated spike in turbidity or as values that substantially deviated from the time-concentration curve. Outliers were selected using professional judgment. After outliers were removed from the dataset, all the data were shifted up or down such that concentration values preceding the arrival of the dye (that is, background values) were zero (appendix 2, adjusted SCUFA data). SCUFA data may have background concentrations different than zero because of calibration error and environmental factors. Raw SCUFA data and adjusted SCUFA data collected at Townsend Bridge are presented in figure 4 as an example of the adjustments made to the dataset.

The discrete grab samples were analyzed with a bench fluorometer for RWT dye concentrations at the USGS Montana Water Science Center, Helena, Mont., and the resulting data were used to develop time-concentration curves. A Turner Designs Model 10 bench fluorometer was calibrated using standards prepared in the laboratory at the Montana Water Science Center with RWT dye concentrations of 1 µg/L, 10 µg/L, and 25 µg/L. RWT dye standards with 0 µg/L and 100 µg/L were used to verify the calibration of the fluorometer. The discrete samples were analyzed at a temperature of 20ºC and are presented in appendix 3.

Time-concentration curves were developed by fitting smooth curves to the SCUFA and discrete sample data (Kilpatrick and Wilson, 1989). Smooth curves were fit to a three-parameter log-normal equation (Salas and others, 2002; figs. 5–7). The three-parameter log-normal equation, parameters, and data for these curves are presented in appendix 4. In instances where the SCUFA data and discrete sample data differed, the three-parameter log-normal curves were adjusted to fit the discrete sample data rather than the SCUFA data because the accuracy of the SCUFA data was more likely to be affected by field conditions such as variations in turbidity and temperature.

For the subreach upstream of Broadwater Dam, a single set of three parameters could not be accurately used to fit a log-normal curve to the discrete sample data. Backwater created by Toston Reservoir above Broadwater Dam slowed down the movement of the dye plume through part of the subreach. The SCUFA and discrete sample data collected at Broadwater Dam began to differ substantially about 16 hours after the dye injection (fig. 6*B*); therefore, the SCUFA data

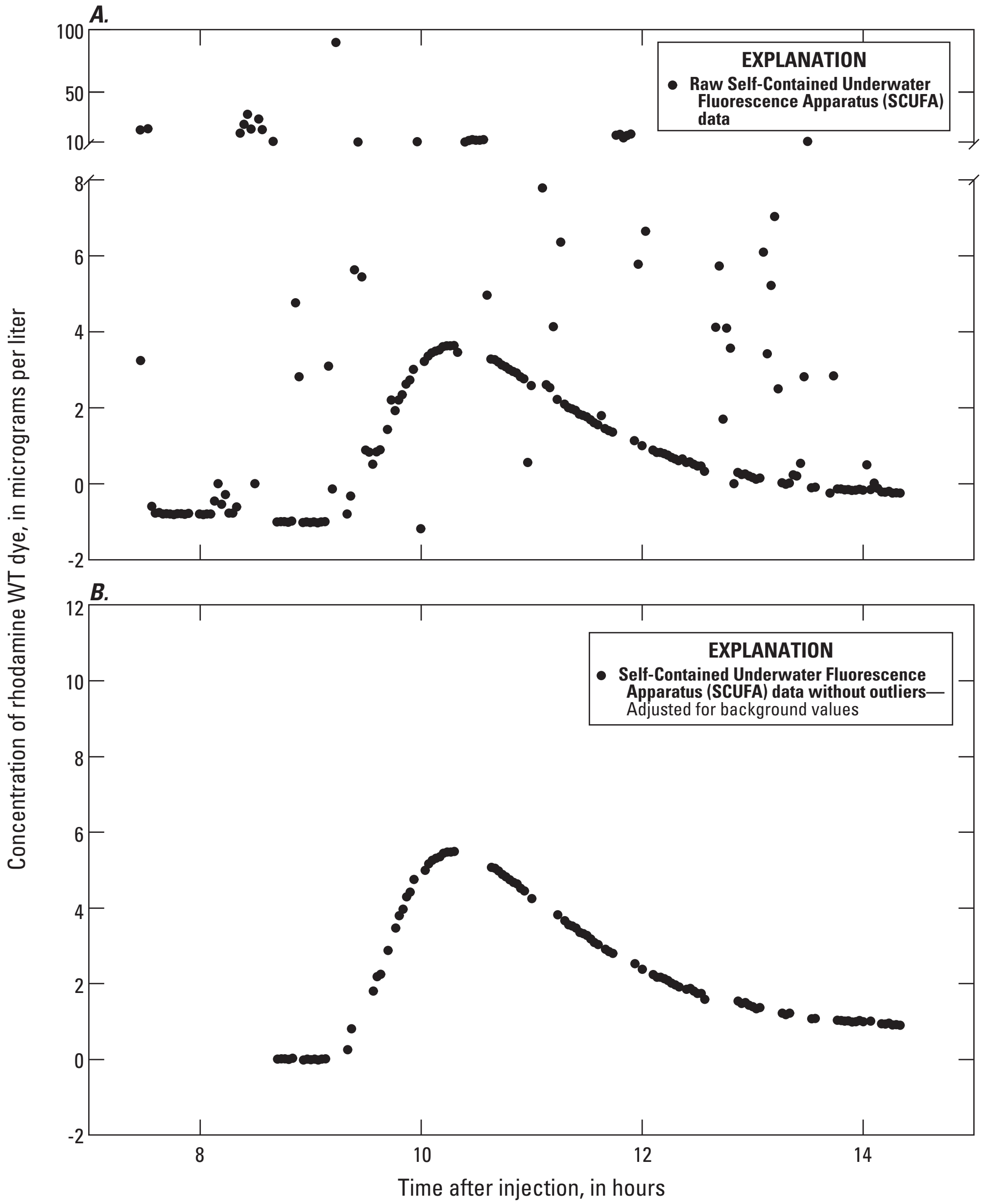



**Figure 4.** Concentration of rhodamine WT dye at Townsend Bridge, Montana. *A*, Raw data from Self-Contained Underwater Fluorescence Apparatus (SCUFA). *B*, Adjusted SCUFA data.

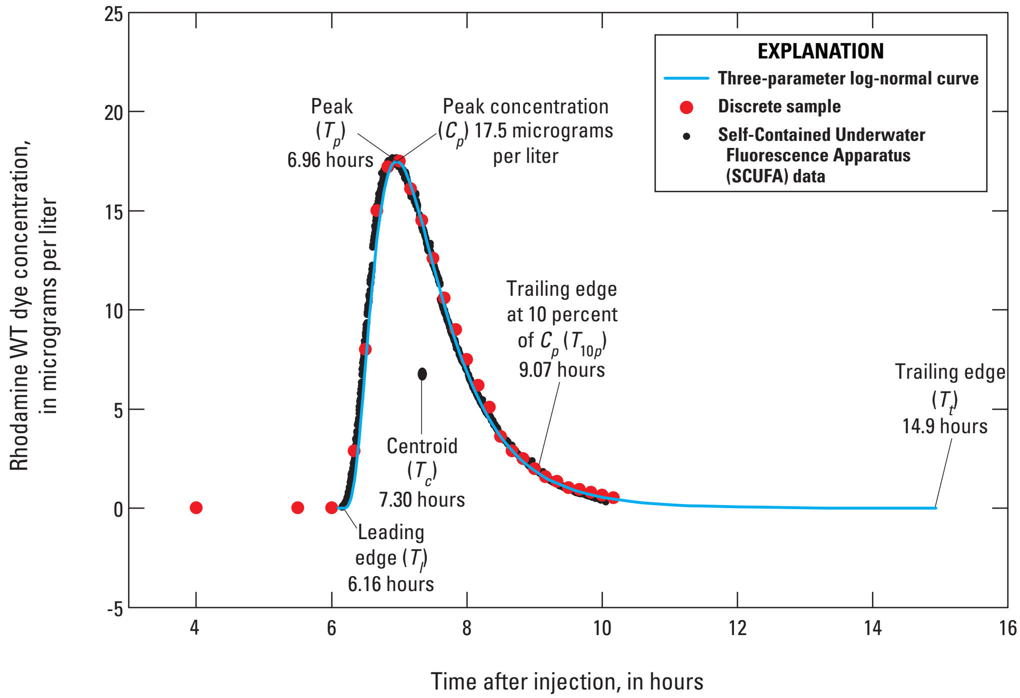



**Figure 5.** Rhodamine WT dye time-concentration curve fit to data from the discrete samples collected at Milwaukee Bridge after September 8, 2010, dye injection at Missouri River Headwaters, Montana.

were only used to determine the leading edge of the dye plume and identify the trend of the time-concentration curve for the duration of the peak concentration. The difference between the SCUFA data and the discrete sample data was because of instrument drift.

The slower velocity of the dye plume through the reservoir resulted in a non-standard time-concentration curve as exhibited by the discrete sample data (fig. 6*B*) because the dye concentration remained slightly elevated from 18.4 hours after the dye injection to the trailing edge when compared to a single standard time-concentration curve. This nonstandard time-concentration curve required three segments of three separate time-concentration curves to define one curve that could be fit to the discrete sample data. Thus, a set of three log-normal parameters were used to define the time-concentration curve from 11.8 to 18.4 hours after the dye injection (Segment 1 on fig. 6*B*, appendix 4). A second set of three log-normal parameters was used to define the time-concentration curve from 18.4 to 20.0 hours after the dye injection (Segment 2 on fig. 6*B*). Similarly, a third set of three log-normal parameters was used to define the time-concentration curve from 20.0 to 29.6 hours after the dye injection (Segment 3 on fig. 6*B*). The three segments were combined to produce a final continuous time-concentration curve for the subreach upstream from Broadwater Dam.

The final time-concentration curves fit to the SCUFA and discrete sample data (for example, Milwaukee Bridge, fig. 5) were then used to determine the travel times for the peak concentration, centroid, trailing edge at 10 percent of the peak concentration, and the trailing edge of the dye plume for each measurement site. The adjusted SCUFA data (appendix 2) were used to determine travel times for the arrival of the leading edge of the dye plume because the SCUFA data were collected at a higher frequency than the discrete samples and better defined the arrival of the dye plume. When the adjusted SCUFA data did define the arrival of the dye plume, the final time-concentration curves fit to the SCUFA and discrete sample data (appendix 4) were used to determine the travel times of the arrival of the leading edge of the dye plume. Time-concentration curves for each of the dye injections are shown in figures 6 and 7.

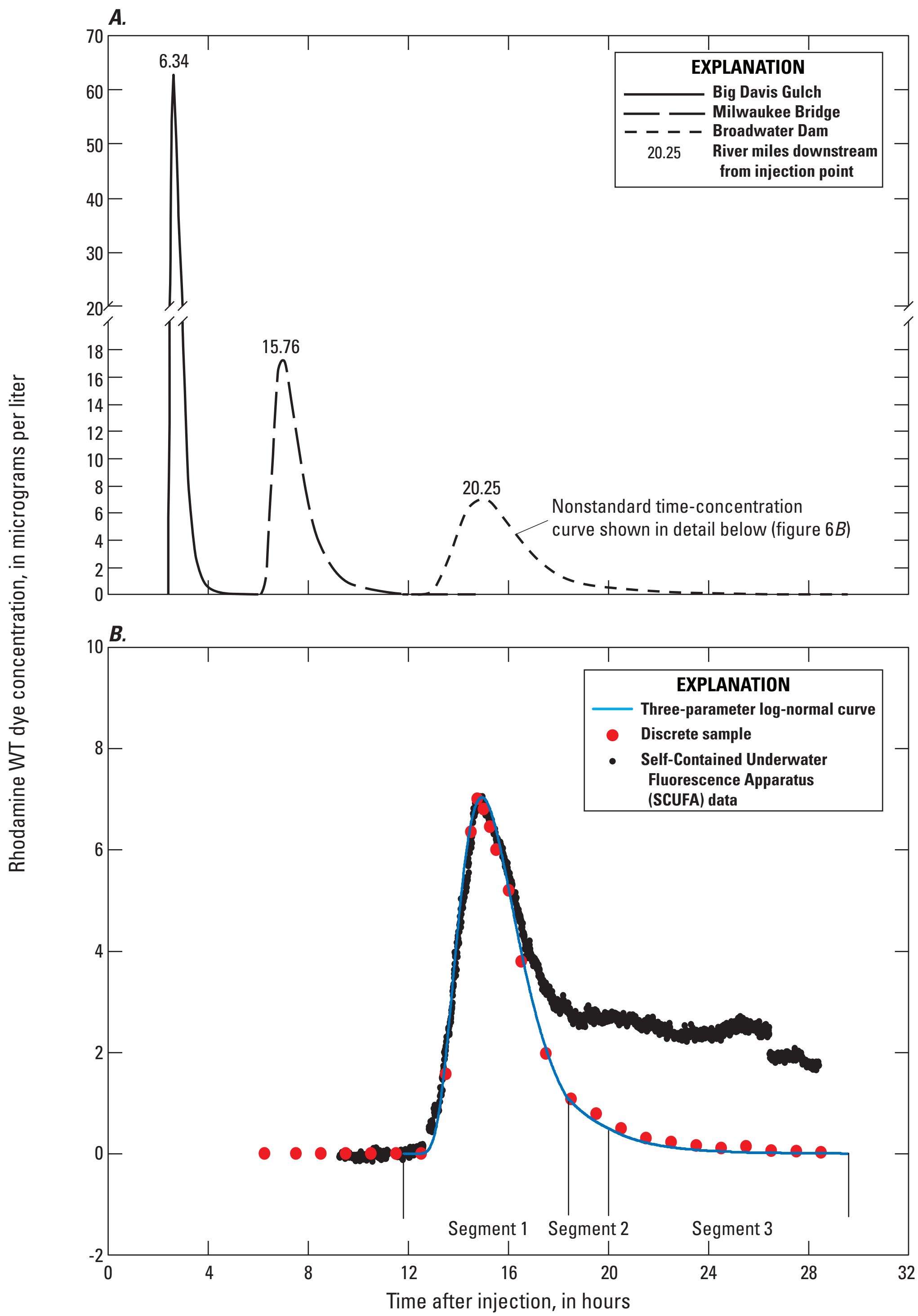



**Figure 6.** Standard and nonstandard time-concentration curves for rhodamine WT dye injected at Missouri River Headwaters, Montana, September 8–9, 2010. *A*, Standard time-concentration curves fit to discrete sample data collected at Big Davis Gulch and Milwaukee Bridge. *B*, Nonstandard time-concentration curve fit to discrete sample data collected at Broadwater Dam.

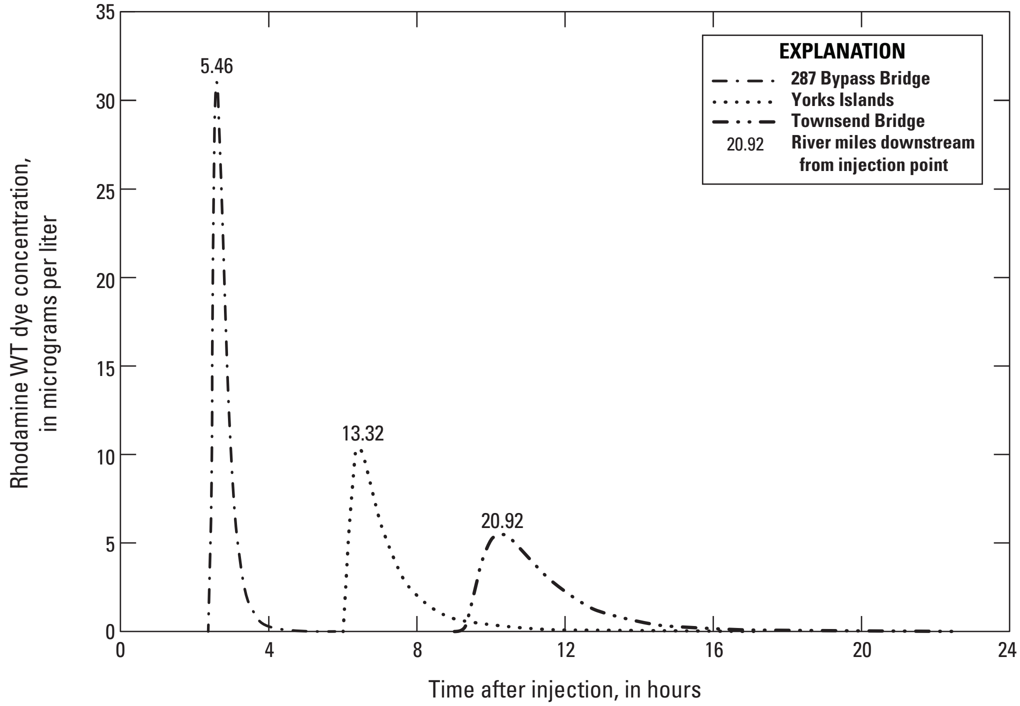



**Figure 7.** Time-concentration curves for rhodamine WT dye injected at Broadwater Dam, Montana, August 30, 2010.

# Travel Times, Streamflow Velocities, and Dispersion Rates in the Upper Missouri River

The travel times, streamflow velocities, and dispersion rates were calculated for each of the subreaches by using the time-concentration curves developed from data collected at the measurement sites. Mean velocities between measurement sites were calculated for the leading edge, peak concentration, centroid, and trailing edge at 10 percent of the peak concentration, and the trailing edge of the dye plume (table 2) for each subreach. The mean velocity for the centroid of the dye plume most accurately represents the mean streamflow velocity of the river, whereas the mean velocities of the other portions of the dye plume suggest the possible rates of the dispersion of contaminants spilled into the river.

The velocities of the centroid of the dye plume in different subreaches (table 2) ranged from 0.80 feet per second (ft/s) for the subreach upstream from Broadwater Dam to 3.02 ft/s for the subreach upstream from Milwaukee Bridge. Excluding the subreach affected by backwater upstream of Broadwater Dam, the mean velocity of the centroid of completely mixed dye plumes for the entire study reach was 2.87 ft/s, for the streamflow conditions during this study, with a standard deviation of 0.12 ft/s. The fastest mean streamflow velocities occurred at the subreach between Big Davis Gulch and Milwaukee Bridge (table 2). The slowest mean streamflow velocities generally occurred downstream from Broadwater Dam.

The velocities of the leading edge, peak concentration, and trailing edge at 10 percent of the completely mixed dye plume can provide information on movement of a contaminant in the event of a spill. The velocities of the leading edge of the dye plume ranged from 1.17 ft/s for the subreach upstream from Broadwater Dam to 3.63 ft/s for the subreach upstream from Milwaukee Bridge (table 2). Excluding the subreach affected by backwater upstream from Broadwater Dam, the mean velocity of the leading edge of completely-mixed dye plumes for the entire study reach was 3.46 ft/s with a standard deviation of 0.17 ft/s. The velocities of the peak concentration of the dye plume ranged from 0.83 ft/s for the subreach upstream from Broadwater Dam to 3.18 ft/s for the subreach upstream from Milwaukee Bridge (table 2). Excluding the subreach affected by backwater upstream from Broadwater Dam, the mean velocity of the peak concentration of the completely mixed dye plume for the entire study reach was 3.04 ft/s with a standard deviation of 0.11 ft/s. Velocities of the trailing edge at 10 percent of the peak concentration of the dye plume ranged from 0.64 ft/s for the subreach upstream from Broadwater Dam to 2.42 ft/s for the subreach upstream from the 287 Bypass Bridge (table 2). Excluding the subreach affected by backwater upstream from Broadwater Dam, the mean velocity of the trailing edge at 10 percent of the peak concentration of

**Table 2.** Travel-time data and mean streamflow velocities for the upper Missouri River, Montana.

[Data are presented in downstream order (fig. 2). $ft^3/s$, cubic feet per second; hr, hours; µg/L; micrograms per liter; ft/s, feet per second; L, liters; --, no data]

| Site name | River miles downstream from dye injection | Instantaneous streamflow ($ft^3/s$) | Travel time after dye injection to measurement site (decimal hr) | | | | | Time for dye plume to pass site (decimal hr), $T_d$ | Measured peak dye concentration (µg/L), $C_p$ | Mean streamflow velocity of dye plume for reach upstream from the site (ft/s) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Leading edge, $T_l$ | Peak concentration, $T_p$ | Centroid, $T_c$ | Trailing edge at 10 percent peak concentration, $T_{10p}$ | Trailing edge, $T_t$ | | | Leading edge | Peak concentration | Centroid | Trailing edge at 10 percent peak concentration | Trailing edge |
| Instantaneous injection of dye (45.4 L) at 07:30 on September 8, 2010, at Missouri River Headwaters | | | | | | | | | | | | | | |
| Missouri River Headwaters | 0.0 | 3,620 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | -- | -- | -- | -- | -- | -- | -- |
| Big Davis Gulch | 6.34 | 3,700 | 2.35 | 2.61 | 2.73 | 3.29 | 5.97 | 3.62 | 62.7 | [1]3.95 | [1]3.56 | [1]3.41 | [1]2.83 | [1,2]1.56 |
| Milwaukee Bridge | 15.76 | 3,460 | 6.16 | 6.96 | 7.30 | 9.07 | 14.9 | 8.78 | 17.5 | 3.63 | 3.18 | 3.02 | 2.39 | [2]1.54 |
| Broadwater Dam | 20.25 | 3,610 | 11.8 | 14.9 | 15.5 | 19.3 | 29.6 | 17.8 | 7.03 | [3]1.17 | [3].83 | [3].80 | [3].64 | [2,3].45 |
| Instantaneous injection of dye (23.0 L) at 07:34 on August 30, 2010, at Broadwater Dam | | | | | | | | | | | | | | |
| Broadwater Dam | 0.0 | 3,070 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | -- | -- | -- | -- | -- | -- | -- |
| 287 Bypass Bridge | 5.46 | [4]3,140 | 2.35 | 2.62 | 2.73 | 3.31 | 5.80 | 3.45 | 30.9 | 3.41 | 3.06 | 2.93 | 2.42 | [2]1.38 |
| Yorks Islands | 13.32 | 3,250 | 5.90 | 6.45 | 6.89 | 8.66 | 17.4 | 11.5 | 10.3 | 3.25 | 3.01 | 2.77 | 2.16 | [2].99 |
| Townsend Bridge | 20.92 | [4]3,250 | 9.05 | 10.3 | 10.9 | 14.0 | 22.8 | 13.7 | 5.50 | 3.54 | 2.91 | 2.77 | 2.11 | [2]2.09 |

[1] Mean streamflow velocity of dye plume is affected by incomplete lateral mixing of dye.

[2] Velocity of the trailing edge of the dye plume was determined from fitting a three-parameter log-normal curve to the travel-time data.

[3] The slower velocity of the dye plume through Toston Reservoir (fig. 1) resulted in slower travel times as described in the section "Development of Time-Concentration Curves."

[4] Instantaneous streamflow was estimated from upstream and downstream streamflow measurements where streamflow could not be measured.

the completely mixed dye plume for the entire study reach was 2.27 ft/s with a standard deviation of 0.16 ft/s.

Velocities of the leading edge and peak concentration of the dye plume averaged 25 and 5.1 percent faster, respectively, than the velocities of the centroid of the dye plume. Velocities of the trailing edge at 10 percent of the peak concentration of the dye plume averaged 21 percent slower than the velocities of the centroid of the dye plume.

Velocities in the subreach upstream from Broadwater Dam were considerably slower because of the effects of Toston Reservoir.  The velocity of the centroid of the dye plume for the subreach upstream from Broadwater Dam was 0.80 ft/s and the velocity of the leading edge, peak concentration, and trailing edge at 10 percent of the peak concentration of the dye plume was 1.17, 0.83, and 0.64 ft/s, respectively. The residence time for dye in Toston Reservoir was estimated using the difference in the time required for the centroid of the dye plume to move through the reservoir. The estimated residence time was 8.2 hours during this study. Various factors can affect residence time in a reservoir such as inflows, outflows, latitudinal and longitudinal reservoir geometry, and reservoir stratification (Pielou, 1998).

Longitudinal dispersion of the dye plume, having no boundaries, continues indefinitely and is the dispersion component of primary interest in dye-tracer studies (Kilpatrick and Wilson, 1989). Longitudinal dispersion occurs when the leading edge of a dye plume travels in the downstream direction faster than the trailing edge of the dye flume. The longitudinal dispersion rate (table 3) was estimated for each subreach by subtracting the velocity of the trailing edge of the dye plume from the velocity of the leading edge of the dye plume. Because longitudinal dispersion continues indefinitely, the trailing edge of the dye plume was estimated from the three-parameter log-normal curves that were fit to the travel-time data collected during this study (figs. 6 and 7). The three-parameter log-normal curves fit may not accurately represent when the trailing edge of the dye plume passes a measurement point, which may affect the estimated dispersion rates in table 3.

Longitudinal dispersion rates are dependent on the stream characteristics of the reach including streamflow discharge, the presence of split channels and pools, and the sinuosity of the river (Kilpatrick and Wilson, 1989). Estimated longitudinal dispersion rates of the dye plume for this study ranged from 0.72 ft/s for the subreach from Milwaukee Bridge to Broadwater Dam to 2.26 ft/s for the subreach from the 287 Bypass Bridge to Yorks Islands (table 3).

Kilpatrick and Wilson (1989) found the time, $T_{10d}$, necessary for the dye plume to pass a sampling point until the concentration of the dye plume on the trailing edge is 10 percent of the peak concentration (duration) can be estimated from the travel time of the peak concentration. A relation was determined between the travel time of the peak concentration and passage time (duration) using data from this study for subreaches where the dye was completely laterally mixed (fig. 8). This relation can be used to estimate when the decreasing concentration of a potential contaminant reaches 10 percent of its peak concentration for accidental contaminant spills into the upper Missouri River. The relation between travel time and peak concentration and passage time (duration) determined from this study closely resembles the relation determined by Kilpatrick and Wilson (1989); however, the relation developed for this study may be affected by different streamflow conditions in the upper Missouri River.

**Table 3.** Longitudinal dispersion rates for the upper Missouri River, Montana.

| Site name | Longitudinal dispersion rate (feet per second) |
|---|---|
| Big Davis Gulch | [1,2]2.39 |
| Milwaukee Bridge | [2]2.09 |
| Broadwater Dam | [2].72 |
| 287 Bypass Bridge | [2]2.03 |
| Yorks Islands | [2]2.26 |
| Townsend Bridge | [2]1.45 |

[1] Longitudinal dispersion rate of dye plume is affected by incomplete lateral mixing of dye.

[2] Velocity of the trailing edge of the dye plume was determined from fitting a three-parameter log-normal curve to the travel-time data.

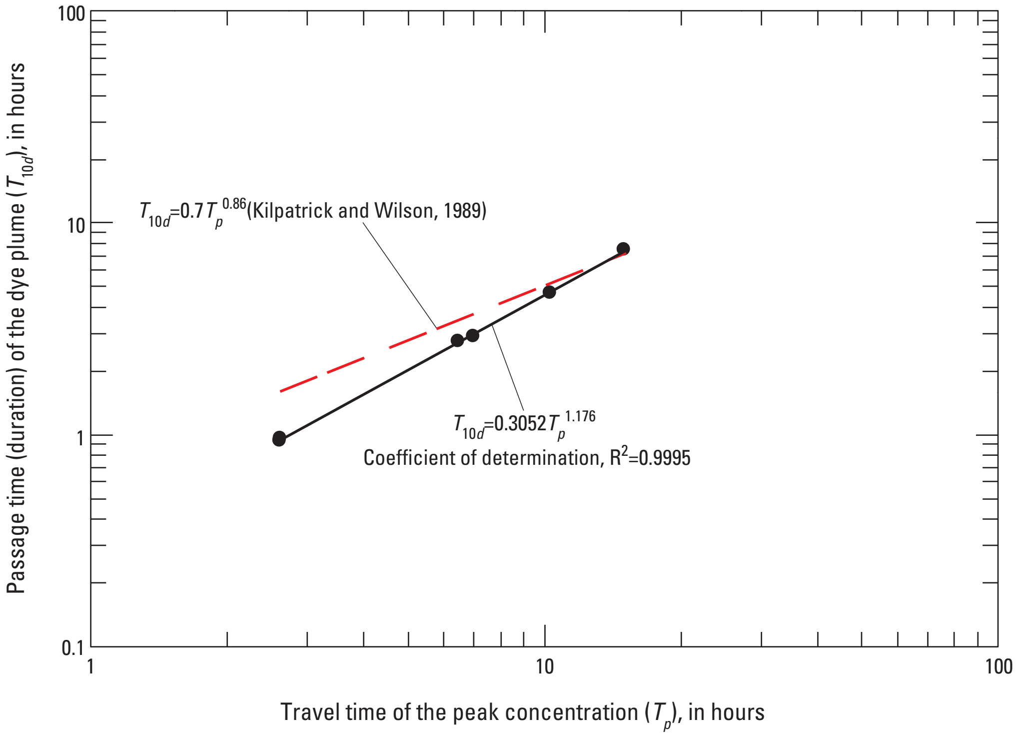



**Figure 8.** Relation between travel times of the peak concentration and passage time (duration) of the dye plume for the upper Missouri River, Montana.

## Limitations of the Travel Times, Streamflow Velocities, and Longitudinal Dispersion Rates

Data collected as part of this study reflect limited hydrologic conditions (reasonably steady streamflow measured from 3,070 $ft^3/s$ to 3,700 $ft^3/s$, table 2) over a limited time period (late August and early September 2010); therefore, the travel times, streamflow velocities, and longitudinal dispersion rates determined in this study are limited to these streamflow conditions. Care should be exercised when estimating travel times, streamflow velocities, and longitudinal dispersion rates for streamflows other than those observed during this study. Determination of travel times, streamflow velocities, and longitudinal dispersion rates for other streamflow conditions would require additional dye-tracer studies under a variety of streamflow conditions.

On August 30, 2010, a partial dam failure occurred at Madison Dam (fig. 1), resulting in a rapid increase in streamflow in the Madison River, a major tributary to the upper Missouri River study reach (Russell, 2010). A small floodwave moved through the study reach as a result of the rapid increase in streamflow. Streamflow data from streamflow-gaging station Missouri River at Toston (06054500, fig. 1) and river-stage data obtained from Montana Department of Environmental Quality for the Missouri River at Townsend Bridge indicated that the floodwave did not affect the dye-tracer study. Data collection was nearly complete at Townsend Bridge prior to the arrival of the floodwave. Discrete sample data indicated the dye concentration at Townsend Bridge had decreased below the data-collection threshold of less than 10 percent of the peak concentration before the floodwave arrived. Streamflow and relative-stage data during each dye injection and subsequent data-collection period are shown in figures 9 and 10.

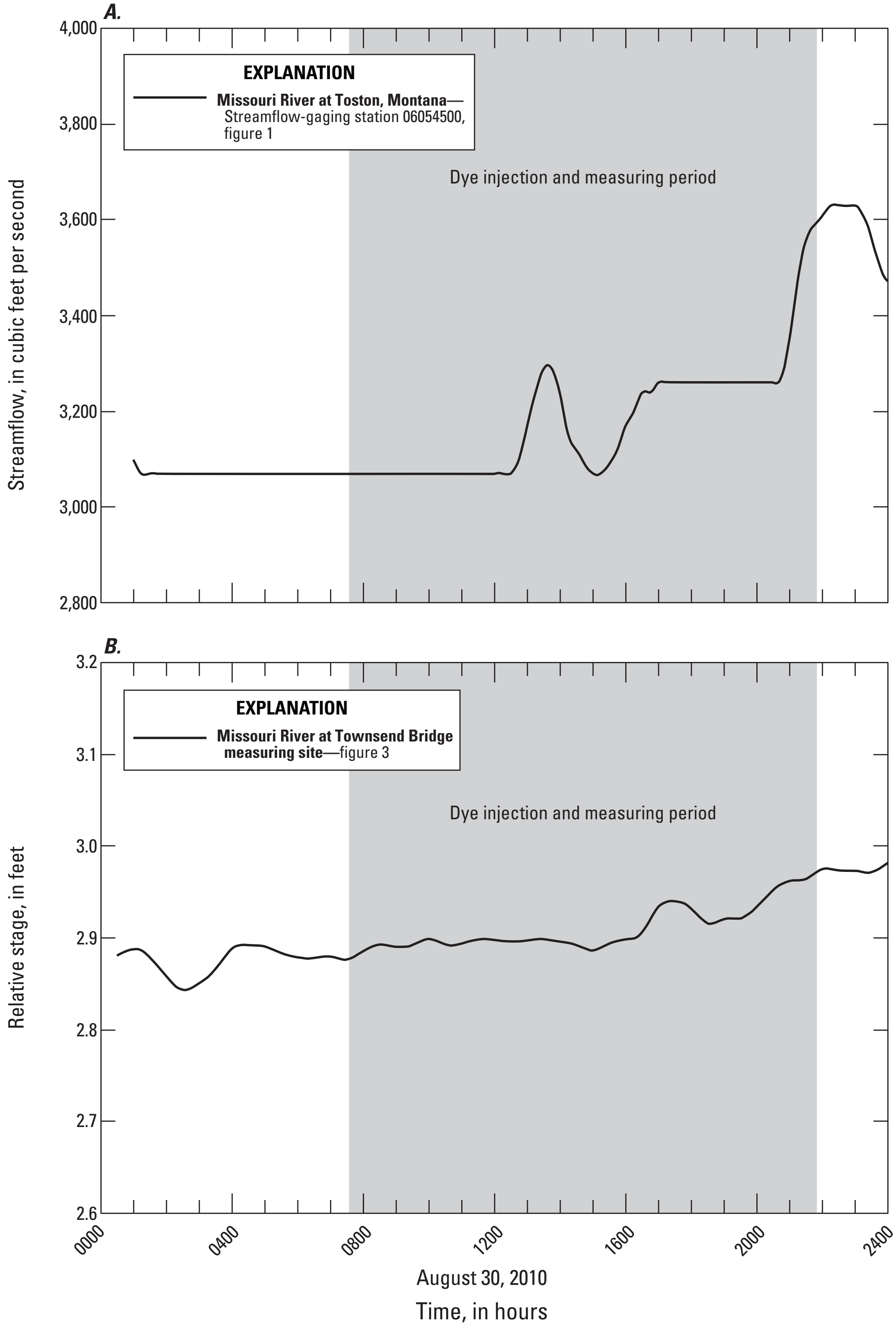



**Figure 9.** Data collected during dye injection and measuring in the upper Missouri River, Montana, August 30, 2010. *A*, Continuous streamflow data, Missouri River at Toston. *B*, Continuous relative stage data, Missouri River at Townsend Bridge.

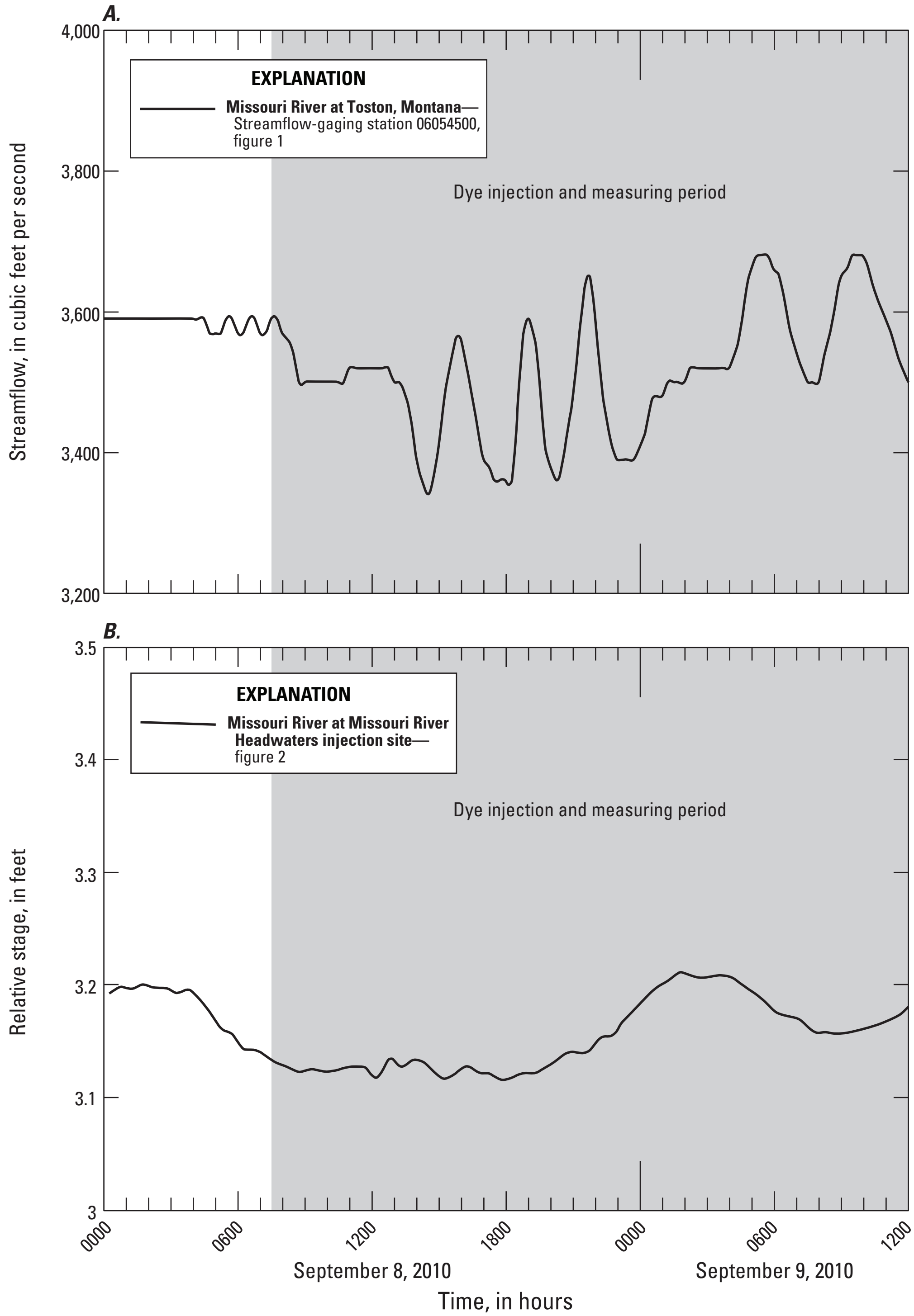



**Figure 10.** Data collected during dye injection and measuring in the upper Missouri River, Montana, September 8 and 9, 2010. A, Continuous streamflow data, Missouri River at Toston. B, Continuous relative stage data, Missouri River at Missouri River Headwaters.

## Summary and Conclusions

In 2010, the U.S. Geological Survey (USGS), in cooperation with the Montana Department of Environmental Quality, initiated a dye-tracer study to determine travel times, streamflow velocities, and longitudinal dispersion rates for the Missouri River upstream from Canyon Ferry Lake. For this study, rhodamine WT (RWT) dye was injected at two locations, Missouri River Headwaters State Park in early September and Broadwater-Missouri Dam (Broadwater Dam) in late August, 2010. Dye concentrations were measured at three sites downstream from each dye-injection location. The study area was a 41.2-mile reach of the Missouri River from Trident, Montana, at the confluence of the Jefferson, Madison, and Gallatin Rivers (Missouri River Headwaters) at river mile 2,319.40 downstream to the U.S. Route 12 Bridge (Townsend Bridge), river mile 2,278.23, near Townsend, Montana. Streamflows were reasonably steady and ranged from 3,070 to 3,700 $ft^3/s$.

Mean streamflow velocities were calculated for each subreach between measurement sites for the leading edge, peak concentration, centroid, trailing edge at 10 percent of the peak concentration, and trailing edge of the dye plume. Velocities for the centroid of the dye plume where the dye plume was completely mixed most accurately represent the mean streamflow velocities of the river and ranged from 0.80 feet per second (ft/s) for the subreach upstream from Broadwater Dam to 3.02 ft/s for the subreach upstream from Milwaukee Bridge. Excluding subreaches where the dye was not completely mixed and the subreach affected by backwater upstream of Broadwater Dam in Toston Reservoir, the mean velocities for the centroid of the dye plume for the entire study reach was 2.87 ft/s. Similarly, the mean velocities of the leading edge, peak concentration, and trailing edge at 10 percent of the peak concentration of the dye plume were 3.46, 3.04, and 2.27 ft/s, respectively.

Velocities in the subreach upstream from Broadwater Dam were considerably slower because of the effects of Toston Reservoir. The velocity of the centroid of the dye plume for the subreach upstream from Broadwater Dam was 0.80 ft/s and the velocity of the leading edge, peak concentration, and trailing edge at 10 percent of the peak concentration of the dye plume was 1.17, 0.83, and 0.64 ft/s, respectively. The residence time for dye in Toston Reservoir was estimated using the difference in the time required for the centroid of the dye plume to move through the Reservoir. The estimated residence time was 8.2 hours during this study.

Longitudinal dispersion of the dye plume, having no boundaries, continues indefinitely and is dependent on the stream characteristics of the reach. The longitudinal dispersion rate was estimated for each subreach by subtracting the velocity of the trailing edge of the dye plume from the velocity of the leading edge of the dye plume. Estimated longitudinal dispersion rates of the dye plume for this study ranged from 0.72 ft/s for the subreach from Milwaukee Bridge to Broadwater Dam to 2.26 ft/s for the subreach from the 287 Bypass Bridge to Yorks Islands.

A relation was determined between travel time of the peak concentration and the time for the dye plume to pass a site (duration of the dye plume). This relation can be used to estimate when the decreasing concentration of a potential contaminant reaches 10 percent of its peak concentration for accidental spills into the upper Missouri River.

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# Appendixes

# Appendixes

The raw SCUFA data (appendix 1), adjusted SCUFA data (appendix 2), bench fluorometer data (appendix 3), and three-parameter log-normal data and equation parameters (appendix 4) were compiled and organized into four Excel spreadsheets (files) and each contain two worksheets. The first worksheet of each appendix contains descriptions of the headings used each appendix. Appendixes 1–4 are located in the CD–ROM on the inside back cover of this report and can be downloaded as Excel files from *http://pubs.usgs.gov/sir/2012/5044/*.

## (Click on link to access table)

1. Raw Data from Self-Contained Underwater Fluorescence Apparatus for Measurement Sites along the Upper Missouri River, Montana.
2. Adjusted Data from Self-Contained Underwater Fluorescence Apparatus for Measurement Sites along the Upper Missouri River, Montana.
3. Bench Analysis of Discrete Samples Measured with Turner Design Model 10 Fluorometer for Measurement Sites along the Upper Missouri River, Montana.
4. Data and Parameters for Three-Parameter Log-Normal Curves of the Self-Contained Underwater Fluorescence Apparatus and Discrete Sample Data for Measurement Sites along the Upper Missouri River, Montana.

Publishing support provided by:
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Whiteman—**Travel Times, Streamflow Velocities, and Dispersion Rates in the Upper Missouri River, Montana**—Scientific Investigations Report 2012–5044