Prepared in cooperation with the
West Virginia Bureau for Public Health, Office of Environmental Health Services

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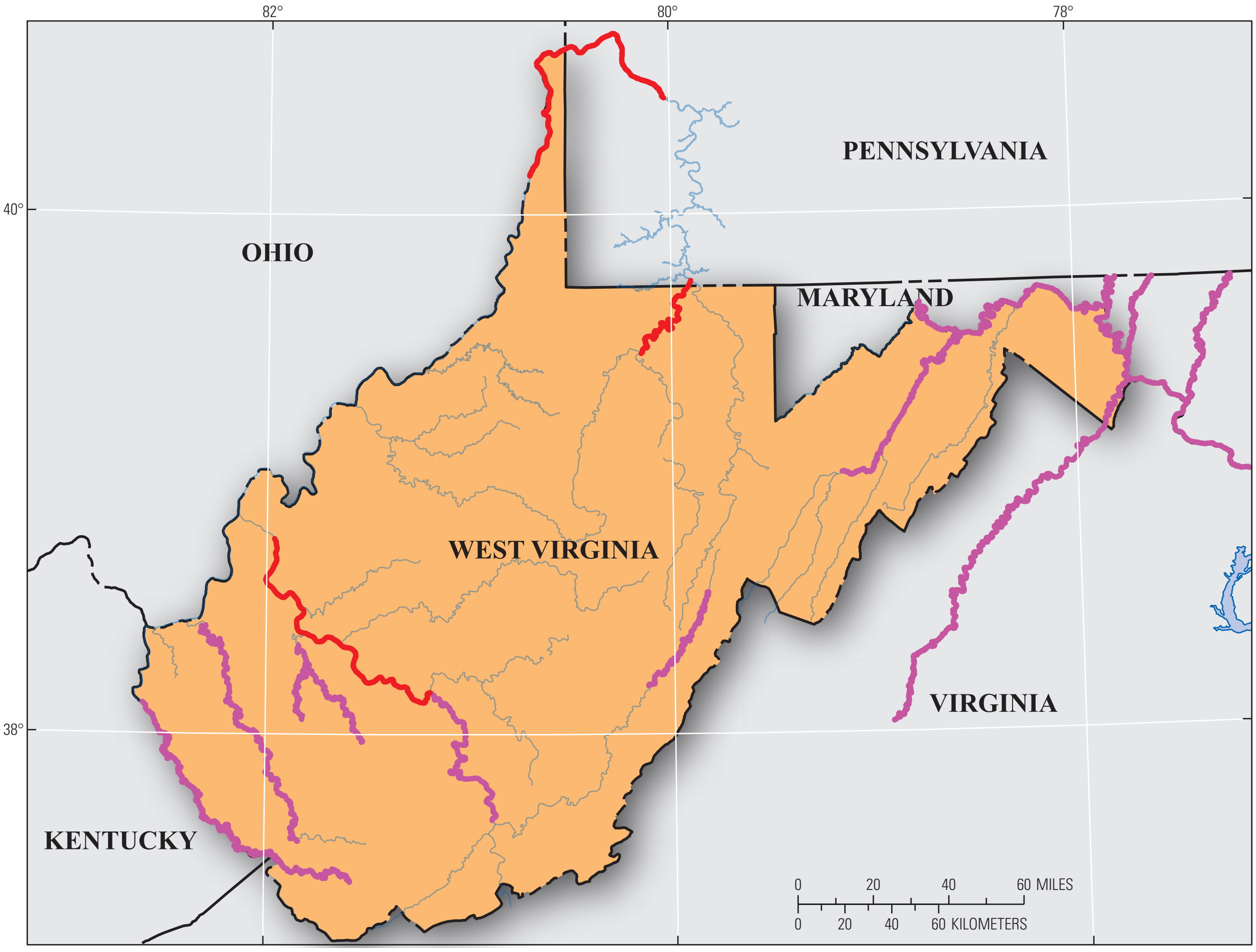

Scientific Investigations Report 2013–5182

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

Cover. Stream reaches in and near West Virginia where traveltime and dispersion have been measured, 1964–85. Free-flowing stream reaches with data shown in purple. Regulated stream reaches with data shown in red.

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By Jeffrey B. Wiley and Terence Messinger

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SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

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Contents

Figures

Conversion Factors, Datums, and Abbreviations

Multiply	By	To obtain
	Length	
inch (in)	2.54	centimeter (cm)
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Mass	
ounce, avoirdupois (oz)	28,349,523	microgram (µg)
pound, avoirdupois (lb)	0.4536	kilogram (kg)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

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

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

Abbreviations

C	concentration
C_p	peak concentration
C_{up}	unit peak concentration
D'_a	dimensionless drainage area
D_a	drainage area
GIS	geographic information system
M_i	injection mass
M_r	recovery mass
NAVD 88	North American Vertical Datum of 1988
ORSANCO	Ohio River Valley Water Sanitation Commission
Q	streamflow
Q'_a	dimensionless flow
Q_a	mean annual streamflow
RMSE	root mean square error
R_r	recovery ratio
S	slope
T_d10	time elapsed until solute concentration is 10 percent of peak concentration
T_l	traveltime of leading edge
T_p	traveltime of peak concentration
USGS	U.S. Geological Survey
V_{mp}	maximum probable velocity
V_p	peak velocity

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Abstract

Traveltime and dispersion data are important for understanding and responding to spills of contaminants in waterways. The U.S. Geological Survey (USGS), in cooperation with West Virginia Bureau for Public Health, Office of Environmental Health Services, compiled and evaluated traveltime and longitudinal dispersion data representative of many West Virginia waterways. Traveltime and dispersion data were not available for streams in the northwestern part of the State. Compiled data were compared with estimates determined from national equations previously published by the USGS. The evaluation summarized procedures and examples for estimating traveltime and dispersion on streams in West Virginia.

National equations developed by the USGS can be used to predict traveltime and dispersion for streams located in West Virginia, but the predictions will be less accurate than those made with graphical interpolation between measurements. National equations for peak concentration, velocity of the peak concentration, and traveltime of the leading edge had root mean square errors (RMSE) of 0.426 log units (127 percent), 0.505 feet per second (ft/s), and 3.78 hours (h). West Virginia data fit the national equations for peak concentration, velocity of the peak concentration, and traveltime of the leading edge with RMSE of 0.139 log units (38 percent), 0.630 ft/s, and 3.38 h, respectively. The national equation for maximum possible velocity of the peak concentration exceeded 99 percent and 100 percent of observed values from the national data set and West Virginia-only data set, respectively. No RMSE was reported for time of passage of a dye cloud, as estimated using the national equation; however, the estimates made using the national equations had a root mean square error of 3.82 h when compared to data gathered for this study.

Traveltime and dispersion estimates can be made from the plots of traveltime as a function of streamflow and location for streams with plots available, but estimates can be made using the national equations for streams without plots. The estimating procedures are not valid for regulated stream reaches that were not individually studied or streamflows outside the limits studied.

Rapidly changing streamflow and inadequate mixing across the stream channel affect traveltime and dispersion, and reduce the accuracy of estimates. Increases in streamflow typically result in decreases in the peak concentration and traveltime of the peak concentration. Decreases in streamflow typically result in increases in the peak concentration and traveltime of the peak concentration. Traveltimes will likely be less than those determined using the estimating equations and procedures if the spill is in the center of the stream, and traveltimes will likely be greater than those determined using the estimating equations and procedures if the spill is near the streambank.

Introduction

Traveltime and dispersion data are needed for streams in West Virginia to protect public water-supply intakes from possible contamination by hazardous materials introduced intentionally or from accidental spills. Accidental spills of hazardous materials into streams can occur along transportation corridors from roads and railroads that parallel or intersect rivers, from transportation on the rivers themselves, and from areas adjacent to rivers where hazardous materials are manufactured, stored, or handled. Information on the traveltime from a point on a stream where a hazardous material might be introduced to a public water-supply intake would allow the water utility to minimize the risk of contaminating the water supply and maximize service to customers. A study was conducted by the U.S. Geological Survey (USGS) in cooperation with the West Virginia Bureau for Public Health, Office of Environmental Health Services, to determine appropriate methods for estimating the traveltime and dispersion of a dye tracer introduced into selected streams in West Virginia.

Dye-Tracer Studies for Estimating Traveltime and Dispersion

Measurements of traveltime and dispersion of a conservative-dye tracer have been used to estimate the movement of water and waterborne solutes in many rivers. Measurement techniques are well documented (Kilpatrick and Wilson, 1989; Hubbard and others, 1982). Methods of water-sample analysis for dyes have been described by Wilson and others (1986). Usually, a fluorescent dye is injected into the river. Water samples are then collected at various locations downstream, beyond the distance required for horizontal and vertical mixing. Results are typically reported as traveltime for the leading edge, peak concentration, and trailing edge of the dye cloud. Longitudinal dispersion, or the elongation of the dye cloud longitudinally, is often shown as time-concentration curves (Hubbard and others, 1982). Details of presentation for both traveltime and dispersion have varied greatly.

Jobson (1996) presented national equations for estimating the traveltime and longitudinal dispersion of a solute in a stream on the basis of results of dye studies conducted by the USGS on many different streams throughout the United States. The national equations were developed from a diverse set of stream reaches with drainage areas ranging from 3.86 to 1,120,000 square miles (mi^2) and slopes ranging from 0.001 to 3.67 percent (Jobson, 1996). Results of dye studies for some streams in West Virginia were not included in the data used to develop those equations because the data were incomplete. In order to simplify the development of the equations, Jobson (1996) used only data that represented complete tracer-response curves and that were tabulated. The national equations have been used to develop preliminary zones for source-water protection upstream from some water-supply intakes in West Virginia. This study was done to determine whether the national equations were representative of traveltime and dispersion characteristics of West Virginia streams.

Purpose and Scope

For this study, traveltime and dispersion data were compiled from all available sources for streams in and near West Virginia and evaluated. Equations developed by Jobson (1996) for the entire United States are compared to traveltime and dispersion measurements made in West Virginia and nearby states to determine whether the equations produce accurate estimates for streams in West Virginia. That determination is based on an evaluation of the prediction errors of the equations when applied to West Virginia streams. Examples of traveltime and dispersion estimates are presented to familiarize readers with the use of the estimation procedures.

Description of Study Area

West Virginia lies within three physiographic provinces (fig. 1), the Appalachian Plateaus, Valley and Ridge, and Blue Ridge (Fenneman, 1938). The State can be separated into two climatic regions (fig. 1) by a line defined as the Climatic Divide (Wiley and others, 2000). Greater precipitation occurs along and west of the Climatic Divide than to the east, as a consequence of the higher elevations along the Divide and the general movement of weather systems approaching from the west and southwest. Generally, the part of the State west of the Climatic Divide is in the Appalachian Plateaus Physiographic Province, where altitudes range from about 2,500 to 4,861 feet (ft; NAVD 88) at Spruce Knob along the Climatic Divide to about 550 to 650 ft along the Ohio River. The part of West Virginia east of the Climatic Divide is in the Valley and Ridge Physiographic Province, except for the extreme eastern tip of the State, which is in the Blue Ridge Physiographic Province. Altitudes decrease eastward from the Climatic Divide to 274 ft at Harpers Ferry in the Eastern Panhandle (U.S. Geological Survey, 1990, 2006; National Oceanic and Atmospheric Administration, 2006a).

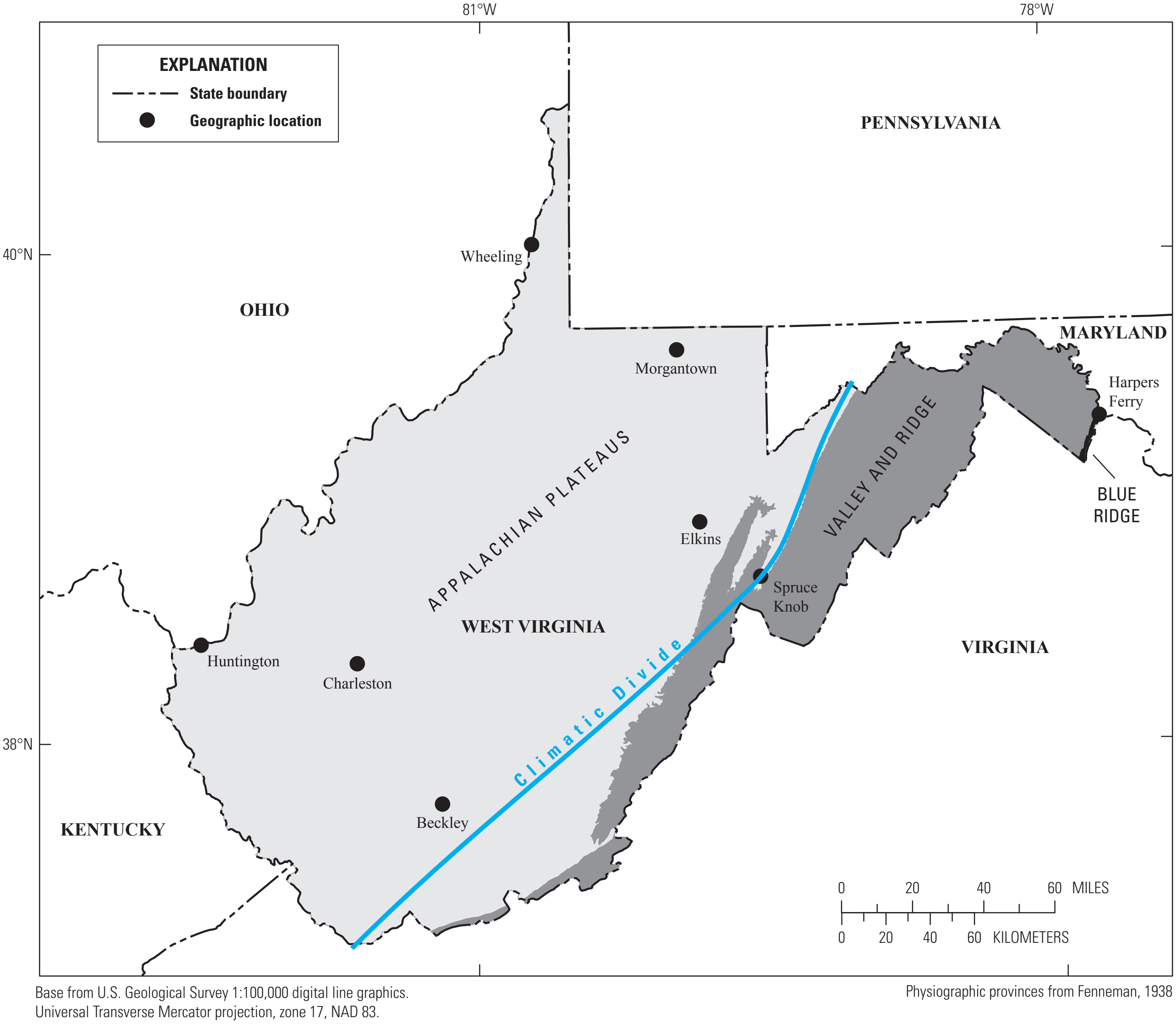
The Appalachian Plateaus Physiographic Province consists of consolidated, mostly siliciclastic sedimentary rocks that have a gentle slope from southeast to northwest near the Climatic Divide and are nearly flat-lying along the Ohio River. One exception is in the northeastern area of the province (west of the Climatic Divide), where the rocks are gently folded, and some carbonate rock crops out (Fenneman, 1938). The rocks in the Appalachian Plateaus Physiographic Province have been eroded to form steep hills and deeply incised valleys. Drainage patterns are dendritic.

The Valley and Ridge Physiographic Province in West Virginia consists of consolidated carbonate and siliciclastic sedimentary rocks that are folded sharply and extensively faulted (Fenneman, 1938). Northeast-trending valleys and ridges parallel the Climatic Divide. Drainage patterns are trellis.

The Blue Ridge Physiographic Province within West Virginia consists predominantly of metamorphosed sandstone and shale (Fenneman, 1938). The province has high relief between mountains and wide valleys that parallel the Climatic Divide. Drainage patterns are trellis.

The climate of West Virginia is primarily continental, with mild summers and cold winters. Major weather systems generally approach from the west and southwest, although polar continental air masses of cold, dry air that approach from the north and northwest are not unusual. Air masses from the Atlantic Ocean sometimes affect the area east of the Climatic Divide and less frequently affect the area west of the Climatic Divide. Generally, tropical continental masses of hot, dry air from the southwest affect the climate west of the Climatic Divide. Tropical maritime masses of warm, moist air from the Gulf of Mexico affect the climate east of the Climatic Divide more than west of the Climatic Divide. Evaporation from local and upwind land surfaces, lakes, and reservoirs also provides a source of moisture that affects the climate of the State (U.S. Geological Survey, 1991; National Oceanic and Atmospheric Administration, 2006a).

Annual precipitation averages about 42 to 45 inches (in.) statewide with about 60 percent received from March through



Base from U.S. Geological Survey 1:100,000 digital line graphics.
Universal Transverse Mercator projection, zone 17, NAD 83.

Physiographic provinces from Fenneman, 1938

Figure 1. Appalachian Plateaus, Valley and Ridge, and Blue Ridge Physiographic Provinces, and Climatic Divide in West Virginia.

August. Typically, the most rain is received in July, and the least rain is received during September through November. Annual average precipitation in the State generally decreases northwestward from about 50 to 60 in. along the Climatic Divide to about 40 in. along the Ohio River and increases from about 30 to 35 in. east of the Climatic Divide to about 40 in. in the extreme eastern tip of the State. Greater precipitation along and west of the Climatic Divide is a consequence of the higher elevations along the Divide and the orographic lifting of weather systems generally approaching from the west and southwest. Annual average snowfall follows the general pattern of annual average precipitation, decreasing northwestward from about 36 to 100 in. along the Climatic Divide to about 20 to 30 in. along the Ohio River. East of the Climatic Divide, annual average snowfall ranges from 24 to 36 in. (U.S. Geological Survey, 1991; Natural Resources Conservation Service, 2006; National Oceanic and Atmospheric Administration, 2006a, 2006b).

Studies of Traveltime and Longitudinal Dispersion in West Virginia Streams

Traveltime has been studied on a variety of stream reaches in and near West Virginia. These reaches may be broadly divided into free-flowing stream reaches and regulated stream reaches, in which backwater is created by dams or other structures. Traveltime and dispersion characteristics measured in free-flowing stream reaches are likely to be representative of regional conditions, whereas for regulated stream reaches, these characteristics are unique to that reach.

Free-Flowing Stream Reaches

A free-flowing stream reach lacks artificial structures that would block streamflow and create backwater. Dams are the most common of these structures, but some culverts or low-water bridges also may cause backwater at some flows. Stream reaches containing dams exhibit increased traveltimes relative to the traveltimes of free-flowing streams because of increased storage in the stream channel, particularly at low streamflows. Traveltime through a reach containing a small dam may exhibit the characteristics of a free-flowing stream at high streamflows because the dam is submerged and storage effects become less dominant.

Studies have been conducted on free-flowing stream reaches in the Tug Fork of the Big Sandy River (Bader and others, 1989b); Guyandotte River (Bader and others, 1989a); Little Coal, Big Coal, and Coal Rivers (J.S. Bader, J.L. Chisholm, S.C. Downs, and F.O. Morris, Water Resources of the Coal River Basin, West Virginia: West Virginia Geological and Economic Survey River Bulletin 5, written commun., 1976); New River (Appel and Moles, 1987); Greenbrier River (Clark and others, 1976); North Branch Potomac and Potomac Rivers (Taylor and others, 1984); South Branch Potomac River (Hobba and others, 1972; Jack, 1986); and South Fork Shenandoah and Shenandoah Rivers (Taylor and others, 1986) within and along the borders of West Virginia (fig. 2). Traveltime and dispersion studies of the Monocacy River (Taylor, 1970) and of Antietam and Conococheague Creeks (Taylor and Solley, 1971) in Maryland were considered to be representative of traveltime and dispersion applicable to streams in West Virginia. Information on the reaches and injections, and the traveltime and dispersion data measured in these studies, are summarized in appendix 1, tables 1-1 and 1-2.

A study of the Tuscarawas River (Westfall and Webber, 1977) in southeastern Ohio was considered but determined to be unrepresentative of traveltime and dispersion in West Virginia, primarily because of dams in the study reach. Two studies of the New River that investigated the effects of rapidly changing streamflow on a dye cloud (Appel, 1987; Wiley and Appel, 1989) were excluded from consideration because of uncertainties in assigning a representative streamflow to the reaches.

Plots of traveltimes of the leading edge, peak concentration, and trailing edge of the dye cloud at selected locations on free-flowing stream reaches were constructed from data collected during previous studies to present the traveltime and dispersion characteristics observed in the streams (figs. 3–13, at end of report). Traveltime increases as streamflow and velocity decrease. Longitudinal dispersion characteristics are determined by comparing differences between the leading and trailing edges of the dye cloud at different locations along the stream. Dispersion in a reach increases as streamflow decreases because the residence time increases. The plots show combined results from multiple dye injections along a stream to represent a single dye injection occurring at the most-upstream location. Each streamflow condition (low-, medium-, and (or) high-flow) was plotted separately when more than one condition was studied.

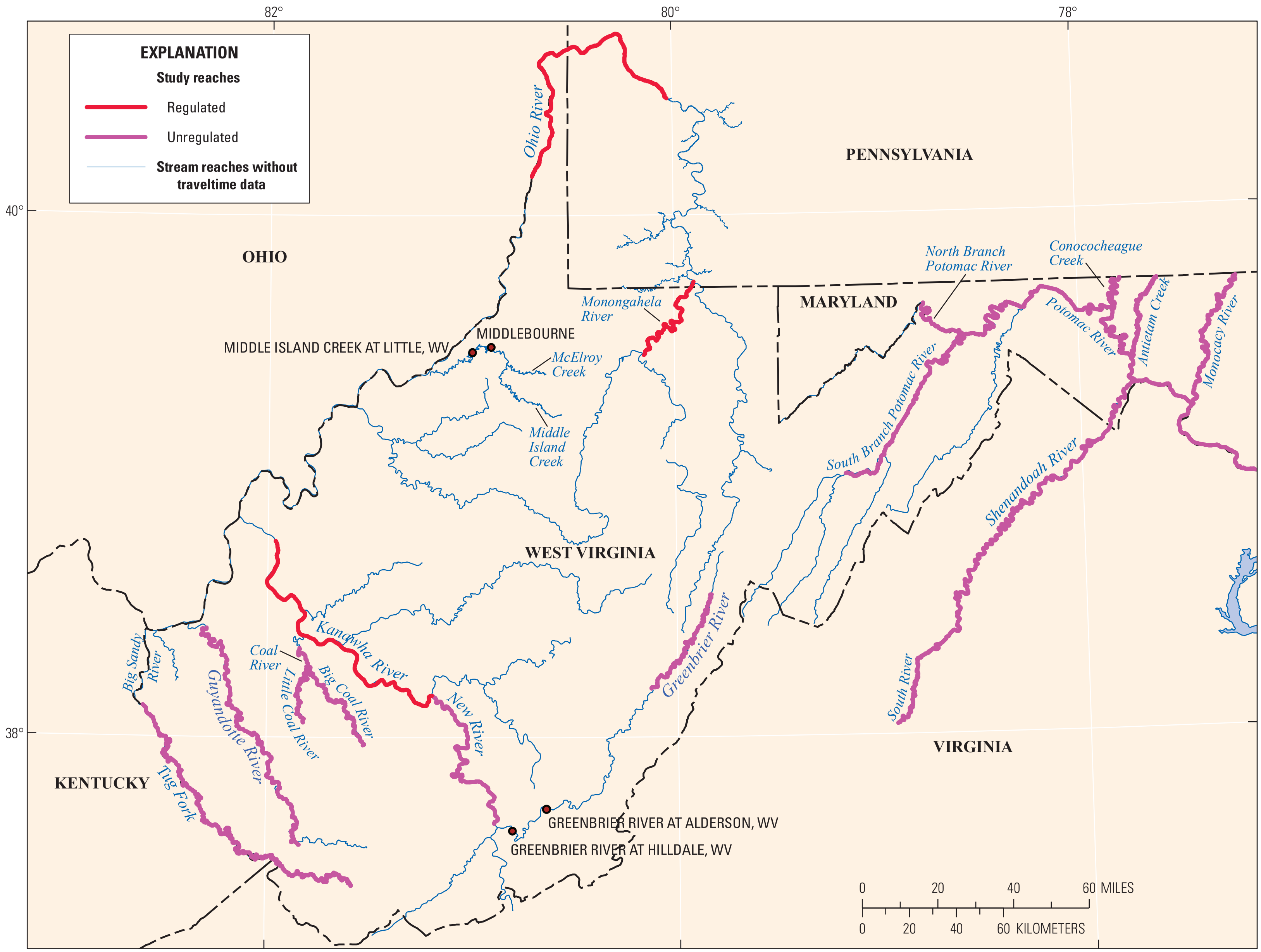
In some of the studies that measured traveltime at different streamflow conditions, dye was injected at different points under different conditions. To allow interpolation between measured traveltimes, all the plots need to be included on the same graph. This required that the curves representing shorter reaches be fit onto curves representing the longest reach for that study. Plots representing reaches that do not begin at the graph origin were positioned by interpolation between measured values when possible. Otherwise, the national equations were used. Traveltime and dispersion plots are not presented for the Monocacy River (Taylor, 1970) or Antietam and Conococheague Creeks (Taylor and Solley, 1971) in Maryland because the streams are not within or along the border of West Virginia and those plots are not needed to estimate traveltimes within West Virginia.

Traveltime and dispersion have not been measured for streams flowing directly into the Ohio River in the northwestern part of West Virginia. Elsewhere in West Virginia, the Bluestone River, Gauley River, Elk River, Little Kanawha River, Middle Island River, Cheat River, Tygart Valley River, and Buckhannon River are large streams containing free-flowing reaches where traveltime and dispersion have not been measured.

Regulated Stream Reaches

Regulated stream reaches, for the purpose of this report, are reaches with dams and other structures that create backwater and affect traveltime and dispersion. Measurements made on regulated reaches are not transferable to either other regulated reaches or free-flowing reaches, and estimates of traveltime made for free-flowing reaches are not transferable to regulated reaches. Measurements are required to characterize each regulated reach.

Dye studies have been conducted on the regulated streams Kanawha River (Appel, 1991; Wiley, 1993; fig. 14 at end of report) and the upper Ohio River (Wiley, 1997a; figs. 14–16, at end of report). Traveltime predictions are available for the Ohio River from a model maintained by the Ohio



Base from U.S. Geological Survey 1:24,000 digital line graphics
Streams from U.S. Geological Survey National Hydrography Dataset, 2012
Universal Transverse Mercator projection, Zone 17, North American Datum of 1983

Figure 2. Stream reaches in and near West Virginia where traveltime and dispersion have been measured, 1964–85, and selected locations discussed in examples.

River Valley Water Sanitation Commission (ORSANCO). These predictions can be made near real time in the event of a significant spill. Traveltimes were determined for the Monongahela River, a regulated stream, using the relations between flow and hydraulic measurements made at a series of cross sections measured in 1948 (Federal Water Pollution Control Administration, 1968; fig. 15, located near the end of this report). Estimates for the Monongahela are likely to be less accurate than dye studies or the ORSANCO model. Traveltimes of the leading edge, peak concentration, and trailing edge of the dye cloud relative to location on the stream are plotted to present the traveltime and dispersion characteristics observed in selected regulated streams.

Estimation of Traveltime and Longitudinal Dispersion in West Virginia Streams Using Plots and National Equations

Only data from studies conducted on free-flowing stream reaches (absent of any dam structures) were compared to results from the national equations developed by Jobson (1996). Jobson (1996) included stream reaches with dam structures to develop the national equations. Data collected for the September 6, 1983, dye injection 4.9 miles upstream from Morgan Ford on the Shenandoah River, injection number 60, (Taylor and others, 1986) were omitted from analysis because a double peak was observed in the study.

Jobson (1996, equation 4, p. 6) defined the unit concentration as

$$C_u = 1\times10^6\left(\frac{C}{R_r}\right)\left(\frac{Q}{M_i}\right) \text{ or } 1\times10^6\left(\frac{C}{M_r}\right)Q\,, \tag{1}$$

where

C_u is the unit concentration, in inverse seconds (1/s);
C is the (measured/observed) concentration, in pounds per cubic feet (lb/ft^3); and
R_r is the recovery ratio, dimensionless:

$$R_r = \left(\frac{M_r}{M_i}\right),$$

where

M_r is the mass recovered, in pounds (lb);
M_i is the mass injected, in lb; and
Q is the streamflow, in cubic feet per second (ft^3/s).

The constant 1×10^6 is used in equation 1 to obtain results near unity. Equation 1 was a redefinition from that described by Hubbard and others (1982, p. 35):

$$C_{UH} = \frac{\left(C_{con}\times Q\right)}{M_i}\,, \tag{2}$$

where

C_{UH} is the unit concentration from Hubbard and others (1982), in (micrograms per liter × cubic feet per second)/pounds ((µg/L)(ft^3/s)/lb) and
C_{con} is the conservative concentration, in µg/L:

$$C_{con} = \frac{C_H}{R_r}\,,$$

where

C_H is the (measured/observed) concentration from Hubbard and others (1982), in µg/L;
R_r is the recovery ratio, dimensionless (see equation 1);
Q is the streamflow, in ft^3/s; and
M_i is the mass injected, in lb.

All traveltime and dispersion studies included in the West Virginia data set computed unit concentrations using equation 2 with the units (µg/L)(ft^3/s)/lb. The unit concentrations in (µg/L)(ft^3/s)/lb were multiplied by 0.06243(1/s)/[(µg/L)(ft^3/s)/lb] to obtain unit concentrations as defined by equation 1 (0.06243 is determined as 28.317 L/ft^3 × 2.205×10^{-9} lb/µg × 1×10^6).

Jobson (1996, equation 7, p. 10) determined unit-peak concentrations of dye were related to the elapsed time since injection using the equation

$$C_{up} = 857T_p^{-0.760(Q/Q_a)^{-0.079}}\,, \tag{3}$$

where

C_{up} is the unit-peak concentration, in 1/s;
T_p is the elapsed time from injection to peak concentration, in hours (h);
Q is the streamflow at the time of the measurement, in ft^3/s; and
Q_a is the mean annual streamflow, in ft^3/s.

Equation 3 was originally developed using 410 data points with a coefficient of determination (R^2) of 0.91 and a root mean square error (RMSE) of 0.426 log units (127 percent) (Jobson, 1996). Fitting West Virginia data (150 points) to Jobsons's (1996) equation for C_{up} resulted in a RMSE of 0.139 log units (32.8 percent).

Unit-peak concentration was plotted against the elapsed time from injection to peak concentration with stream reaches separated into those with Q/Q_a greater than 0.5, indicating above-average flows, and values less than 0.5, indicating below-average flows for the West Virginia data set. Additionally, line plots of equation 3 evaluated for Q/Q_a equal to 1.0 for above-average flow and 0.2 for below-average flow were

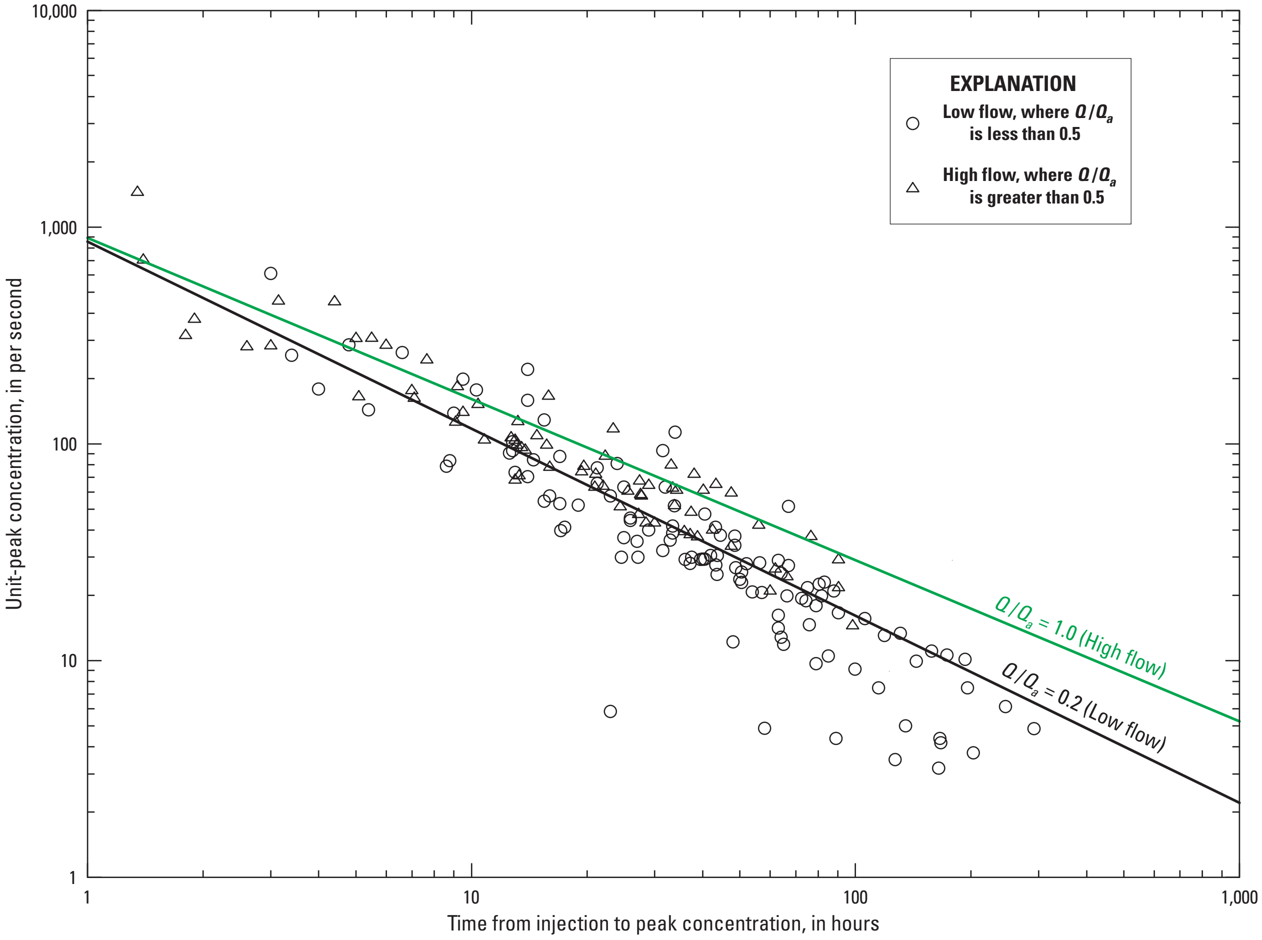


Figure 17. Unit-peak concentrations as a function of traveltime for measurements made in and near West Virginia, 1964–1985, with equation 3 plotted for two values of Q/Q_a.

added to the plot (fig. 17; Jobson, 1996, fig. 3). The values for Q/Q_a for the West Virginia data set averaged 1.11 when Q/Q_a was greater than 0.5 (41 data points) and 0.25 when Q/Q_a was less than 0.5 (109 data points); values from the national equations (Jobson, 1996) were 1.0 and 0.2, respectively.

Jobson (1996, equation 12, p. 14) determined that the velocity of the peak concentration (V_p) could be estimated from the following equation modified for use with inch-pound units (the constant 0.094 meters per second (m/s) was converted to 0.308 feet per second (ft/s)):

$$V_p = 0.308 + \left(0.0143 \times D_a'^{0.919} Q_a'^{-0.469} S^{0.159} \frac{Q}{D_a}\right), \qquad (4)$$

where

V_p is the velocity of the peak concentration, in ft/s;

D_a' is the dimensionless drainage area:

$$D_a' = \frac{D_a^{1.25} g^{0.5}}{Q_a},$$

where

D_a is the drainage area (at the end of the reach), in ft^2;

g is the acceleration due to gravity, in feet per square second (ft/s^2) (32.2 ft/s^2);

Q_a is the mean annual streamflow (at the end of the reach), in ft^3/s; and

Q_a' is the dimensionless streamflow:

$$Q_a' = \frac{Q}{Q_a},$$

where

Q is the streamflow (at the end of the reach), in ft^3/s, and

Q_a is the mean annual streamflow (at the end of the reach), in ft^3/s;
S is the reach slope, in ft per ft;
Q is the streamflow (at the end of the reach), in ft^3/s; and
D_a is the drainage area (at the end of the reach), in ft^2.

Dimensionless variables permit the use of any consistent system of units to obtain equal results. Constants need to be in the same system of units as the variables. Foot-pound units are used in this report because the data were originally reported in foot-pound units. (V_p in m/s is obtained by replacing the constant 0.3084 with 0.094 and using Q in cubic meters per second (m^3/s) and D_a in cubic meters (m^3)).

Velocity of the peak concentration (V_p) was plotted against the variables on the right side of equation 4 for the West Virginia data set (fig. 18; Jobson, 1996, fig. 9, p. 15). Equation 4 was originally developed using 939 data points with an R^2 of 0.70 and a RMSE of 0.157 m/s or 0.505 ft/s. Equation 4 resulted in a RMSE of 0.630 ft/s (83 percent) using 198 West Virginia data points.

Jobson (1996; equation 13, p. 14; fig. 9, p. 15) determined the maximum probable velocity of the peak concentration (V_{mp}) using the following equation modified for use with inch-pound units (the constant 0.25 m/s was multiplied by 3.28 ft/m to obtain a constant of 0.82 ft/s):

$$V_{mp} = 0.82 + \left(0.02 \times D_a'^{0.919} Q_a'^{-0.469} S^{0.159} \frac{Q}{D_a}\right), \tag{5}$$

where

V_{mp} is the maximum probable velocity of the peak concentration, in ft/s;
D_a' is the dimensionless drainage area (see equation 4);
Q_a' is the dimensionless streamflow (see equation 4);
S is the reach slope, in ft per ft;
Q is the streamflow (at the end of the reach), in ft^3/s; and
D_a is the drainage area (at the end of the reach), in ft^2.

Equation 5 was evaluated by Jobson (1996, Equation 13, p. 14) as an envelope line where 99 percent of the observed values of V_p were less than the values of V_{mp}. All observed values of V_p from the West Virginia data were less than the values predicted for V_{mp} by equation 5, and most of them (195 of 239) were less than the values predicted for V_p by equation 4 (fig. 18). Most of the values of V_p near V_{mp} are for injection reaches (fig. 18). Dye in injection reaches may travel at higher velocities because of incomplete mixing of the dye with the stream at the beginning of the reach and because many injections were made into the fastest flowing part of the stream.

Jobson (1996; equation 18, fig 12, p. 17) determined the traveltime of the leading edge (T_l) of a dye cloud in a stream could be predicted by the traveltime of the peak concentration (T_p) using the following equation with an R^2 of 0.99 and RMSE of 3.78 h developed from 520 data points:

$$T_l = 0.890 T_p, \tag{6}$$

where

T_l is the traveltime of the leading edge since injection, in h, and
T_p is the traveltime of the peak concentration since injection, in h.

When equation 6 was applied to the West Virginia data set (189 data points), the RMSE was 3.38 h (10 percent).

Jobson (1996, equation 19, p. 18) discussed work by Kilpatrick and Taylor (1986) in which a dye response curve is approximated by a scalene triangle (three unequal sides), and the time of passage of a dye cloud (to the point at which the concentration recedes to 10 percent of the peak concentration) was estimated using the following equation:

$$T_d 10 = \frac{2 \times 10^6}{C_{up}}, \tag{7}$$

where

$T_d 10$ is duration from the leading edge until the tracer concentration has reduced to within 10 percent of the peak concentration, in s, and
C_{up} is the unit-peak concentration, in 1/s, determined from equation 3.

$T_d 10$ was divided by 3,600 s/h, then compared to the difference between T_l and the traveltime of the trailing edge (T_t) for the West Virginia data set (no comparisons were made by Jobson, 1996). $T_d 10$ was estimated using equation 7, and the RMSE was 3.82 h (20 percent) using 149 data points. There would have been 150 data points, except a value for T_t was not measured on the Hancock to Fort Frederick reach with the dye injection at Paw Paw on May 25, 1984, in the Potomac River, although T_t was estimated as 80 h in order to produce figure 10 for this study.

For equations 3–7, error terms computed using only West Virginia data are similar to, or less than, error terms from the national data set. This indicates that the national equations developed by Jobson (1996) can be used to predict traveltime and dispersion for streams located in West Virginia, but predictions will be less accurate than graphical interpolation between measurements.

Procedures for Estimating Traveltime and Longitudinal Dispersion with Examples

Reach-specific information, where available, can be used to estimate traveltime and longitudinal dispersion with greater accuracy than can be achieved with the national equations.

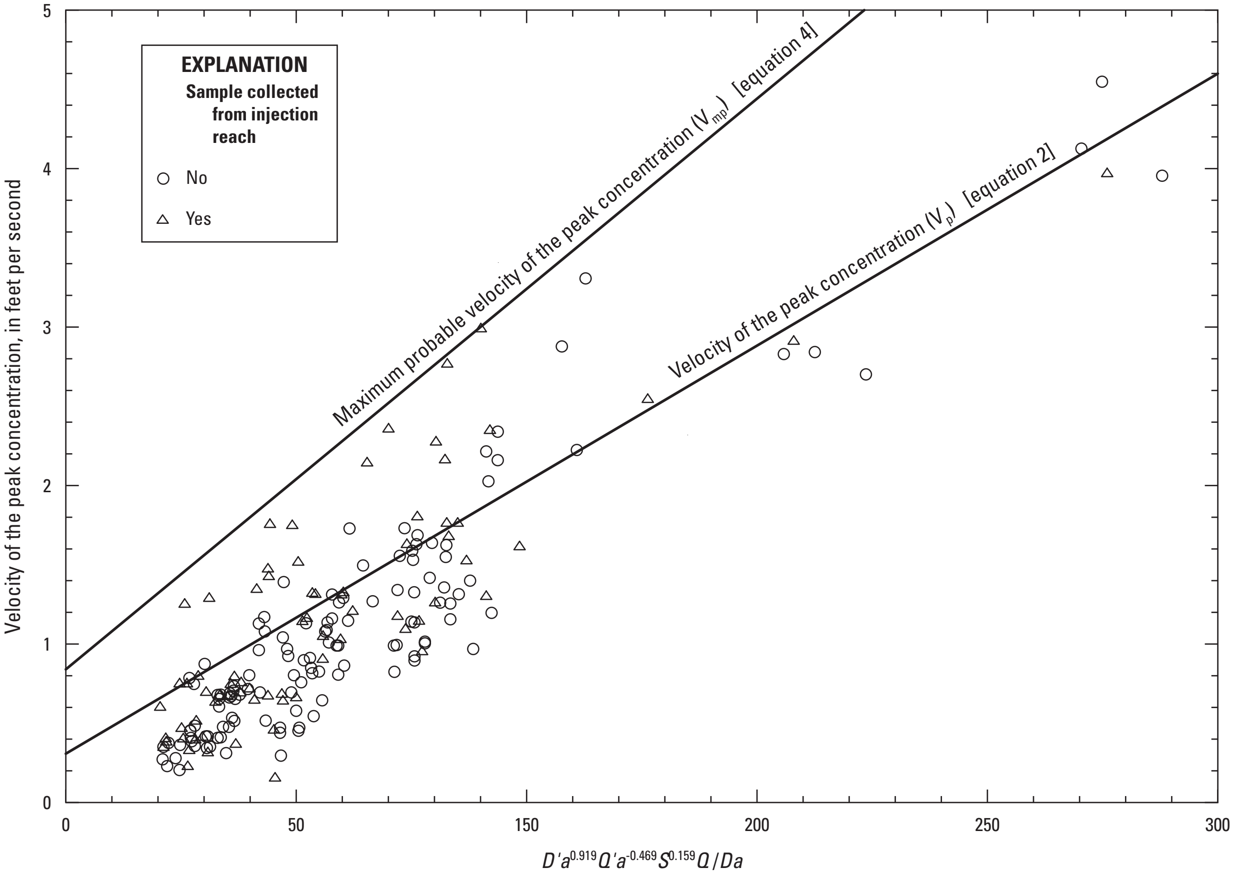


Figure 18. Velocity of the peak concentration as a function of dimensionless drainage area, dimensionless streamflow, dimensionless slope, local streamflow, and drainage area for measurements made in and near West Virginia, 1964–1985.

Estimates of traveltime and dispersion may be made from the plots of traveltime in relation to distance downstream on reaches where studies have been conducted, as long as the streamflows are within the ranges of those studied. Equations may be used to estimate traveltime and dispersion in naturally falling stream reaches where studies have not been conducted or where streamflow is outside the limits of those studied. Maximum probable velocities (estimated from equation 6) and associated traveltime of the leading edge can be determined when not estimating traveltime and dispersion from the plots of traveltime in relation to distance downstream. No estimating procedures are presented for estimating traveltime and dispersion in regulated stream reaches not studied or with flows outside the limits of streamflows studied. Traveltime studies would be needed for each of these reaches to provide reliable estimates.

Estimating traveltime and dispersion requires determining Q, Q_a, D_a, and S for streams in West Virginia. Current Q data are available for many USGS streamflow-gaging stations at *http://waterdata.usgs.gov/wv/nwis/current/?type=flow*. If Q is needed at an ungaged location, estimates may be made by comparing the D_a with that of one or more nearby USGS streamflow-gaging stations; in some cases, Q for the ungaged location can be approximated by multiplying the drainage-area ratio (D_a at the ungaged location divided by D_a at a nearby streamflow-gaging station) by Q for the nearby streamflow-gaging station (drainage-area ratio method). Flow estimates made using the drainage-area ratio method are likely to be more accurate when they are made for ungaged locations on a gaged stream than when they are made for ungaged locations on an ungaged stream or if the differences in drainage areas are large. Q_a has been published for many USGS streamflow-gaging stations by Evaldi and others (2009) and in Annual Water Data Reports (*http://wdr.water.usgs.gov/*). Q_a at an ungaged location may be estimated using the drainage-area ratio method described above with one or more nearby USGS streamflow-gaging stations. D_a may be determined from a geographic information system (GIS) and has been published for many gaged and ungaged locations in West Virginia by Mathes (1977), Wilson (1979), Mathes and others (1982), Preston and Mathes (1984), Stewart and Mathes (1995), Wiley and others (1995), and Wiley (1997b). Reach slope (S) is determined by dividing the difference in altitude at the beginning and end of a stream reach by the reach length, ensuring altitude and reach are in the same units. Altitudes can be determined from USGS topographic maps or from a GIS, such as the interactive map available at *http://www.mapwv.gov/* (a mouse click in the map viewer will show the altitude at the indicated location). Reach lengths can be measured on USGS topographic maps or from a GIS. The USGS Web application StreamStats (*http://streamstats.usgs.gov/*) provides access to the information needed to estimate traveltime for the states for which it is available. As of 2013, StreamStats is not available in West Virginia but is available or under development for all the states surrounding West Virginia, so it can be used to obtain information needed to estimate traveltime to the state border for streams that enter West Virginia from an adjacent state.

Below are examples showing the procedures for estimating traveltime and longitudinal dispersion. In all examples, the spill is assumed to be instantaneous and completely mixed. The estimating procedure would be the same if these assumptions were not met, and consequences of this are discussed below in the section "Limitations of Estimating Procedures."

Example 1: A 500 lb spill has occurred on the Tug Fork of the Big Sandy River at Matewan, W.Va. How long does the spill take to reach Kermit, W.Va., and what peak concentration is expected? The streamflow (*Q*) at the USGS streamflow-gaging station 03214500 Tug Fork at Kermit at the time of the spill was available from *http://waterdata.usgs.gov/wv/nwis/uv?site_no=03214500*. For this example, we assume a *Q* of 1,000 ft^3/s. A study for this stream reach has been conducted, and the streamflow is within the limits of those studied, 650 ft^3/s to 1,800 ft^3/s (fig. 19).

The traveltime of the leading edge and peak concentration can be estimated from information depicted in figure 19, without the use of the national equation. In this study, no data were reported for the trailing edge, and longitudinal dispersion can be determined only from the leading edge to the peak. Estimates can be made in the following way.

1. From figure 19, interpolate the traveltime of the peak concentration for 1,000 ft^3/s at Kermit:

$$69\text{ h}+\left(\left(160\text{ h}-69\text{ h}\right)\left(\frac{1{,}800\text{ ft}^3/\text{s}-1{,}000\text{ ft}^3/\text{s}}{1{,}800\text{ ft}^3/\text{s}-650\text{ ft}^3/\text{s}}\right)\right)=132\text{ h}\ .$$

2. Interpolate the streamflow for the reach upstream from Matewan:

$$1{,}250\text{ ft}^3/\text{s}-\left(\left(1{,}250\text{ ft}^3/\text{s}-350\text{ ft}^3/\text{s}\right)\left(\frac{1{,}800\text{ ft}^3/\text{s}-1{,}000\text{ ft}^3/\text{s}}{1{,}800\text{ ft}^3/\text{s}-650\text{ ft}^3/\text{s}}\right)\right)=623\text{ ft}^3/\text{s}\ .$$

3. Interpolate the traveltime of the peak concentration at Matewan:

$$47\text{ h}+\left(\left(121\text{ h}-47\text{ h}\right)\left(\frac{1{,}250\text{ ft}^3/\text{s}-623\text{ ft}^3/\text{s}}{1{,}250\text{ ft}^3/\text{s}-350\text{ ft}^3/\text{s}}\right)\right)=98.5\text{ h}\ .$$

4. Determine the dispersion between Matewan and Kermit, and correct the traveltimes for a spill occurring at Matewan rather than traveltimes downstream from Welch. The dispersion for the peak concentration and the leading edge between Matewan and Kermit is determined by interpolating the difference in traveltimes between the leading edge and peak concentration for 1,000 ft^3/s from figure 19:

$$1\text{ h}+\left(\left(4\text{ h}-1\text{ h}\right)\left(\frac{1{,}800\text{ ft}^3/\text{s}-1{,}000\text{ ft}^3/\text{s}}{1{,}800\text{ ft}^3/\text{s}-650\text{ ft}^3/\text{s}}\right)\right)=3\text{ h}\ ,$$

for 1,800 ft^3/s:

$$1\text{ h}\times((69\text{ h}-61\text{ h})-(47\text{ h}-40\text{ h}))=1\text{ h},$$

for 650 ft^3/s:

$$((160\text{ h}-143\text{ h})-(121\text{ h}-108\text{ h}))=4\text{ h}.$$

5. To correct for the spill occurring at Matewan, the traveltime of the peak concentration is calculated as 33.5 h by subtracting the traveltime from Welch to Matewan (98.5 h) from the traveltime from Welch to Kermit (132 h), and the traveltime of the leading edge is calculated as 30.5 by subtracting 3 h for the dispersion of the peak concentration and the leading edge between Matewan and Kermit (3 h was subtracted from 132 h to plot the leading edge in fig. 19 at 129 h).

The unit-peak concentration can be estimated using equation 3:

$$C_{up}=857T_p^{-0.760(Q/Q_a)^{-0.079}}\ .$$

Q at the time of the spill was 1,000 ft^3/s, and Q_a is available from Evaldi and others (2009, p. 277) as 1,441 ft^3/s. Substituting these values into equation 3 gives:

$$C_{up}=857(33.5\text{ h})^{-0.760\left(1{,}000\frac{\text{ft}^3}{\text{s}}/1{,}441\frac{\text{ft}^3}{\text{s}}\right)^{-0.079}}\quad\text{and}$$

$$C_{up}=55.0\ 1/\text{s}\ .$$

No traveltime of the trailing edge was presented in figure 19, but the traveltime to the trailing edge of the spill can be estimated. The traveltime of the leading edge, 30.7 h, has been interpolated from the plot. The time of passage can be estimated from equation 7 (2×10^6 / 55.0 1/s, and dividing by 3,600 s/h to convert s to h), giving 10.1 h. The traveltime of the trailing edge is the sum of the traveltime of the leading edge and the estimated time of passage, giving 30.7 h + 10.1 h = 40.8 h.

The peak concentration can be estimated by rearranging equation 1 to solve for *C*, and replacing *C* with C_p and C_u with

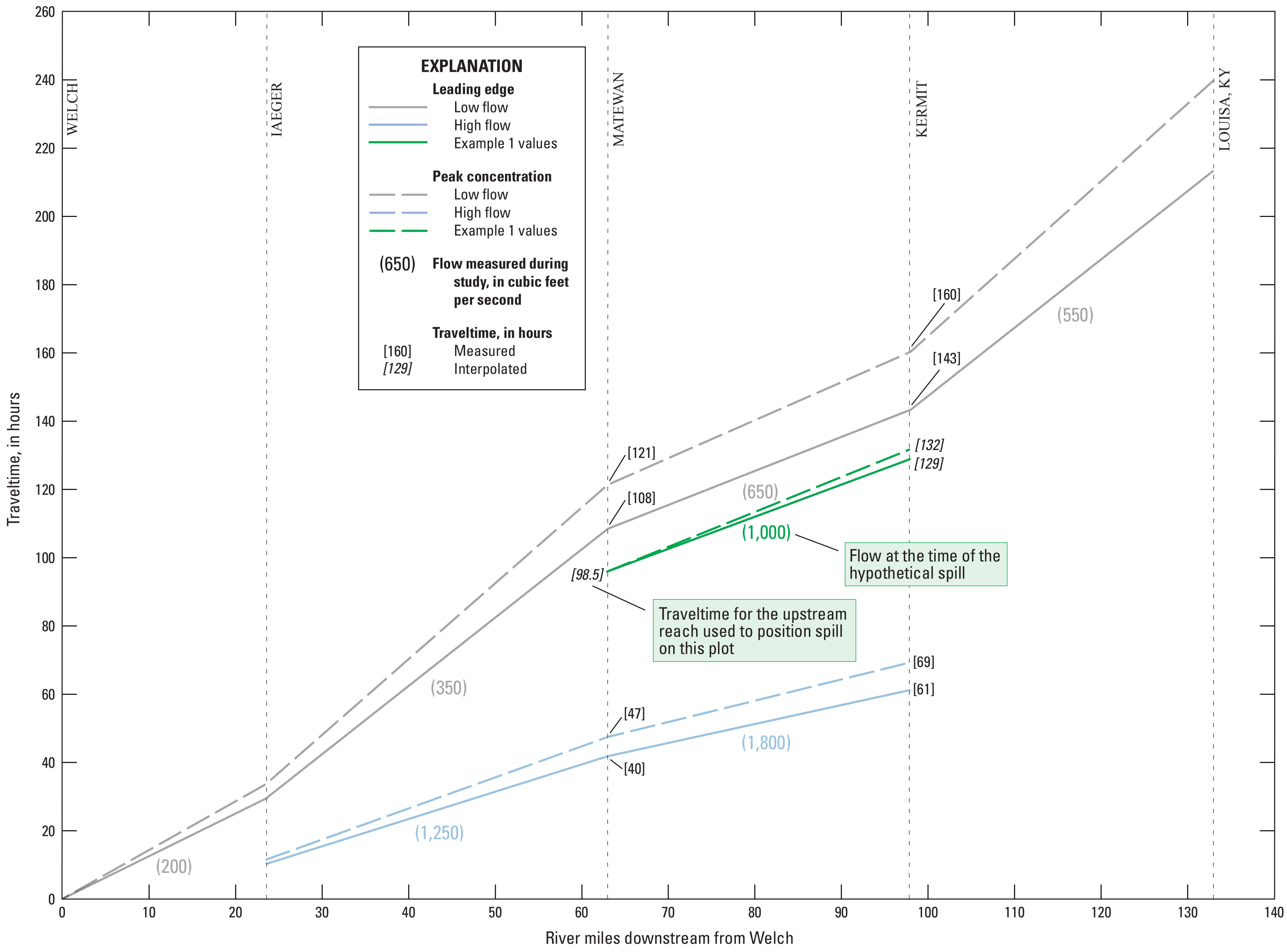


Figure 19. Traveltime and dispersion characteristics for selected reaches of the Tug Fork of the Big Sandy River, West Virginia, and selected characteristics used in estimating traveltime and dispersion of a hypothetical spill discussed in example 1 of the report.

C_{up} to designate that the particular concentration of interest is the peak concentration:

$$C_p = \left(\frac{C_{up} \times R_r \times M_i}{1 \times 10^6 Q} \right).$$

M_i, the spill, was 500 lb, and Q was 1,000 ft³/s. C_{up} has been estimated as 55.0 1/s. Assuming that all the spilled material is transported to the end of the reach, M_r is equal to M_i and R_r equals 1. Substituting these values into equation 8 gives:

$$C_p = \left(\frac{55.0 \text{ 1/s} \times 1 \times 500 \text{ lb}}{1 \times 10^6 \times 1{,}000 \text{ ft}^3\text{/s}} \right)$$

$$= 2.75 \times 10^{-5} \text{ lb/ft}^3.$$

(The peak concentration of 2.75×10^{-5} lb/ft³can be converted to 440 micrograms per liter (µg/L) by dividing 2.75×10^{-5} lb/ft³ by the product of 28.317 L/ft³ and 2.205×10^{-9} lb/µg.)

Example 2: A spill has occurred on the Greenbrier River at a bridge adjacent to the USGS streamflow-gaging station 03183500 Greenbrier River at Alderson, W.Va. How long does it take the spill to arrive at a bridge adjacent to the USGS streamflow-gaging station 03184000 Greenbrier River at Hilldale, W.Va., and what is the peak concentration that is expected? There are no dye studies for this reach of the Greenbrier River, so estimates will be made using the national equations. The velocity of the peak concentration can be estimated using equation 4:

$$V_p = 0.308 + \left(0.0143 \times D_a'^{0.919} Q_a'^{-0.469} S^{0.159} \frac{Q}{D_a} \right)$$

D_a, Q_a, and the river-mile location of the streamflow-gaging station 03183500 Greenbrier River at Alderson, W.Va., are 1,619 mi², 2,290 ft³/s, and river mile 5.5, respectively (Evaldi and others, 2009). The streamflow at the time of the spill (Q) is available from *http://waterdata.usgs.gov/wv/nwis/uv?site_no=03184000*, and for this example, the Q is 1,500 ft³/s. The river-mile location of the USGS streamflow-gaging station 03183500 Greenbrier River at Alderson, W.Va., is 29.2 mi (Evaldi and others, 2009, p. 161). The altitudes of the Greenbrier River at the Hilldale and Alderson streamflow-gaging stations were obtained from the GIS interactive map application at *http://www.mapwv.gov/* as 1,394 ft and 1,535 ft, respectively.

The dimensionless drainage area is computed as

$$D_a' = \left(\frac{\left(1{,}619 \text{ mi}^2 \times 5{,}280^2 \text{ft}^2 / \text{mi}^2\right)^{1.25} \times \left(32.2 \text{ ft/s}^2\right)^{0.5}}{2{,}290 \text{ ft}^3\text{/s}} \right)$$

$$= 5.16 \times 10^{10}.$$

The dimensionless streamflow is computed as

$$Q_a' = \frac{1{,}500 \text{ ft}^3\text{/s}}{2{,}290 \text{ ft}^3\text{/s}}$$

$$= 0.655.$$

The dimensionless reach slope is computed as

$$S = \frac{\left(1{,}535 \text{ ft} - 1{,}394 \text{ ft}\right)}{\left(29.2 \text{ mi} - 5.5 \text{ mi}\right) \times \left(5{,}280 \text{ ft/mi}\right)}$$

$$= 1.13 \times 10^{-3}.$$

Substituting into equation 4 gives

$$V_p = 0.308 \text{ ft/s} + (0.0143)(5.16 \times 10^{10})^{0.919} (0.655)^{-0.469}$$

$$(1.13 \times 10^{-3})^{0.159} \left(\frac{1{,}500 \text{ ft}^3\text{/s}}{1{,}619 \text{ mi} \times \left(5{,}280\right)^2 \text{ft}^2\text{/mi}^2} \right)$$

$$= 0.308 \text{ ft/s} + (0.0143)\left(6.99 \times 10^9\right)(1.22)(0.340)\left(3.32 \times 10^{-8} \text{ft/s}\right)$$

$$= 1.685 \text{ ft/s}.$$

The time for the peak concentration of the spill at Alderson to travel the 23.7 mi (29.2 mi – 5.5 mi) to Hilldale, T_p, traveling at 1.685 ft/s is 20.6 h ((23.7 mi × 5,280 ft/mi) / (1.685 ft/s × 3,600 s/h)). The leading edge of the spill arrives before the peak concentration in 18.4 h (0.890 × 20.6 h), as determined from equation 6:

$$T_l = 0.890 T_p.$$

The probable maximum velocity of the peak concentration can be determined from equation 5:

$$V_{mp} = 0.82 + \left(0.02 \times D_a'^{0.919} Q_a'^{-0.469} S^{0.159} \frac{Q}{D_a} \right).$$

Substituting values into equation 5 gives

$$V_{mp} = 0.82 \text{ ft/s} + (0.02)\left(5.16 \times 10^{10}\right)^{0.919} (0.655)^{-0.469}$$

$$\left(1.127 \times 10^{-3}\right)^{0.159} \left(\frac{1.500 \text{ ft}^3\text{/s}}{1{,}619 \text{ mi} \times 5{,}280^2 \text{ ft}^2\text{/mi}^2} \right)$$

$$= 0.82 \text{ ft/s} + (0.02)\left(6.99 \times 10^9\right)(1.22)(0.340)\left(3.32 \times 10^{-8} \text{ ft/s}\right)$$

$$= 2.75 \text{ ft/s}.$$

The probable minimum time for the peak concentration of the spill at Alderson to travel the 23.7 mi (29.2 mi – 5.5 mi) to Hilldale traveling at 2.75 ft/s is 12.6 h ((23.7 mi × 5,280 ft/mi) / (2.75 ft/s × 3,600 s/h)). Assuming the peak concentration has a velocity of V_{mp}, the leading edge of the spill is expected to arrive in 11.2 h (0.890 × 12.6 h), as determined from equation 6.

The unit-peak concentration can be estimated using equation 3:

$$C_{up} = 857 T_p^{-0.760(Q/Q_a)^{-0.079}}$$

Substituting values into equation 3 gives

$$C_{up} = 857(20.6\text{ h})^{-0.760\left(\frac{1{,}500\text{ ft}^3/\text{s}}{2{,}290\text{ ft}^3/\text{s}}\right)^{-0.079}}$$

$$= 79.4\text{ 1/s}.$$

The time of passage of the spill (until the contaminant concentration falls to 10 percent of its peak concentration) at Middlebourne can be estimated from equation 7:

$$T_d 10 = \frac{2\times 10^6}{C_{up}}$$

Substituting values into equation 7 gives:

$$T_d 10 = \frac{2\times 10^6}{(79.4\text{ 1/s})(3{,}600\text{ s/h})}$$

$$= 6.99\text{ h}.$$

The peak concentration can be estimated by rearranging equation 1 to solve for C and replacing C with C_p and C_u with C_{up} to designate that the particular concentration of interest is the peak concentration:

$$C_p = \left(\frac{C_{up}\times R_r \times M_i}{1\times 10^6 Q}\right)$$

M_i, the spill, was 500 lb, and Q was 1,500 ft³/s. C_{up} has been estimated as 79.4 1/s. Assuming that all the spilled material is transported to the end of the reach, M_r is equal to M_i and R_r equals 1. Substituting these values into equation 8 gives:

$$C_p = \left(\frac{79.4\text{ 1/s} \times 1 \times 500\text{ lb}}{1\times 10^6 \times 1{,}500\text{ ft}^3/\text{s}}\right)$$

$$= 2.65\times 10^{-5}\text{ lb/ft}^3.$$

The peak concentration of 2.65×10^{-5} lb/ft³can be converted to 424 µg/L by dividing 2.65×10^{-5} lb/ft³ by the product of 28.317 L/ft³ and 2.205×10^{-9} lb/µg.

Example 3: A 100 lb spill has occurred on Middle Island Creek 8.8 mi upstream from Middleborne, W.Va. (near the town of Tyler and the confluence of McElroy Creek). What is the peak concentration and time to arrival at Middleborne? There are no dye studies for Middle Island Creek, so estimates will be made using the national equations. The velocity of the peak concentration can be estimated using equation 4:

$$V_p = 0.308 + \left(0.0143 \times D_a'^{0.919} Q_a'^{-0.469} S^{0.159} \frac{Q}{D_a}\right).$$

There is no USGS streamflow-gaging station at Middlebourne, but there is a station downstream, 03114500 Middle Island Creek at Little, W.Va. The streamflow and drainage area at Little, W.Va., at the time of the spill was 200 ft³/s and 458 mi², respectively, from *http://waterdata.usgs.gov/wv/nwis/uv?site_no=03114500*. D_a at Middlebourne is 359 mi² (Wiley, 1997b, p. 41). Q at Middlebourne is estimated as 157 ft³/s using drainage-area ratios ((359/458) × 200). (Note, if the stream is rising, this Q estimate may be low and result in a low estimate of V_p). The mean annual streamflow at 03114500 Middle Island Creek at Little, W.Va., is reported by Evaldi and others (2009, p. 119) as 648 ft³/s, and Q_a at Middlebourne is estimated using drainage-area ratios as 508 ft³/s ((359/458) × 648). Once D_a, Q, and Q_a have been obtained, the rest of the estimating procedure is the same as in example 2.

The altitudes of the stream at Middlebourne and 8.8 mi upstream from Middlebourne are determined from the GIS interactive map application available at *http://www.mapwv.gov/* as 665 ft and 687 ft, respectively.

The dimensionless drainage area is computed as

$$D_a' = \left(\frac{\left(359\text{ mi}^2 \times 5{,}280^2\text{ ft}^2/\text{mi}^2\right)^{1.25}\left(32.2\text{ ft/s}^2\right)^{0.5}}{508\text{ ft}^3/\text{s}}\right)$$

$$= 3.54\times 10^{10}.$$

The dimensionless streamflow is computed as

$$Q_a' = \frac{157\text{ ft}^3/\text{s}}{508\text{ ft}^3/\text{s}}$$

$$= 0.309.$$

The dimensionless reach slope is computed as

$$S = \frac{(687\text{ ft} - 665\text{ ft})}{(8.8\text{ mi})\times(5{,}280\text{ ft/mi})}$$

$$= 4.73\times 10^{-4}.$$

Substituting into equation 4 gives:

$$V_p = 0.308 \text{ ft/s} + (0.0143)\left(3.54\times10^{10}\right)^{0.919}(0.309)^{-0.469}$$

$$\left(4.73\times10^{-4}\right)^{0.159}\left(\frac{157 \text{ ft}^3/\text{s}}{359 \text{ mi}^2 \times 5{,}280^2 \text{ ft}^2/\text{mi}^2}\right)$$

$$= 0.308 \text{ ft/s} + (0.0143)\left(4.94\times10^{9}\right)(1.74)(0.296)\left(1.57\times10^{-8} \text{ ft/s}\right)$$

$$= 0.877 \text{ ft/s.}$$

The time for the peak concentration (T_p) of the spill to travel the 8.8 mi to Middlebourne, traveling at 0.877 ft/s, is 14.7 h ((8.8 mi × 5,280 ft/mi) / (0.877 ft/s × 3,600 s/h)). The leading time of arrival of the leading edge of the spill is determined from equation 6:

$$T_l = 0.890 T_p ,$$

and substituting into equation 6 gives and arrival time for the leading edge of 13.1 h = 0.890(14.7 h).

The probable maximum velocity of the peak concentration can be determined from equation 5:

$$V_{mp} = 0.82 + \left(0.02 \times D_a'^{0.919} Q_a'^{-0.469} S^{0.159} \frac{Q}{D_a}\right).$$

Substituting values into equation 5 gives

$$V_{mp} = 0.82 \text{ ft/s} + (0.02)\left(3.54\times10^{10}\right)^{0.919}(0.309)^{-0.469}$$

$$\left(4.73\times10^{-4}\right)^{0.159}\left(\frac{157 \text{ ft}^3/\text{s}}{359 \text{ mi}^2 \times 5{,}280^2 \text{ ft}^2/\text{mi}^2}\right)$$

$$= 0.82 \text{ ft/s} + (0.02)\left(4.94\times10^{9}\right)(1.74)(0.296)\left(1.57\times10^{-8} \text{ ft/s}\right)$$

$$= 1.62 \text{ ft/s.}$$

The time for the peak concentration of the spill to travel the 8.8 mi to Middlebourne traveling at the probable maximum velocity of 1.62 ft/s is 7.99 h ((8.8 mi × 5,280 ft/mi) / (1.62 ft/s × 3,600 s/h)). On the basis of the probable maximum velocity of the peak concentration, the leading edge of the spill would be expected to arrive in 7.11 h (0.890 × 7.99 h), as determined using equation 6.

The unit-peak concentration can be estimated using equation 3:

$$C_{up} = 857 T_p^{-0.760(Q/Q_a)^{-0.079}}$$

Substituting values into equation 3 gives

$$C_{up} = 857(14.7 \text{ h})^{-0.760\left(\frac{157 \text{ ft}^3/\text{s}}{508 \text{ ft}^3/\text{s}}\right)^{-0.079}}$$

$$= 91.0 \text{ 1/s.}$$

The time of passage of the spill (until the contaminant concentration falls to 10 percent of its peak concentration) at Middlebourne can be estimated as 6.10 h from equation 7:

$$T_d 10 = \frac{2\times10^6}{C_{up}} .$$

Substituting values into equation 7 gives:

$$T_d 10 = \frac{2\times10^6}{(91.0 \text{ 1/s})(3{,}600 \text{ s/h})}$$

$$= 6.10 \text{ h.}$$

The peak concentration can be estimated by rearranging equation 1 to solve for C and replacing C with C_p and C_u with C_{up} to designate that the particular concentration of interest is the peak concentration:

$$C_p = \left(\frac{C_{up} \times R_r \times M_i}{1\times10^6 Q}\right).$$

M_i, the spill, was 100 lb, and Q was estimated as 157 ft^3/s. C_{up} has been estimated as 91.0 1/s. Assuming that all the spilled material is transported to the end of the reach, M_r is equal to M_i and R_r equals 1. Substituting these values into equation 8 gives:

$$C_p = \left(\frac{91.0 \text{ 1/s} \times 1 \times 100 \text{ lb}}{1\times10^6 \times 157 \text{ ft}^3/\text{s}}\right)$$

$$= 5.80\times10^{-5} \text{ lb/ft}^3 .$$

The peak concentration of 5.80×10^{-5} lb/ft^3can be converted to 929 µg/L by dividing 5.80×10^{-5} lb/ft^3 by the product of 28.317 L/ft^3 and 2.205×10^{-9} lb/µg.

Limitations of Estimating Procedures

Regulated stream reaches include those navigable waters controlled by lock and dam structures in West Virginia. Stream reaches with uncontrolled dams or structures that create backwater can have similar hydraulic properties to those that are actively managed. This report does not distinguish which of the stream reaches contain structures that prevent the national equations from being applicable.

Traveltime and dispersion typically were measured when streamflows were relatively steady. Typically, streamflows were slightly receding rather than rising. Dye was injected in the center of streamflow or in multiple locations at the center points of halves or thirds of the total cross-sectional streamflow. The streamflow, injection, and solute characteristics used in the study may not be those that occur in an actual spill.

Traveltime and dispersion characteristics of a stream reach are functions of streamflow and vary greatly throughout the range of flows. If flows are higher or lower in a reach than they were when traveltime and dispersion were determined, traveltime and dispersion values may differ greatly from the values at the time of the study. The national equations may provide the most accurate estimates of these characteristics. In Pennsylvania streams with velocity measurements made at flows higher than those used to develop the national equations, Reed and Stuckey (2002) found that the national equations produced velocity estimates greater than those that had been measured. This indicates that management actions, such as shutting down water intakes, are likely to protect the water supply from intake of the spills if management actions occur within the times predicted using the national equations.

Rapidly changing streamflow can affect traveltime, and estimates are likely to be in error when streamflow is changing. Both increases and decreases in streamflow occur as a wave that travels faster than the spill. Two experimental dye studies were conducted on the New River by Appel (1987) and Wiley and Appel (1989) in which streamflow was increased and decreased by changing releases from Bluestone Dam. The wave passed through the dye cloud as the dye cloud moved downstream. Increases in streamflow decreased the peak concentration (C_p) and traveltime of the peak concentration (T_p). Decreases in streamflow increased the peak concentration (C_p) and traveltime of the peak concentration (T_p). The decreased traveltime associated with rising streamflow is likely to be of great concern to water managers responding to a spill.

Estimates will be affected when a spill is inadequately mixed across the channel. A dye injection near the edge of a streambank (or from a much smaller tributary stream) will take four times as much stream length for adequate mixing across the channel as a dye injection in the center of the stream (Kilpatrick and Wilson, 1989, p. 13). Also, most of the values of V_p that were close in magnitude to the V_{mp} line in figure 18 are injection reaches. Traveltimes will likely be less than those determined by the estimating equations and procedures if the spill is in the center of the stream, and traveltimes will likely be greater than those determined by the estimating equations and procedures if the spill is near the streambank. Material that was carried away from a floodplain by rising flood waters would be transported much the same way, as if it had been spilled on or near the streambank.

Contaminant characteristics might differ from dye by being more or less conservative or less soluble. Rhodamine dye is not conservative, and it may be adsorbed to sediment or taken up by vegetation. Salts, including those already dissolved in brine, are likely to be conservative. Many organic materials and fertilizers are less conservative and less soluble than dye. Some volatile organic compounds are insoluble and, when spilled, remain on the surface of streams instead of dispersing throughout the water column.

Field work for the oldest reach-specific studies discussed in this report was done as early as 1964 (Taylor and others, 1984). Traveltimes that were determined more than 40 years ago likely represent present conditions well in stream channels that remain substantially the same. Traveltime between two points on a stream could be affected by changes in reach length or slope, as in the case of a reconfigured stream channel. Changes to the bed profile could also change traveltime. Decreases in bed complexity caused by dredging or channelization could decrease traveltime. Increases in bed complexity, such as fish habitat enhancement or a natural stream channel design project, could increase traveltime. Construction or removal of a dam or dam-like structure could also change traveltime of a stream reach. The authors are not aware of studies that have measured changes in traveltime and dispersion in relation to stream-channel modifications and would not rely on assumptions about increased traveltime during response to a spill. Channel and bed features are likely to affect traveltime through a reach so that it is not constant, and the plots that show traveltime increasing in a linear manner through the reach are intended as approximations.

Summary

The U.S. Geological Survey, in cooperation with West Virginia Bureau for Public Health, Office of Environmental Health Services, compiled and evaluated traveltime and dispersion information representative of West Virginia, validated national equations, and presented examples for estimating traveltime and dispersion for streams in West Virginia. Traveltime and dispersion data were not available for streams flowing directly into the Ohio River in the northwestern part of the State. The Bluestone River, Gauley River, Elk River, Little Kanawha River, Middle Island Creek, Cheat River, Tygart Valley River, and Buckhannon River are large streams in West Virginia without any traveltime and dispersion information available.

Traveltime in a free-flowing stream reach increases as streamflow decreases. Dispersion in a free-flowing stream reach increases as streamflow decreases because the residence time in the reach increases as streamflow and velocity decrease. Dispersion in a regulated stream reach generally is less than dispersion in a free-flowing reach. National equations (Jobson, 1996) were found to predict traveltime and dispersion for streams located in West Virginia with error characteristics comparable to those reported for the national data set. The root mean square error (RMSE) of the national equation for predicting unit-peak concentration was reported by Jobson (1996) to be 0.426 log units (127 percent). The national equations were used to predict the unit-peak concentrations for reaches in the West Virginia data set with an RMSE of 0.139 log units (32.8 percent). The RMSE of the national equation for the velocity of the peak concentration was reported to be 0.157 meters per second (m/s) or 0.505 feet per second (ft/s); the RMSE was 0.630 ft/s (83 percent) when the equation was applied to reaches in the West Virginia data set. Ninety-nine percent of the observations in the national data set have velocities less than or equal to the maximum probable velocities estimated for the peak concentration. All observed velocities of the peak concentration in the West Virginia data set are less than the maximum probable velocities estimated from the national equations. The national equation resulted in a traveltime for the leading edge of a dye cloud for reaches in West Virginia with an RMSE of 3.38 h (10 percent); the RMSE for all data was 3.78 h. Time of passage of a dye cloud was estimated using the national equation without a statistical measure, but an RMSE of 3.82 h (20 percent) was determined for reaches in West Virginia.

Where reach-specific information is available, it may be used to make traveltime estimates that are more accurate than those made using the national equations. Traveltime and dispersion estimates can be made from the reach-specific plots of traveltime as a function of streamflow and location on streams where plots are available. In the absence of reach-specific plots, or where streamflow is outside the limits of historic studies, traveltime and dispersion estimates for free-flowing stream reaches can be made from equations. No estimating procedures are presented for traveltime and dispersion for regulated stream reaches not studied or for studied reaches when streamflows are outside the range of streamflows studied.

Rapidly changing streamflows can affect traveltime and dispersion. In two experimental studies in the New River, increases in streamflow decreased the peak concentration and its traveltime. Decreases in streamflow increased the peak concentration and its traveltime.

Inadequate mixing across the stream channel can affect traveltime and dispersion. Traveltimes will likely be greater than those determined using the estimating equations and procedures if the spill is in the center of the stream, and traveltimes will likely be less than those determined using the estimating equations and procedures if the spill is near the streambank.

Acknowledgments

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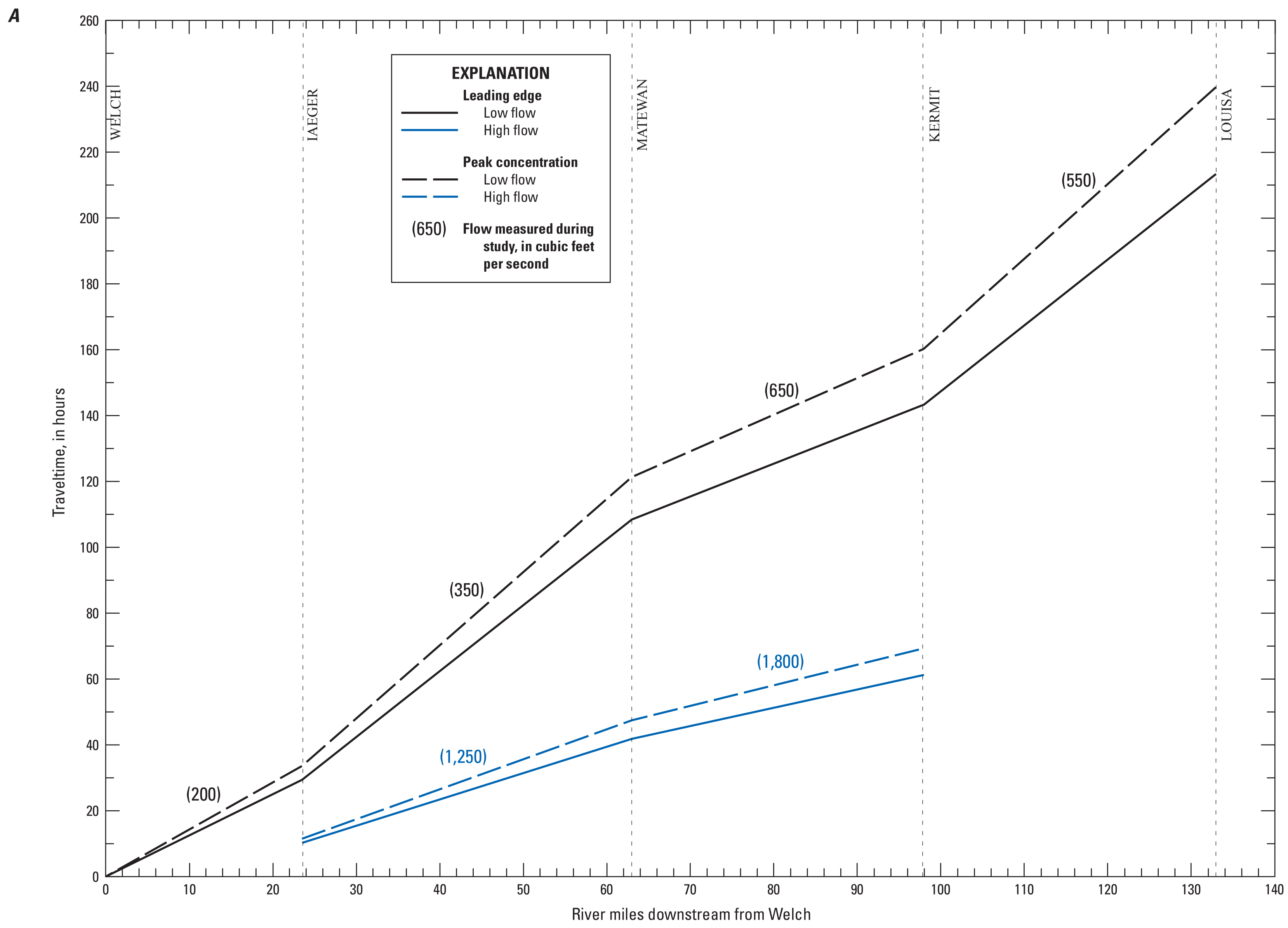

Figure 3. *A*, Traveltime and dispersion characteristics for selected reaches, and *B*, location of the reaches of the Tug Fork of the Big Sandy River, West Virginia.

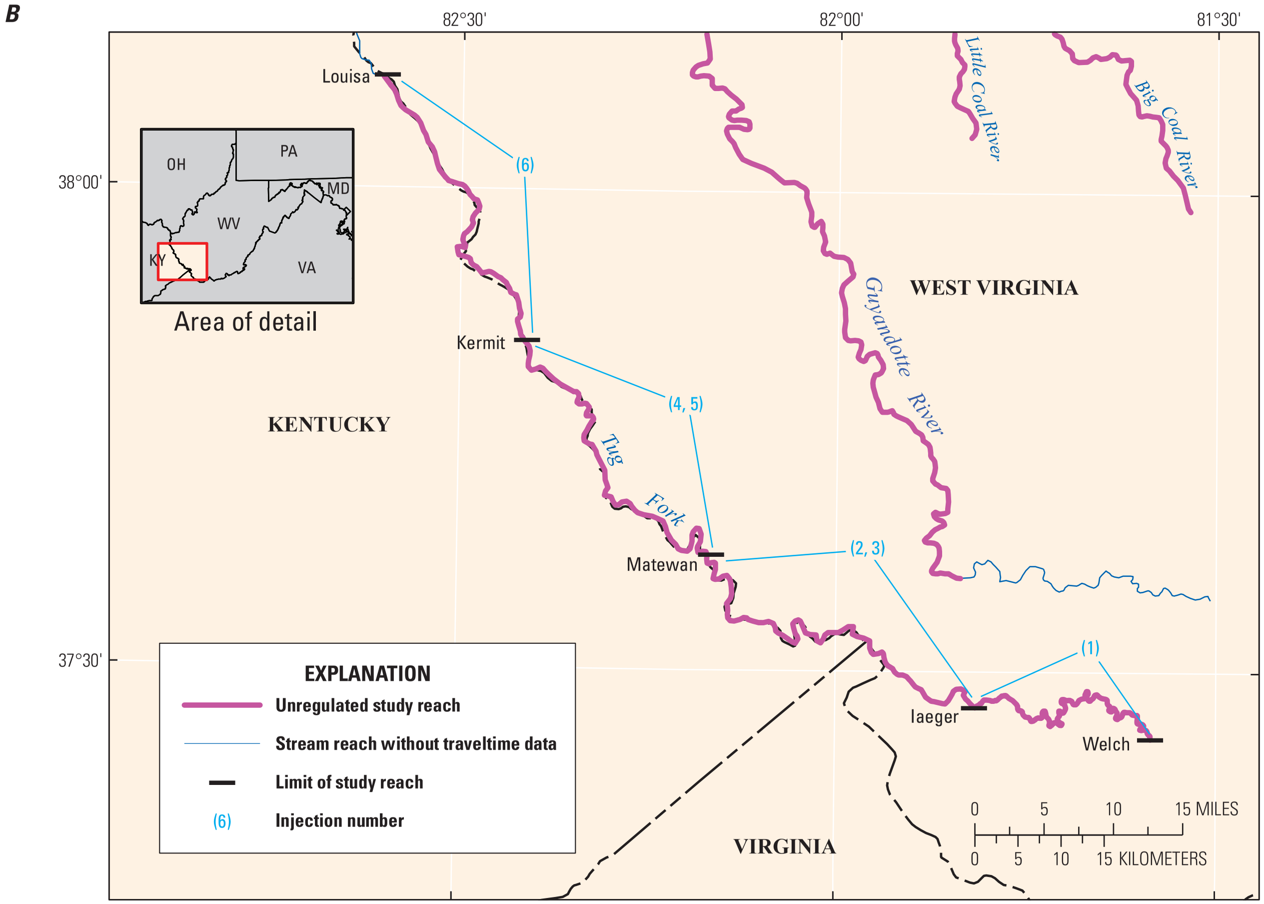

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Figure 3. *A*, Traveltime and dispersion characteristics for selected reaches, and *B*, location of the reaches of the Tug Fork of the Big Sandy River, West Virginia.—Continued

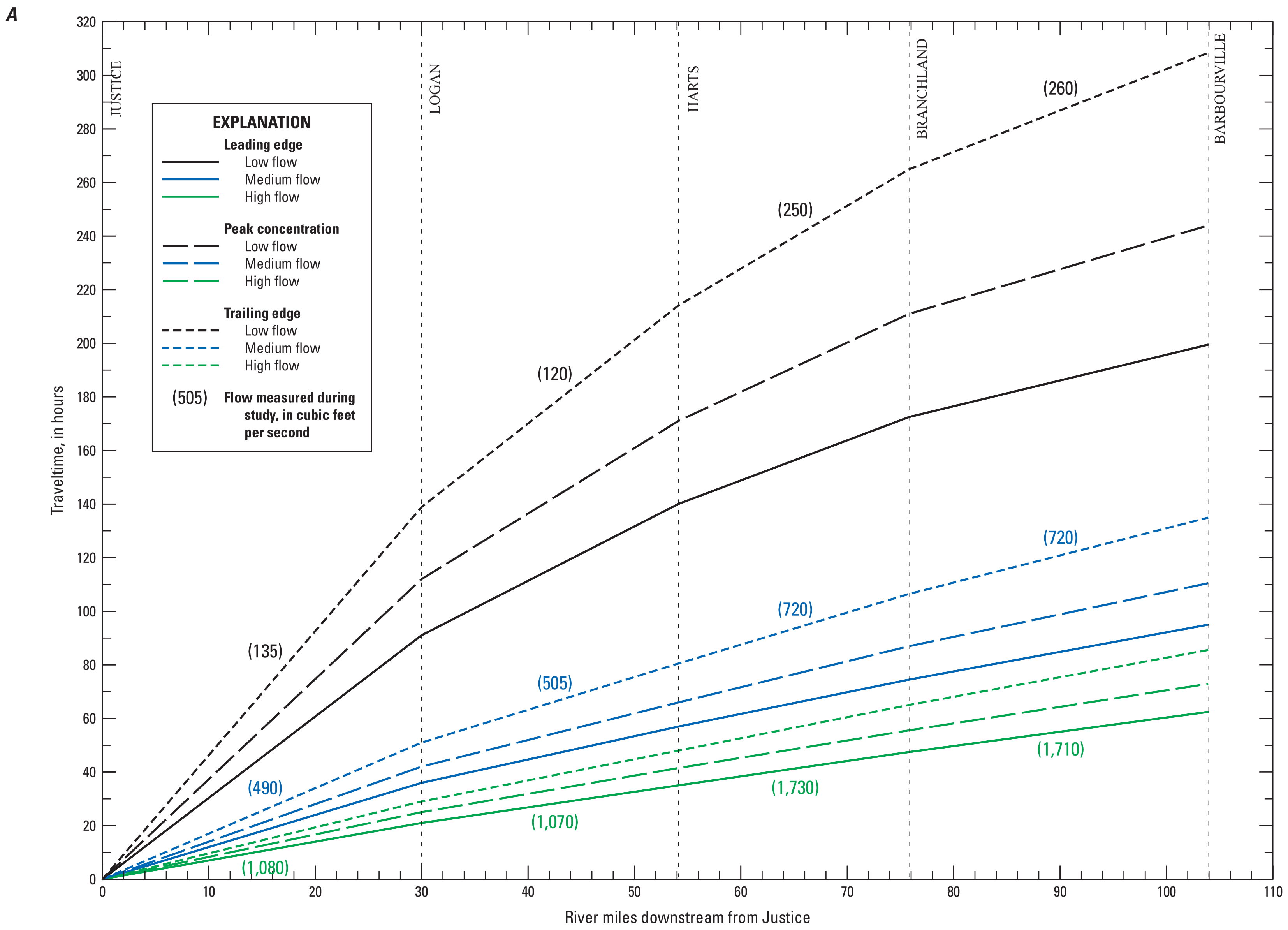

Figure 4. *A*, Traveltime and dispersion characteristics of selected reaches, and *B*, location of the reaches of the Guyandotte River, West Virginia.

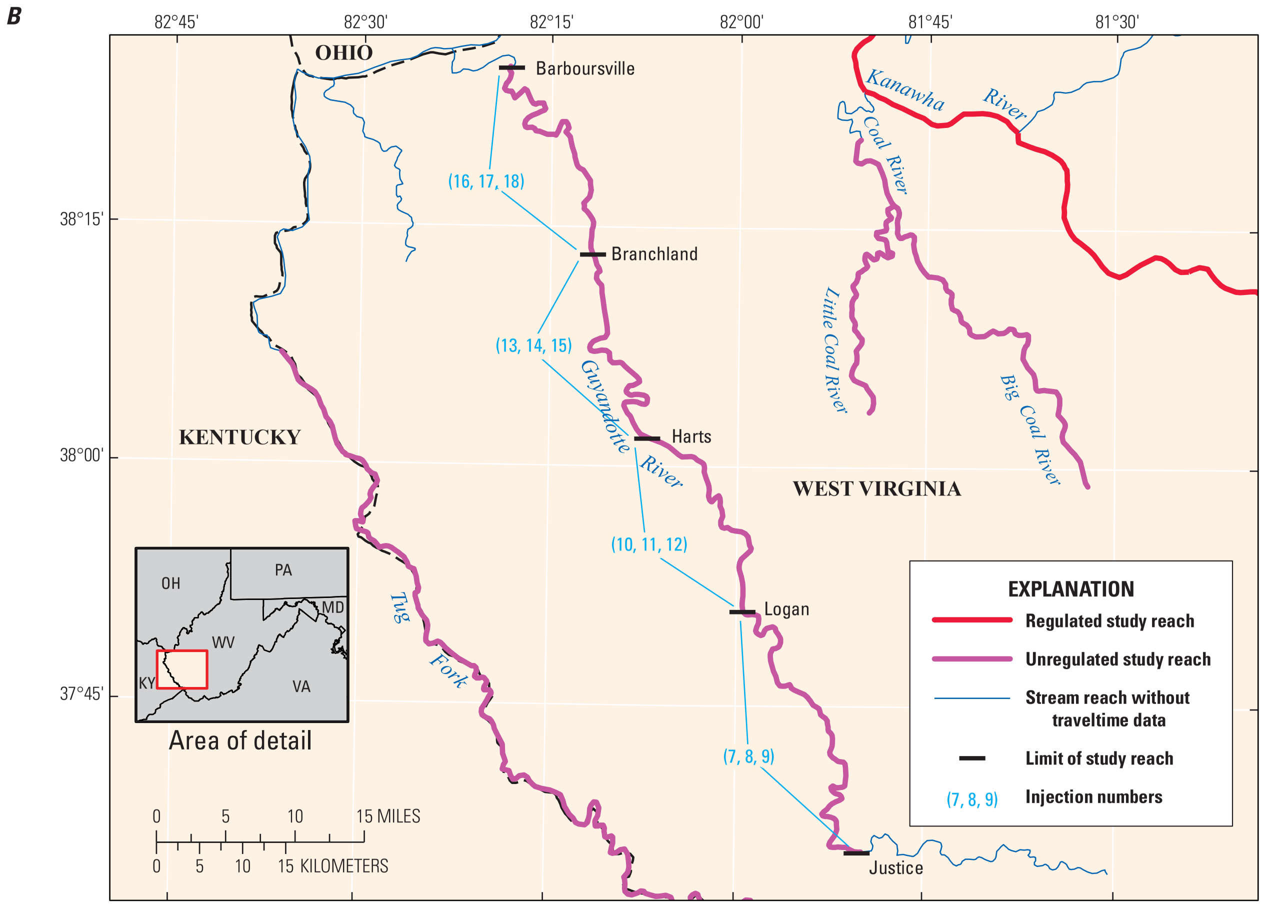

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Figure 4. *A*, Traveltime and dispersion characteristics of selected reaches, and *B*, location of the reaches of the Guyandotte River, West Virginia.—Continued

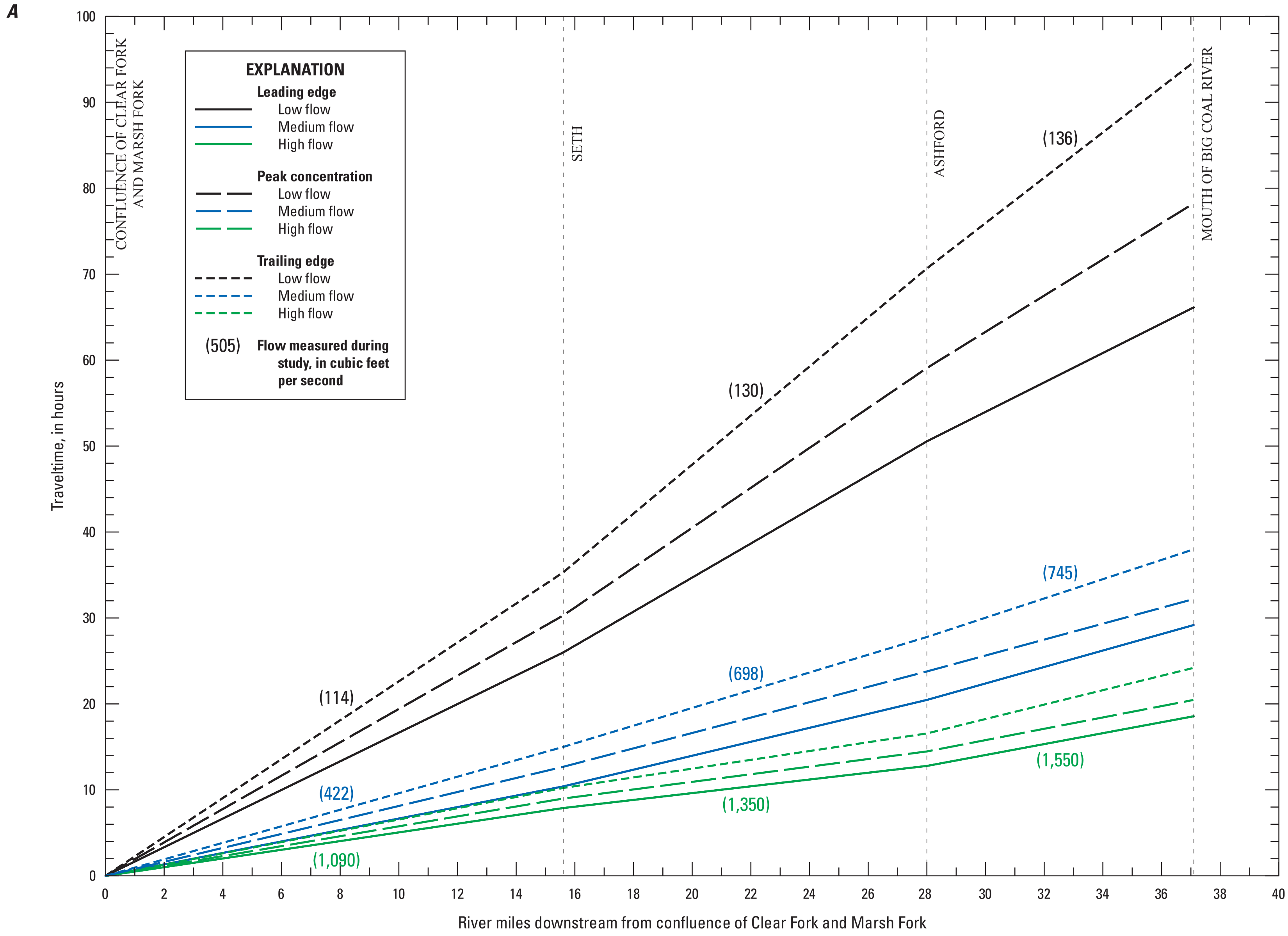

Figure 5. *A*, Traveltime and dispersion characteristics of selected reaches of the Big Coal River, and *B*, location of the reaches of the Big Coal River, Little Coal River, and Coal River, West Virginia.

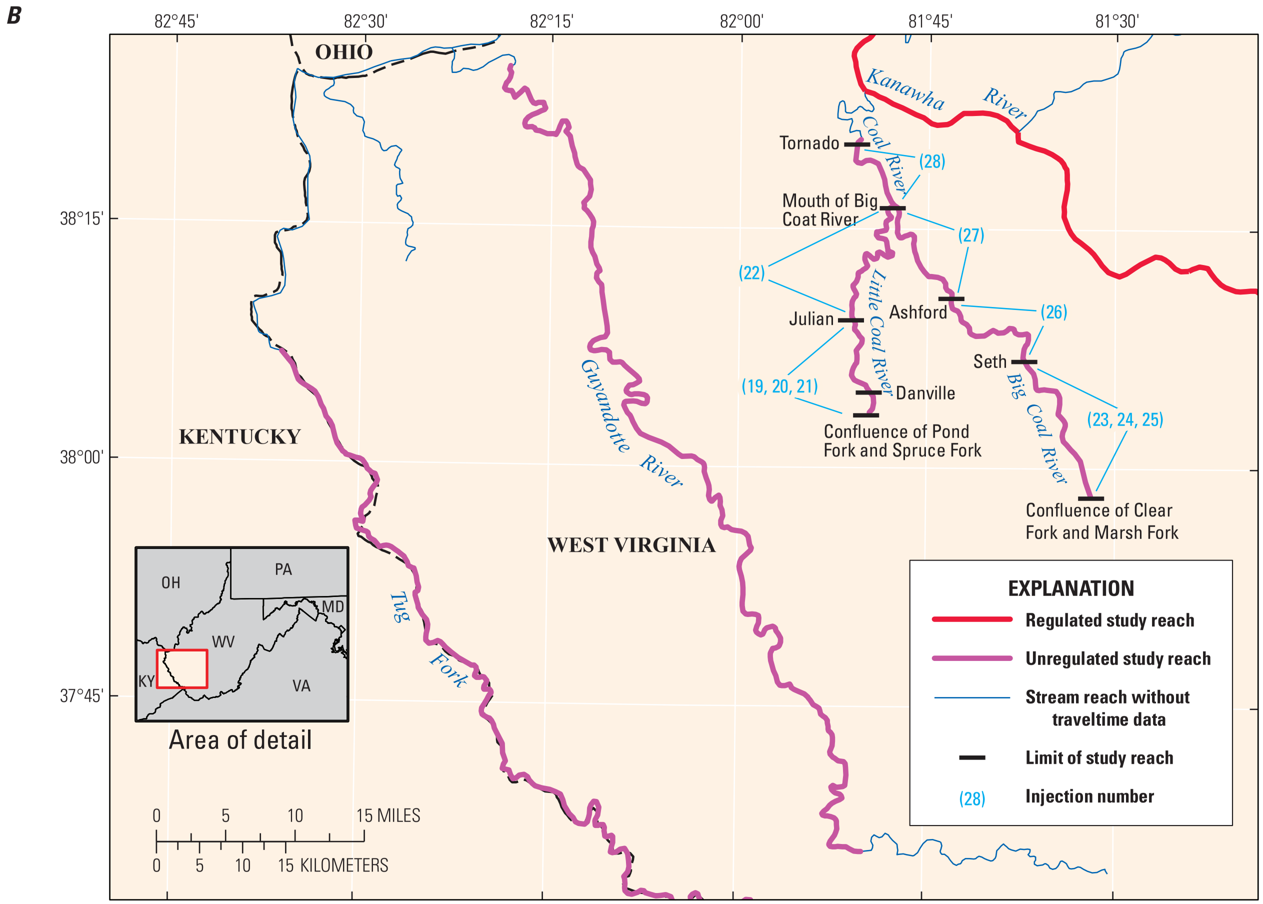

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Figure 5. *A*, Traveltime and dispersion characteristics of selected reaches of the Big Coal River, and *B*, location of the reaches of the Big Coal River, Little Coal River, and Coal River, West Virginia.—Continued

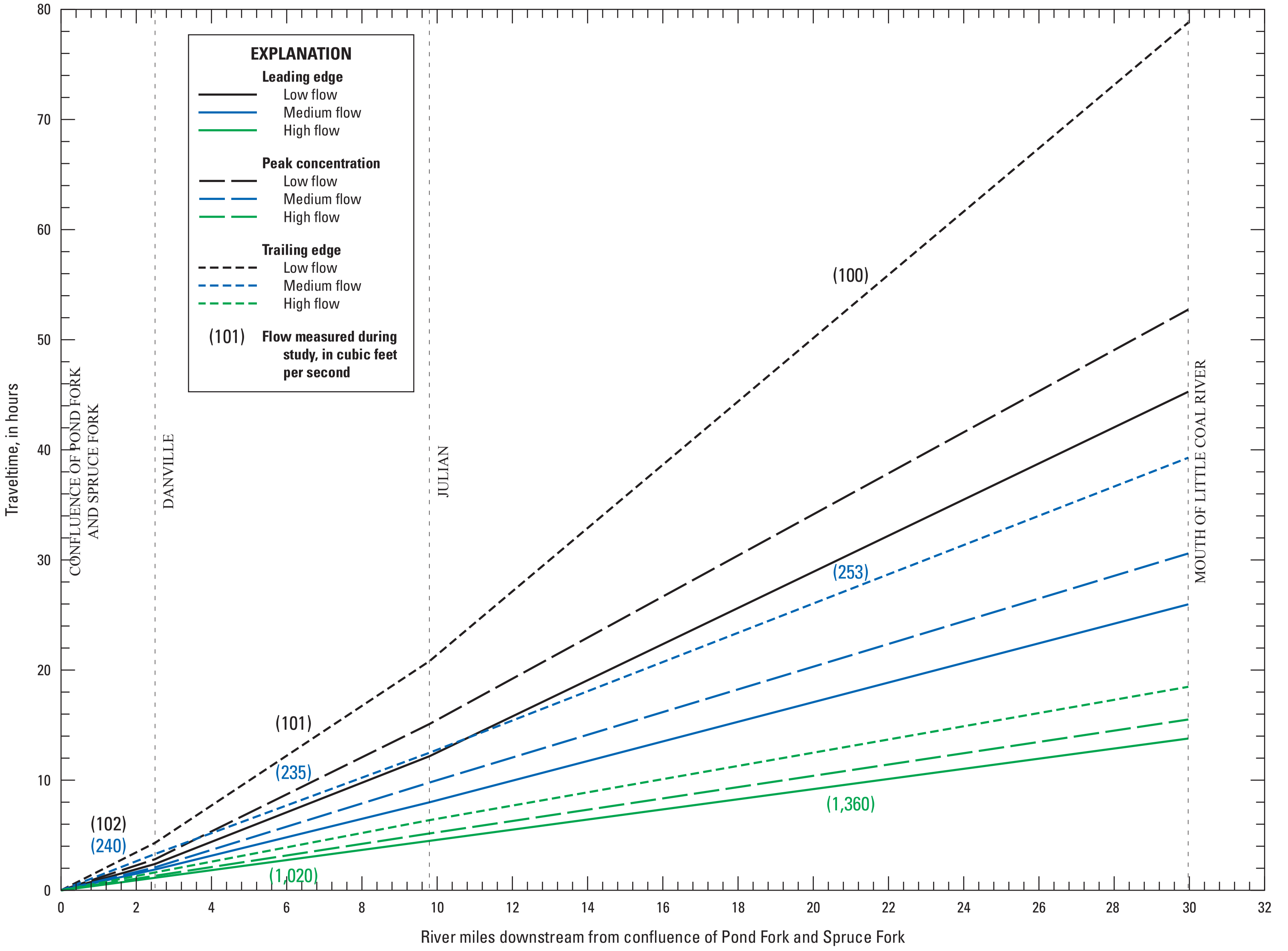

Figure 6. Traveltime and dispersion characteristics of selected reaches of the Little Coal River, West Virginia.

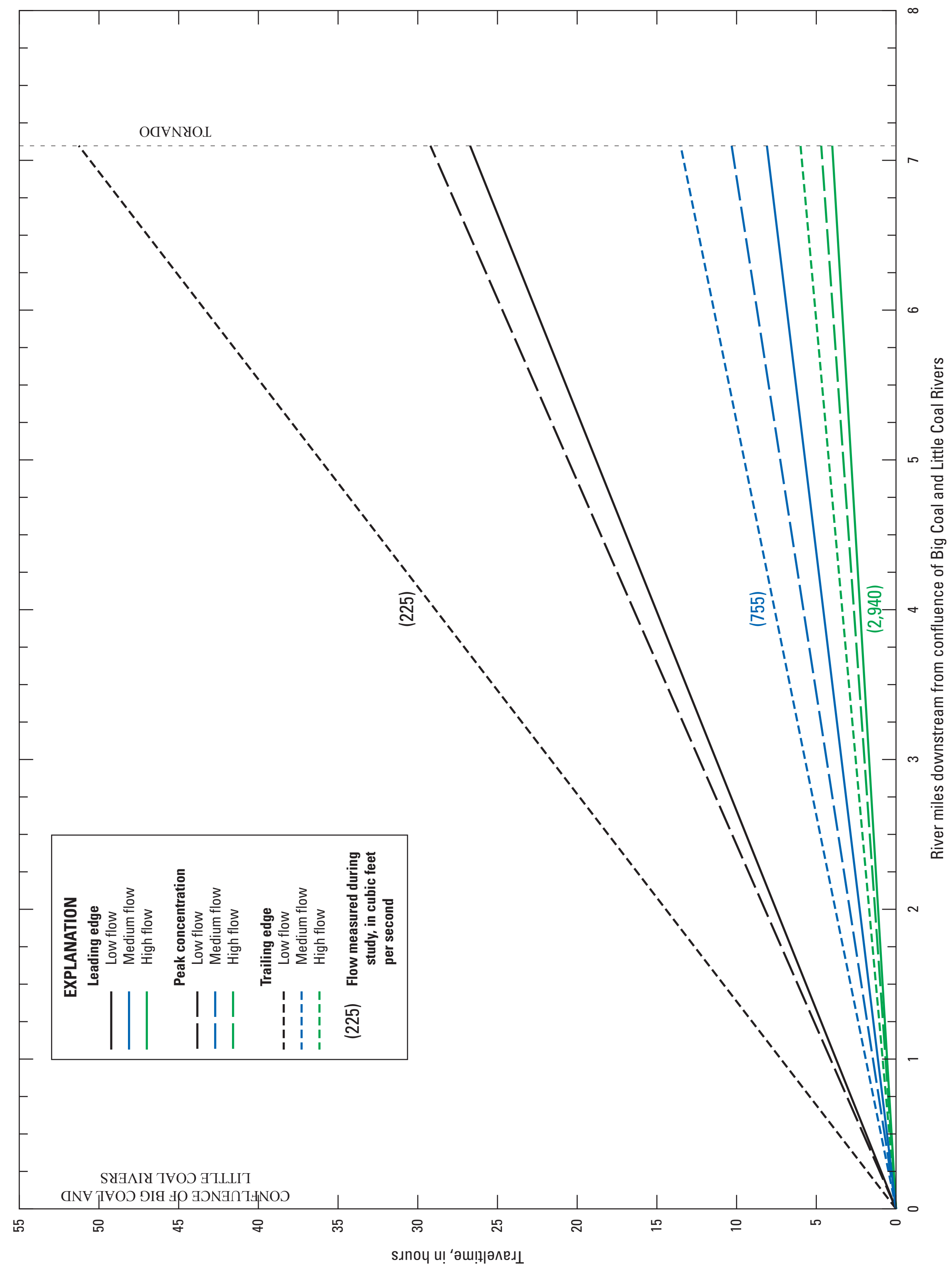

Figure 7. Traveltime and dispersion characteristics of selected reaches of the Coal River, West Virginia.

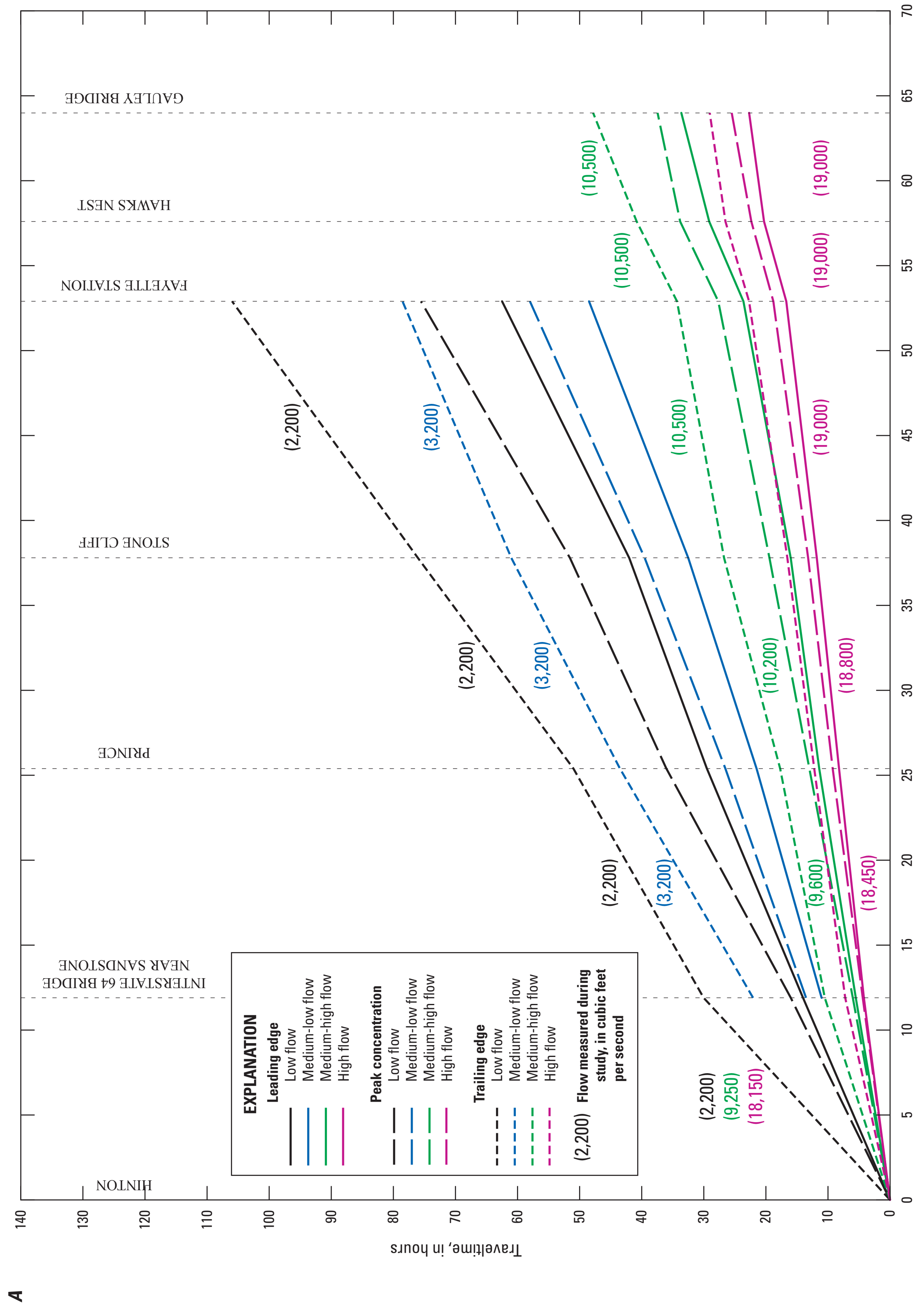

Figure 8. *A*, Traveltime and dispersion characteristics of selected reaches, and *B*, location of the reaches of the New River, West Virginia.

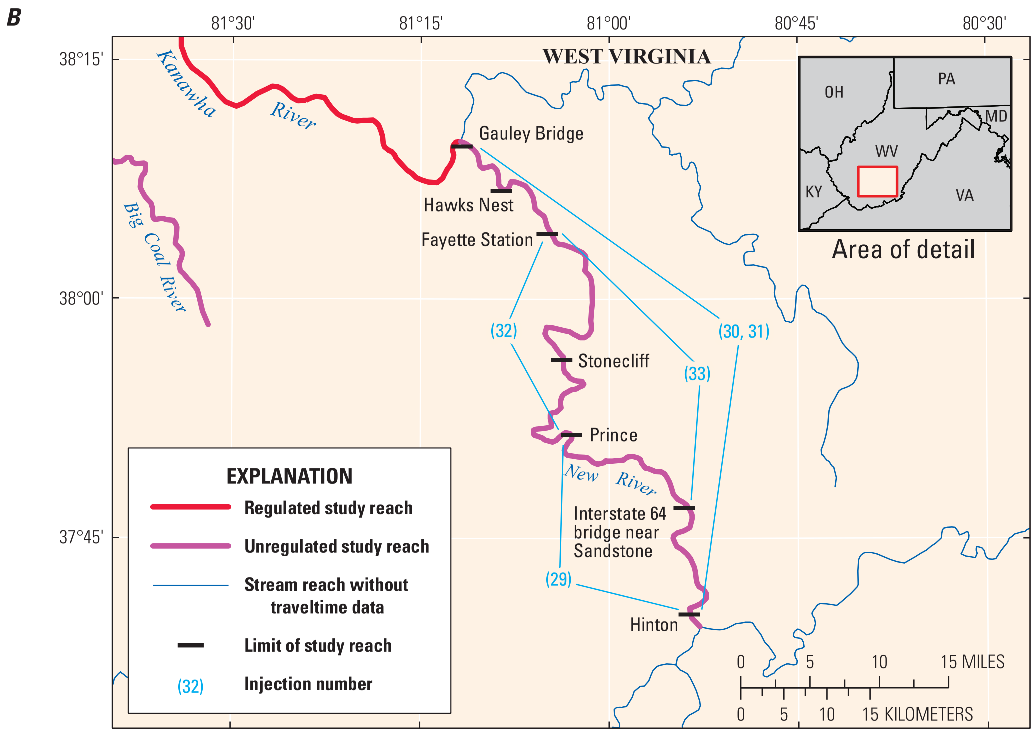

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Figure 8. *A*, Traveltime and dispersion characteristics of selected reaches, and *B*, location of the reaches of the New River, West Virginia.—Continued

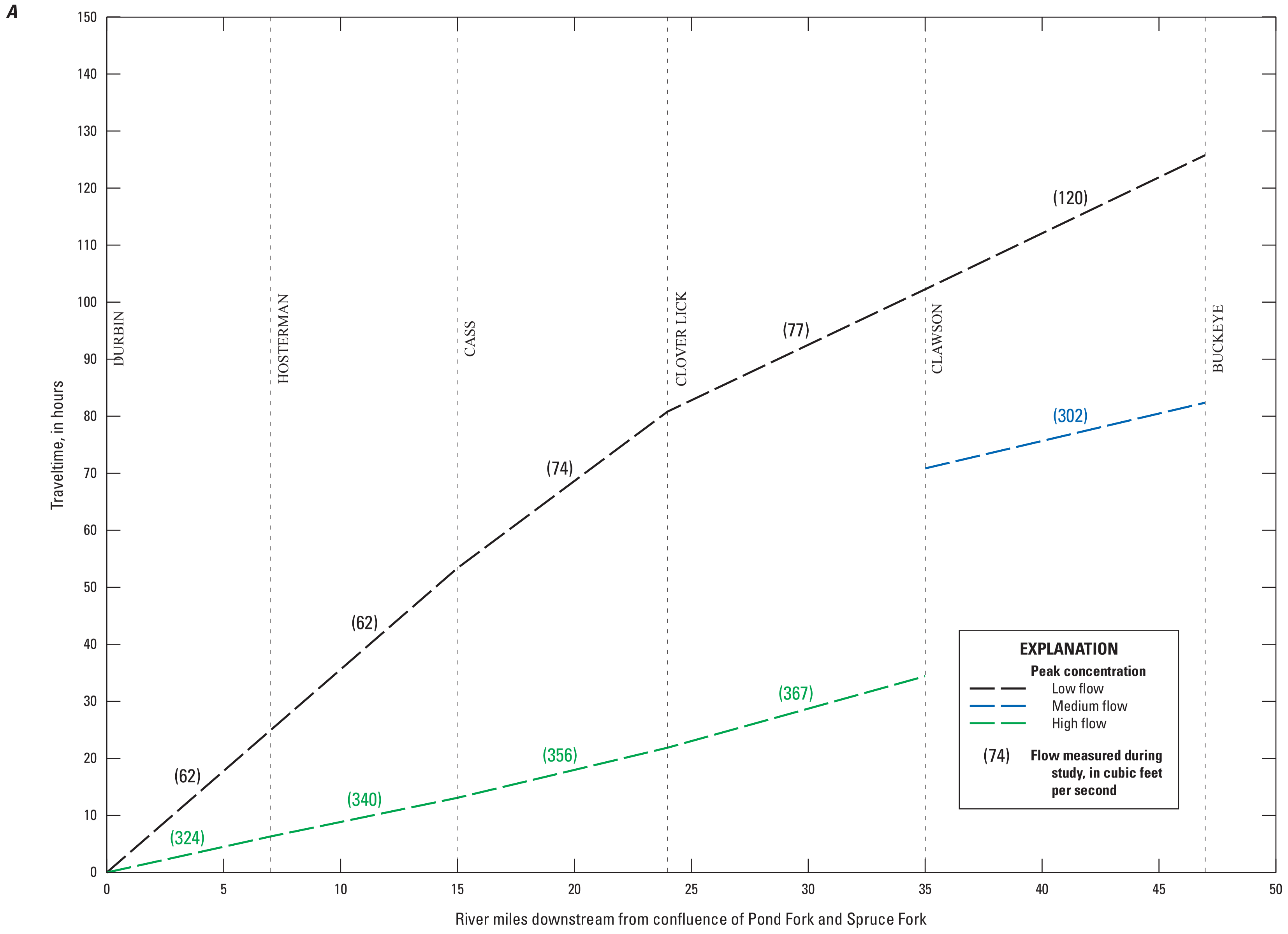

Figure 9. *A*, Traveltime and dispersion characteristics of selected reaches, and *B*, location of the reaches of the Greenbrier River, West Virginia.

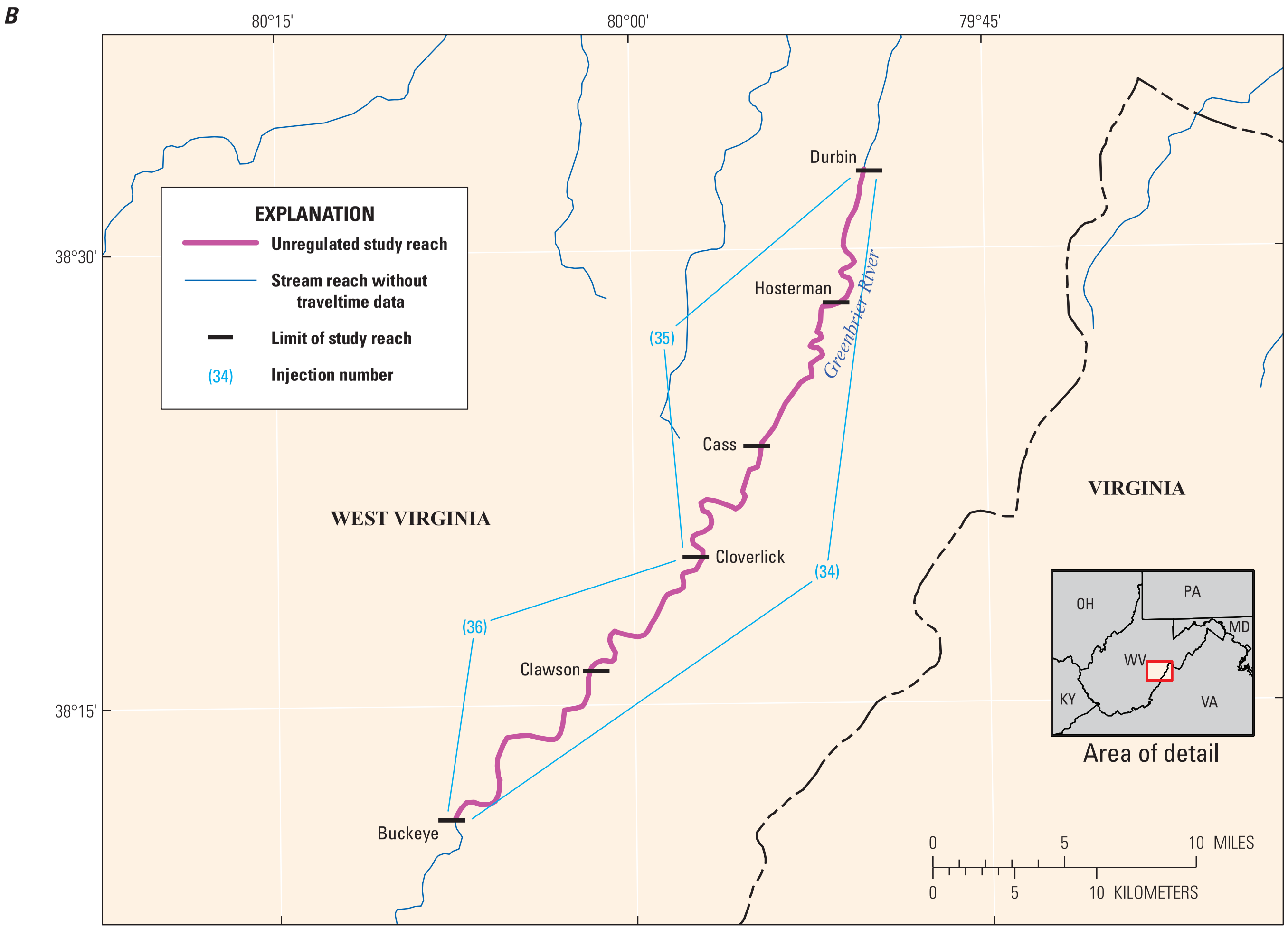

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Figure 9. *A*, Traveltime and dispersion characteristics of selected reaches, and *B*, location of the reaches of the Greenbrier River, West Virginia.—Continued

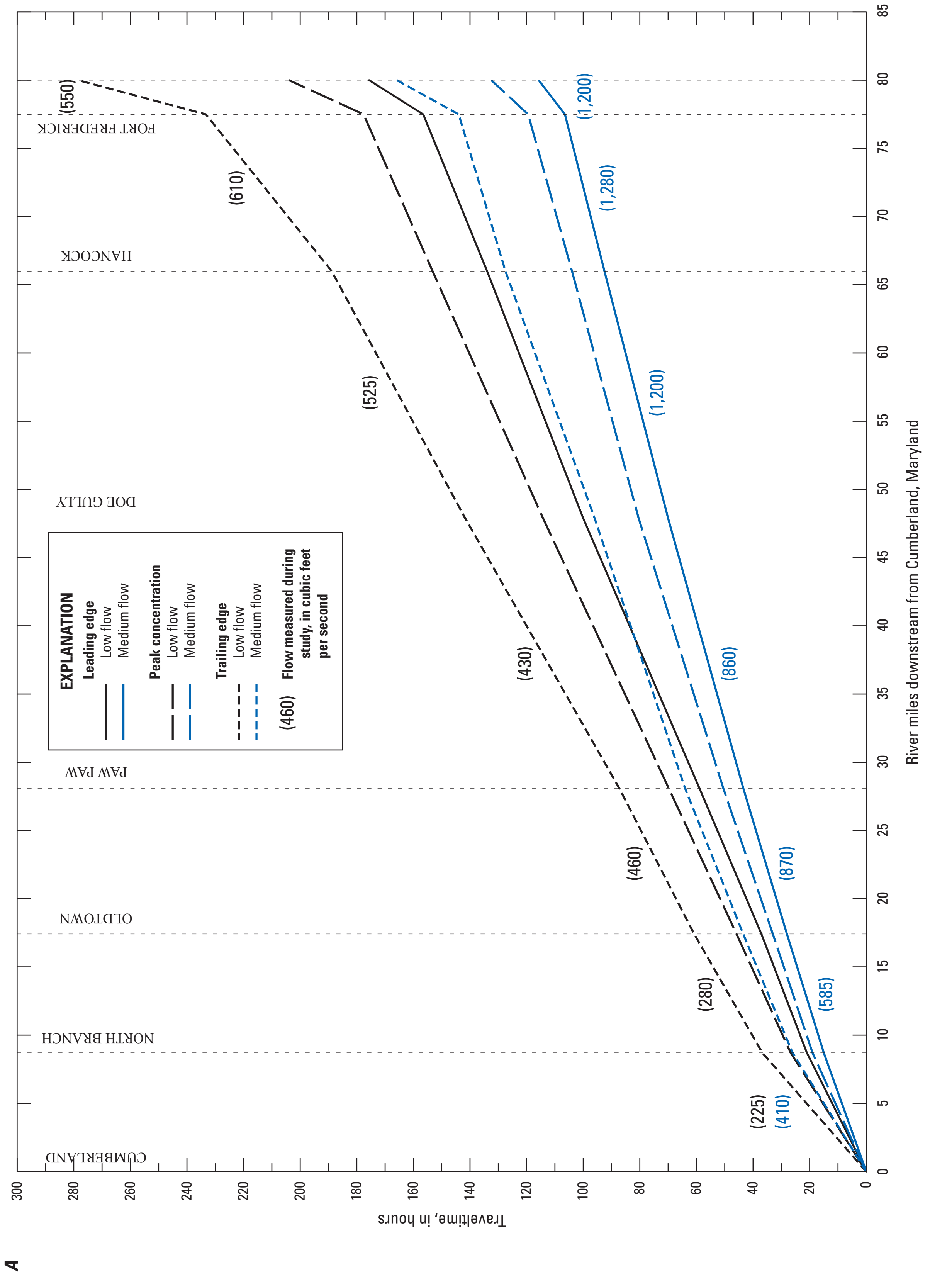
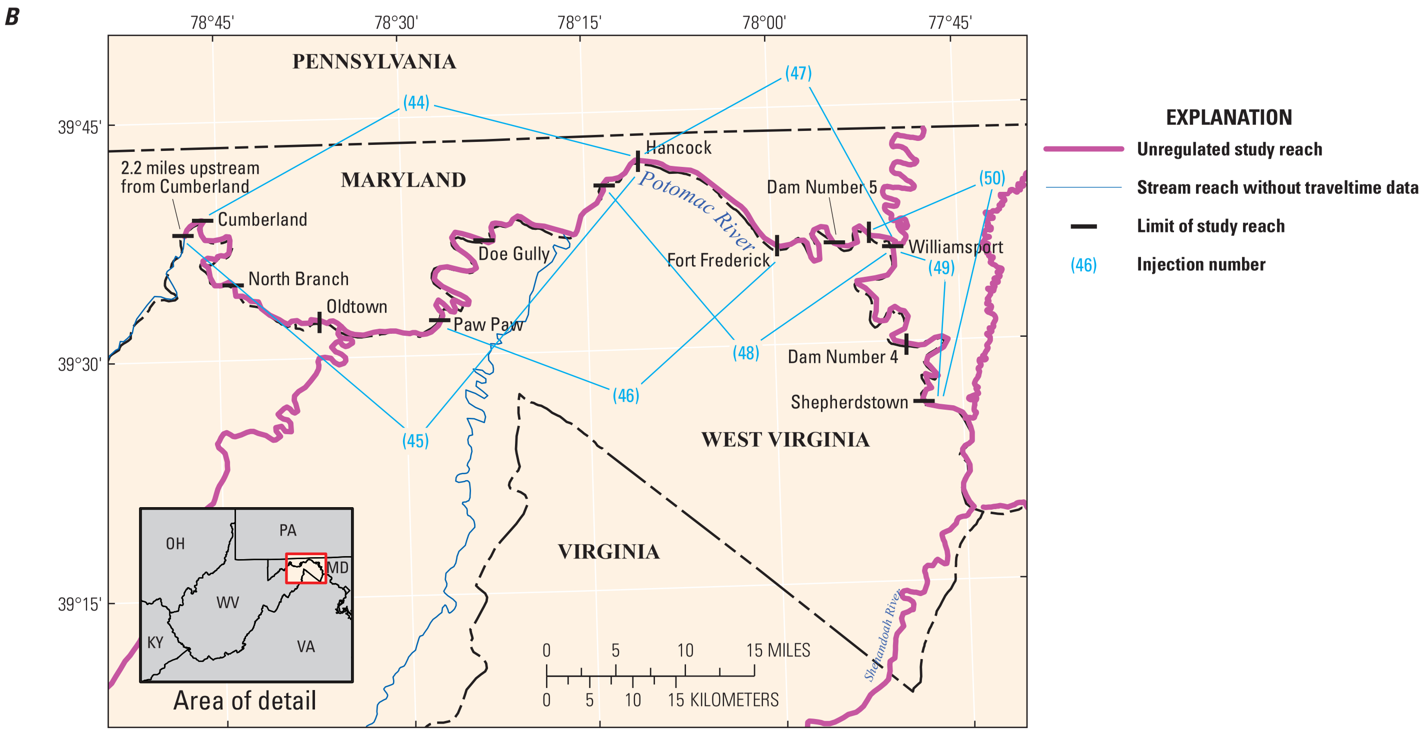


Figure 10. *A*, Traveltime and dispersion characteristics of selected reaches, and *B*, location of the reaches of the North Branch Potomac and Potomac Rivers upstream from Dam Number 5, Maryland, Virginia, and West Virginia.



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Streams from U.S. Geological Survey National Hydrography Dataset, 2012
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Figure 10. *A*, Traveltime and dispersion characteristics of selected reaches, and *B*, location of the reaches of the North Branch Potomac and Potomac Rivers upstream from Dam Number 5, Maryland, Virginia, and West Virginia.—Continued

A

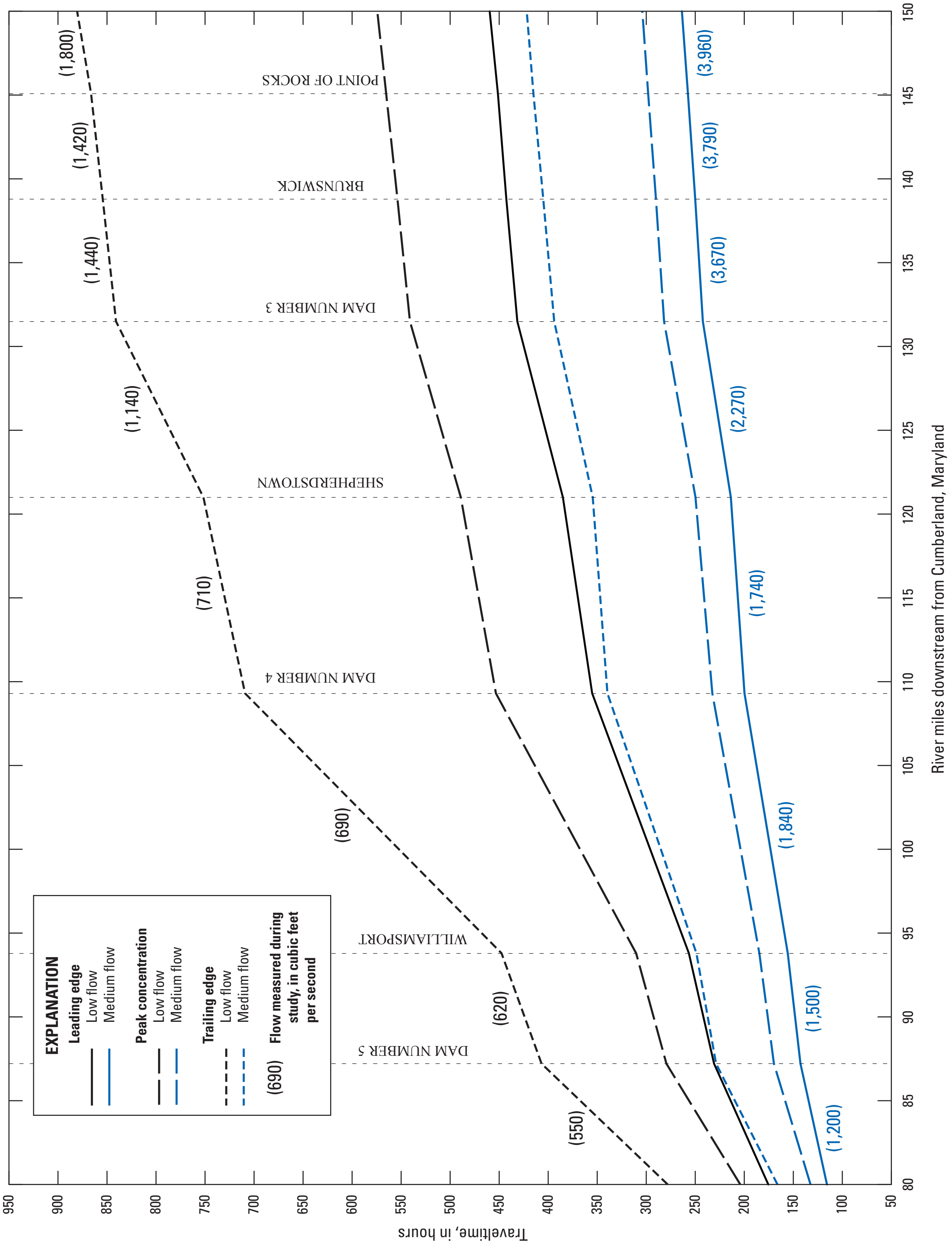
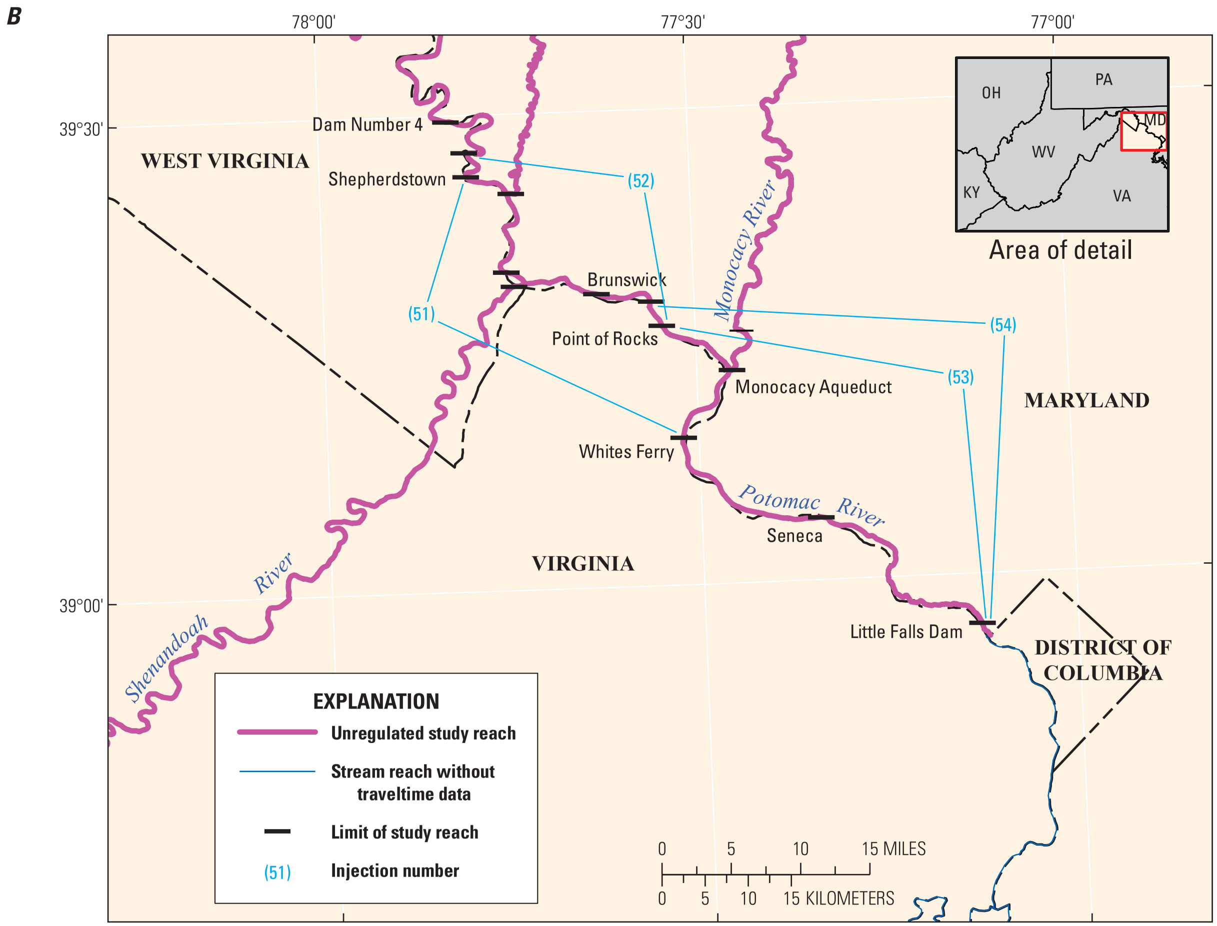


Figure 11. *A*, Traveltime and dispersion characteristics of selected reaches, and *B*, locations of the reaches of the Potomac River downstream from Fort Frederick, Maryland, Virginia, and West Virginia.



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Universal Transverse Mercator projection, Zone 17, North American Datum of 1983

Figure 11. *A*, Traveltime and dispersion characteristics of selected reaches, and *B*, locations of the reaches of the Potomac River downstream from Fort Frederick, Maryland, Virginia, and West Virginia.—Continued

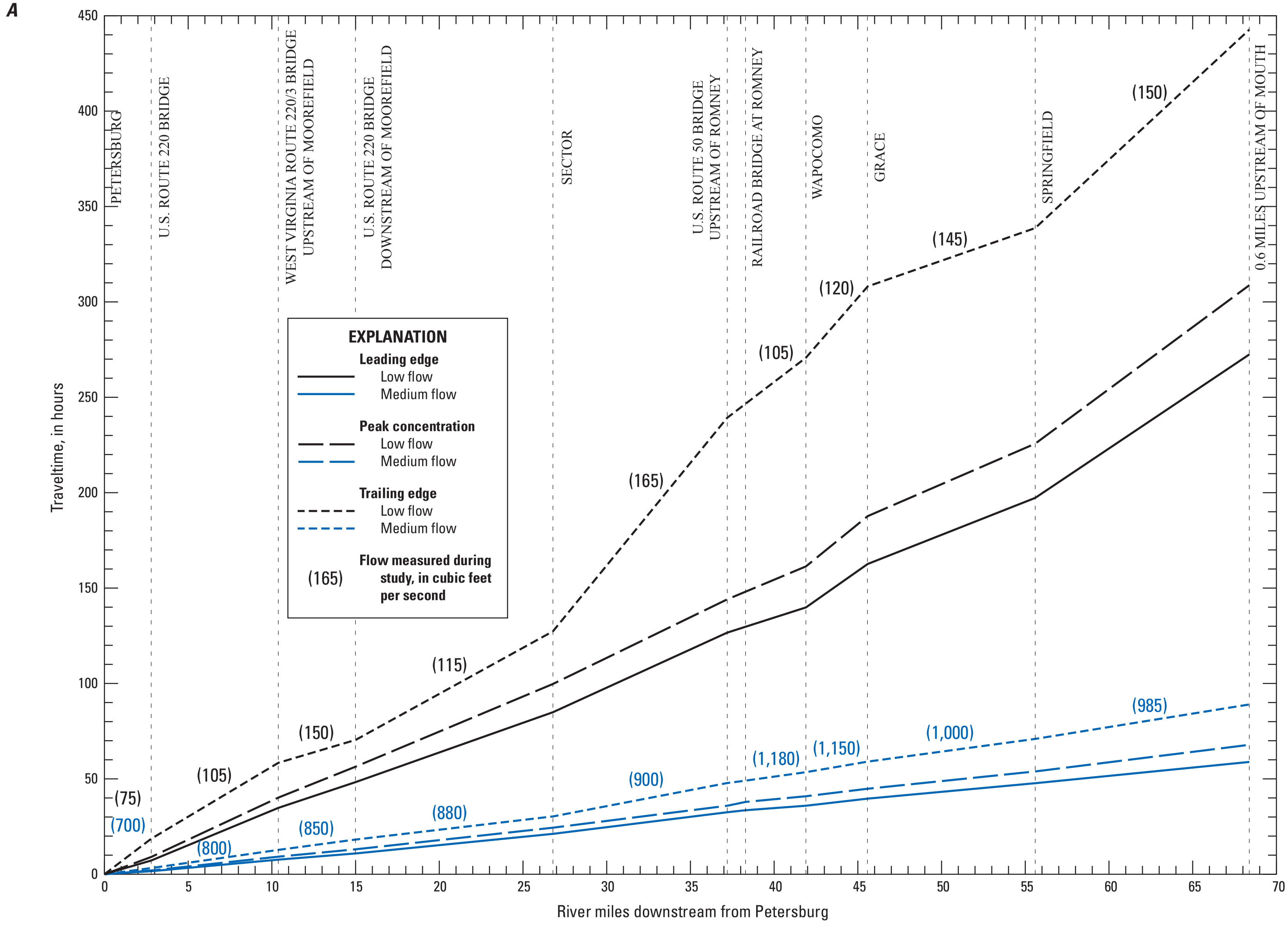

Figure 12. *A*, Traveltime and dispersion characteristics of selected reaches, and *B*, locations of the reaches of the South Branch Potomac River, West Virginia.

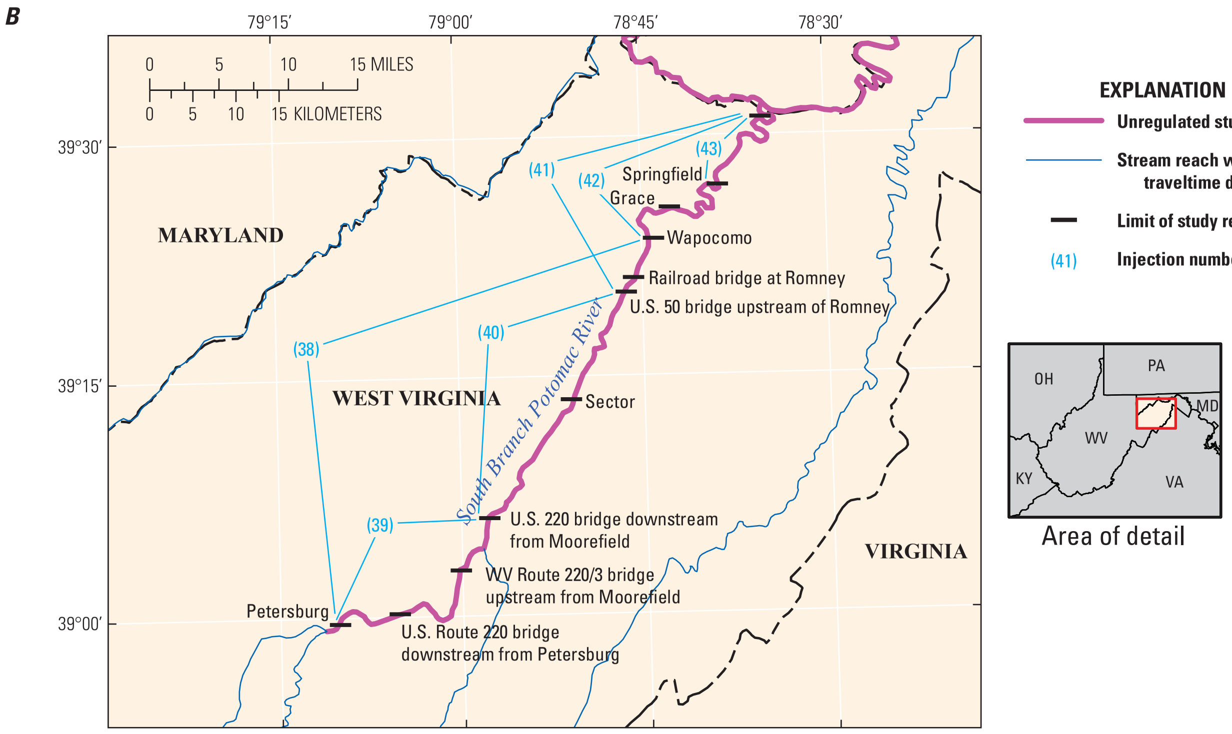

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Figure 12. *A*, Traveltime and dispersion characteristics of selected reaches, and *B*, locations of the reaches of the South Branch Potomac River, West Virginia.—Continued

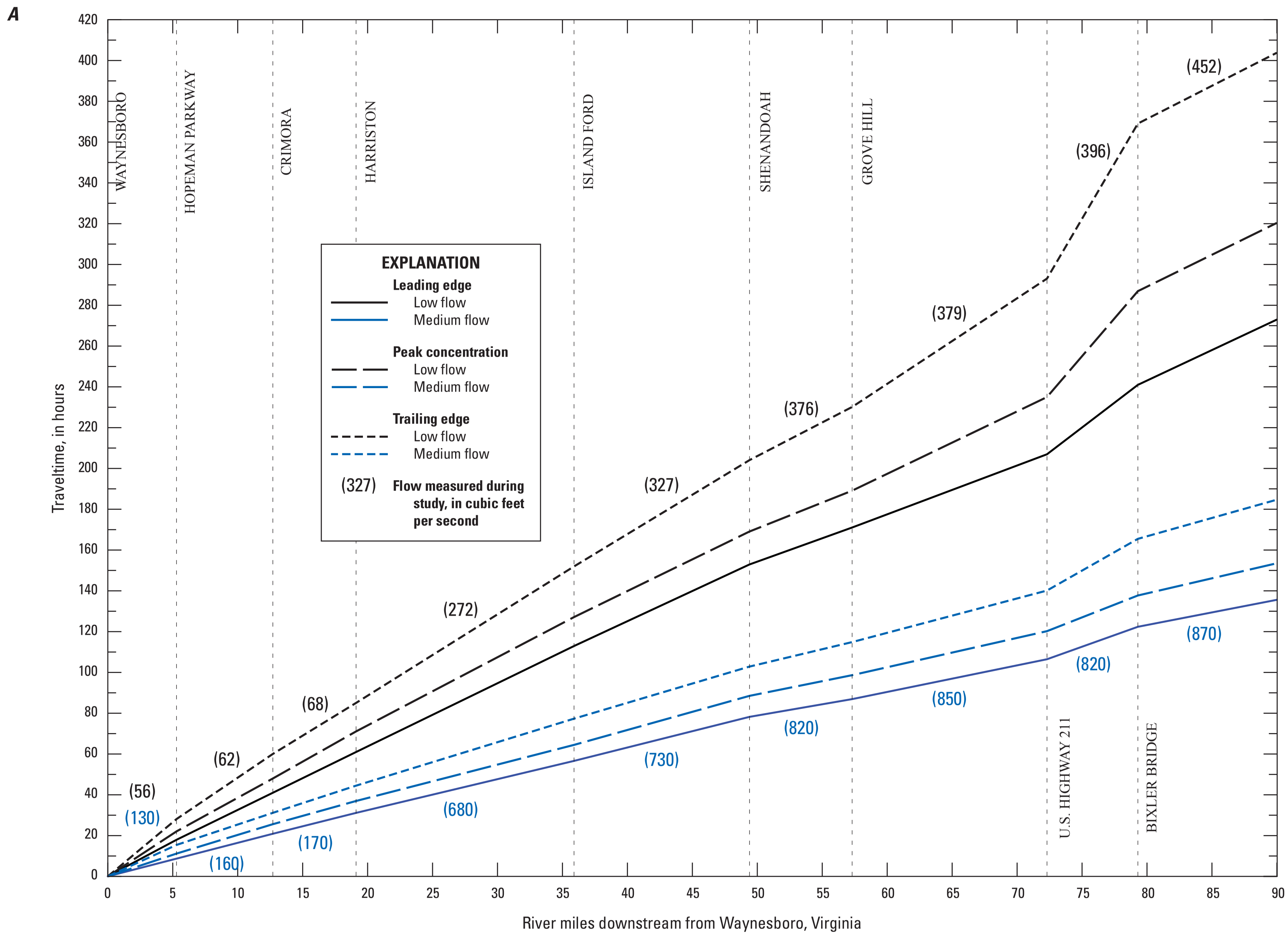


Figure 13. Traveltime and dispersion characteristics of selected reaches of the South Fork Shenandoah and Shenandoah Rivers, Virginia and West Virginia, *A*, up to 90 miles downstream from Waynesboro, Virginia, *B*, more than 90 miles downstream from Waynesboro, Virginia, and *C*, location of the reaches.

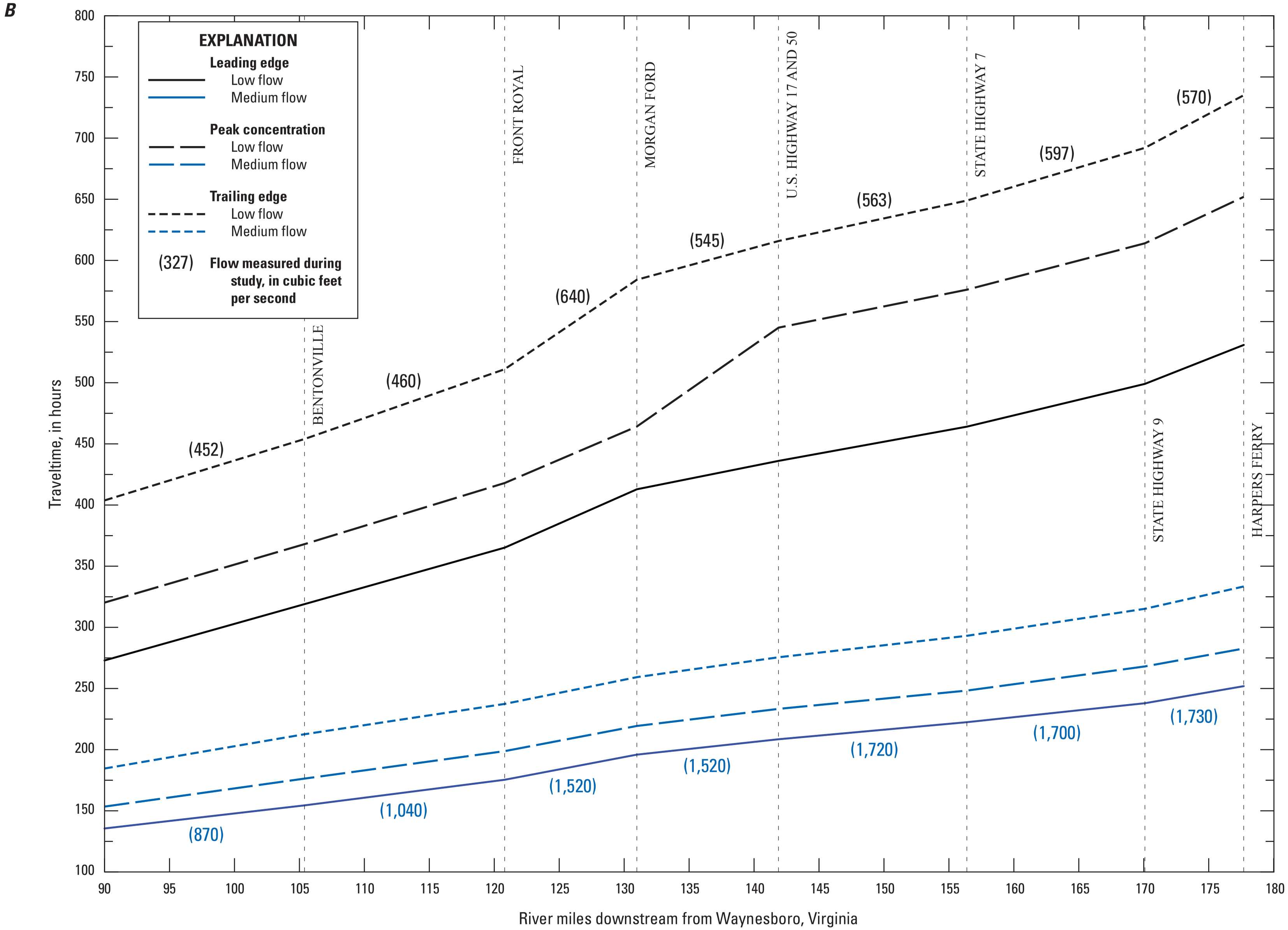
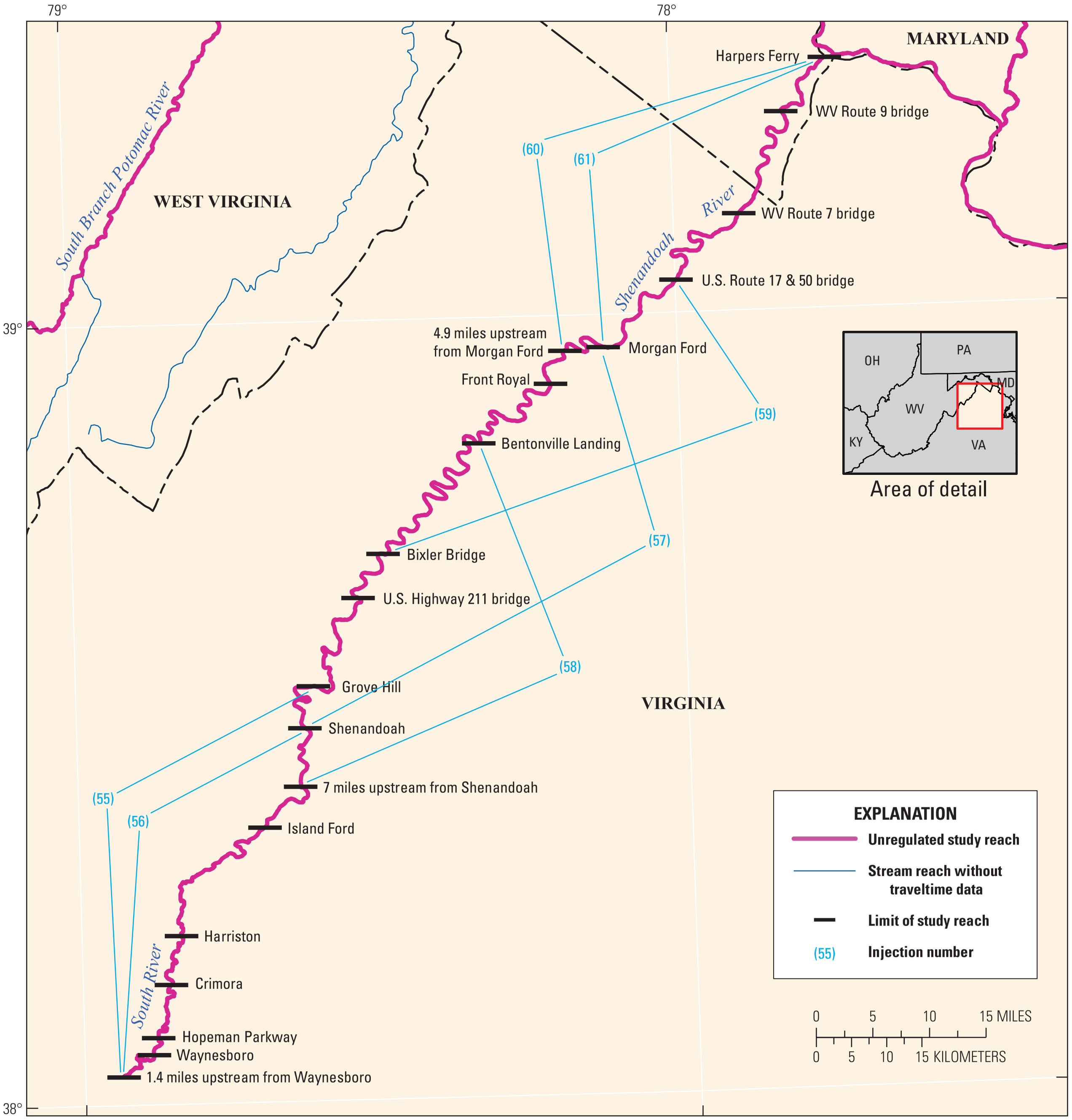


Figure 13. Traveltime and dispersion characteristics of selected reaches of the South Fork Shenandoah and Shenandoah Rivers, Virginia and West Virginia, *A*, up to 90 miles downstream from Waynesboro, Virginia, *B*, more than 90 miles downstream from Waynesboro, Virginia, and *C*, location of the reaches.—Continued

C



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Streams from U.S. Geological Survey National Hydrography Dataset, 2012
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Figure 13. Traveltime and dispersion characteristics of selected reaches of the South Fork Shenandoah and Shenandoah Rivers, Virginia and West Virginia, *A*, up to 90 miles downstream from Waynesboro, Virginia, *B*, more than 90 miles downstream from Waynesboro, Virginia, and *C*, location of the reaches.—Continued

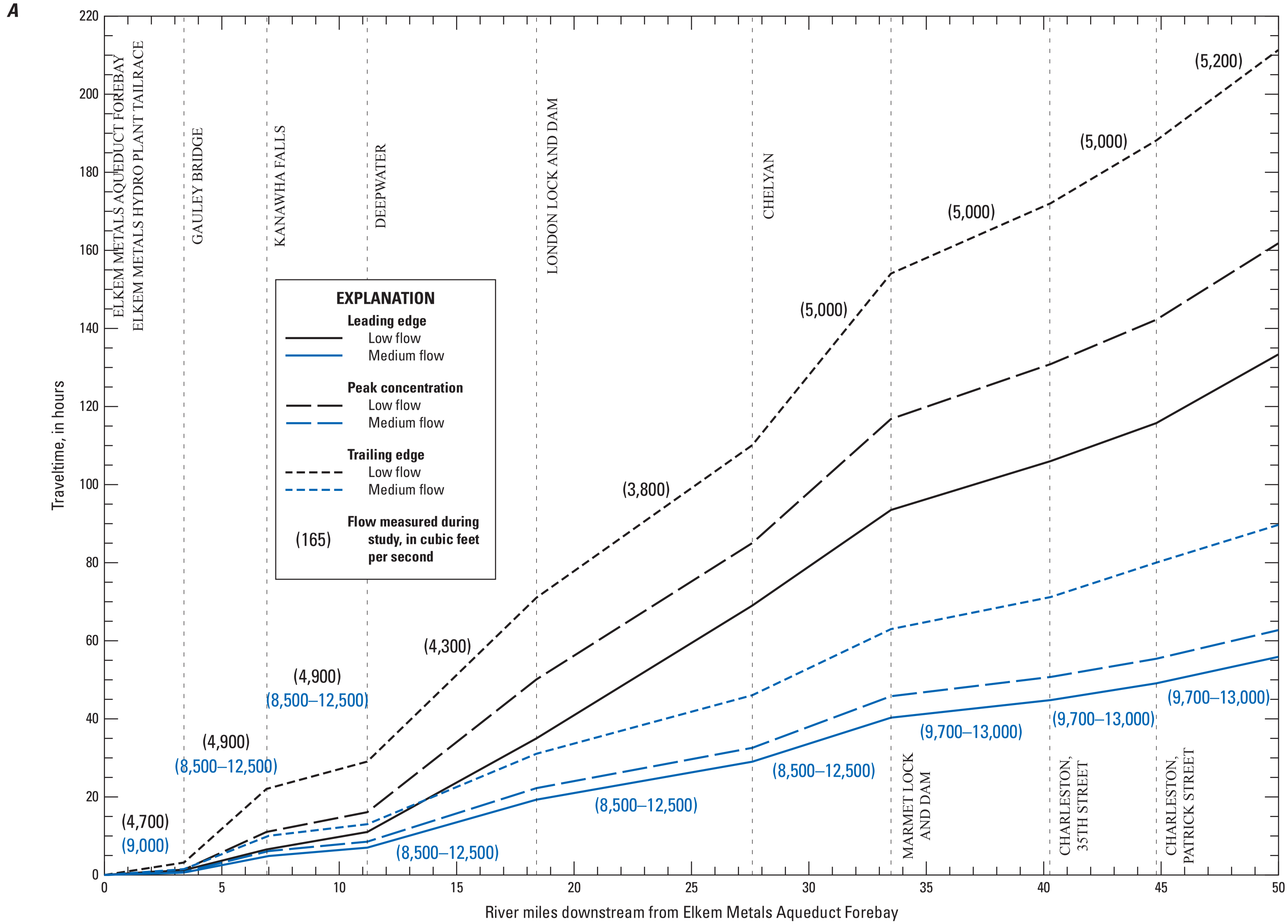


Figure 14. Traveltime and dispersion characteristics of the Kanawha River, West Virginia, *A*, up to 50 miles downstream from the Elkem Metals Aqueduct Forebay, *B*, more than 50 miles downstream from the Elkem Metals Aqueduct Forebay, and *C*, location of the reaches.

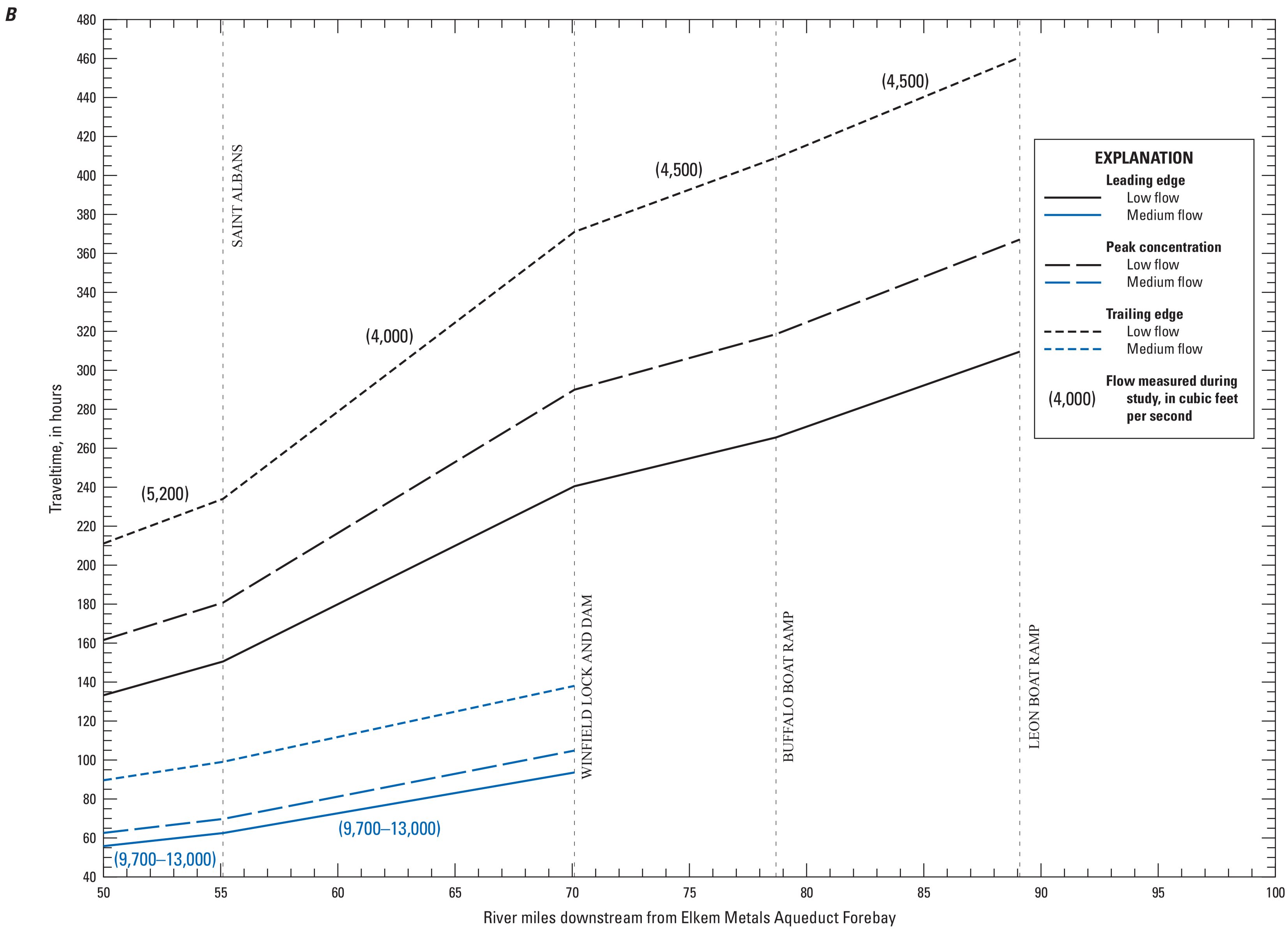
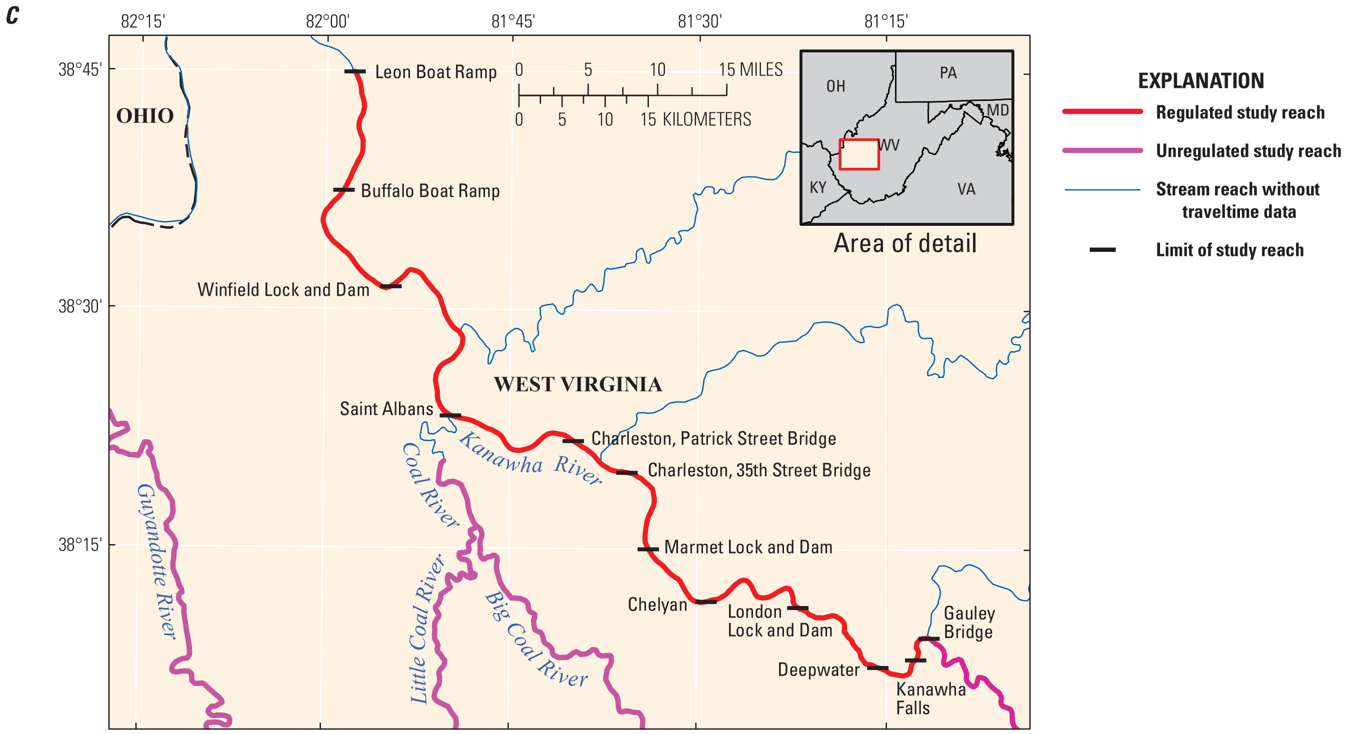


Figure 14. Traveltime and dispersion characteristics of the Kanawha River, West Virginia, *A*, up to 50 miles downstream from the Elkem Metals Aqueduct Forebay, *B*, more than 50 miles downstream from the Elkem Metals Aqueduct Forebay, and *C*, location of the reaches.—Continued



Base from U.S. Geological Survey 1:24,000 digital line graphics
Streams from U.S. Geological Survey National Hydrography Dataset, 2012
Universal Transverse Mercator projection, Zone 17, North American Datum of 1983

Figure 14. Traveltime and dispersion characteristics of the Kanawha River, West Virginia, *A*, up to 50 miles downstream from the Elkem Metals Aqueduct Forebay, *B*, more than 50 miles downstream from the Elkem Metals Aqueduct Forebay, and *C*, location of the reaches.—Continued

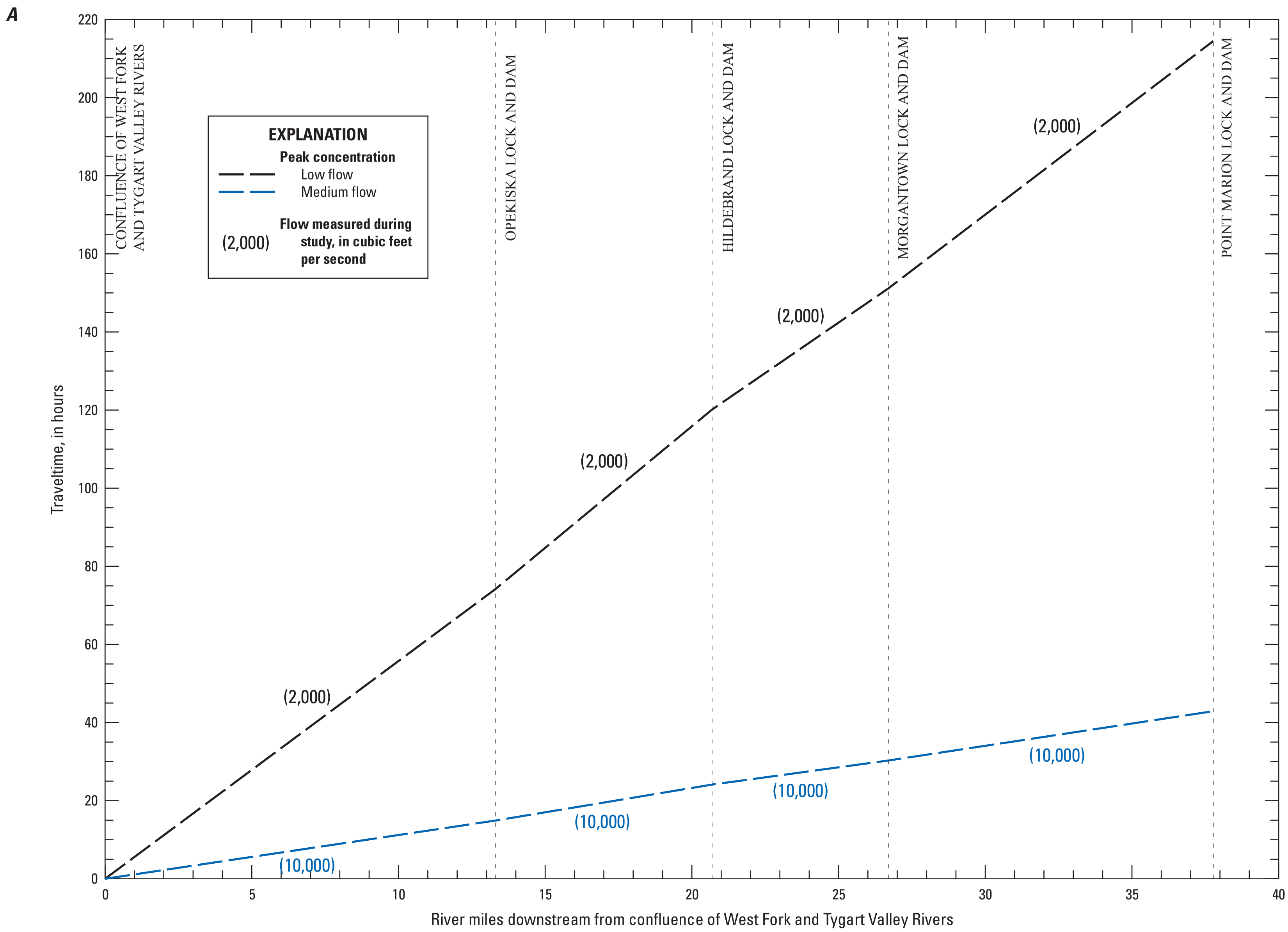
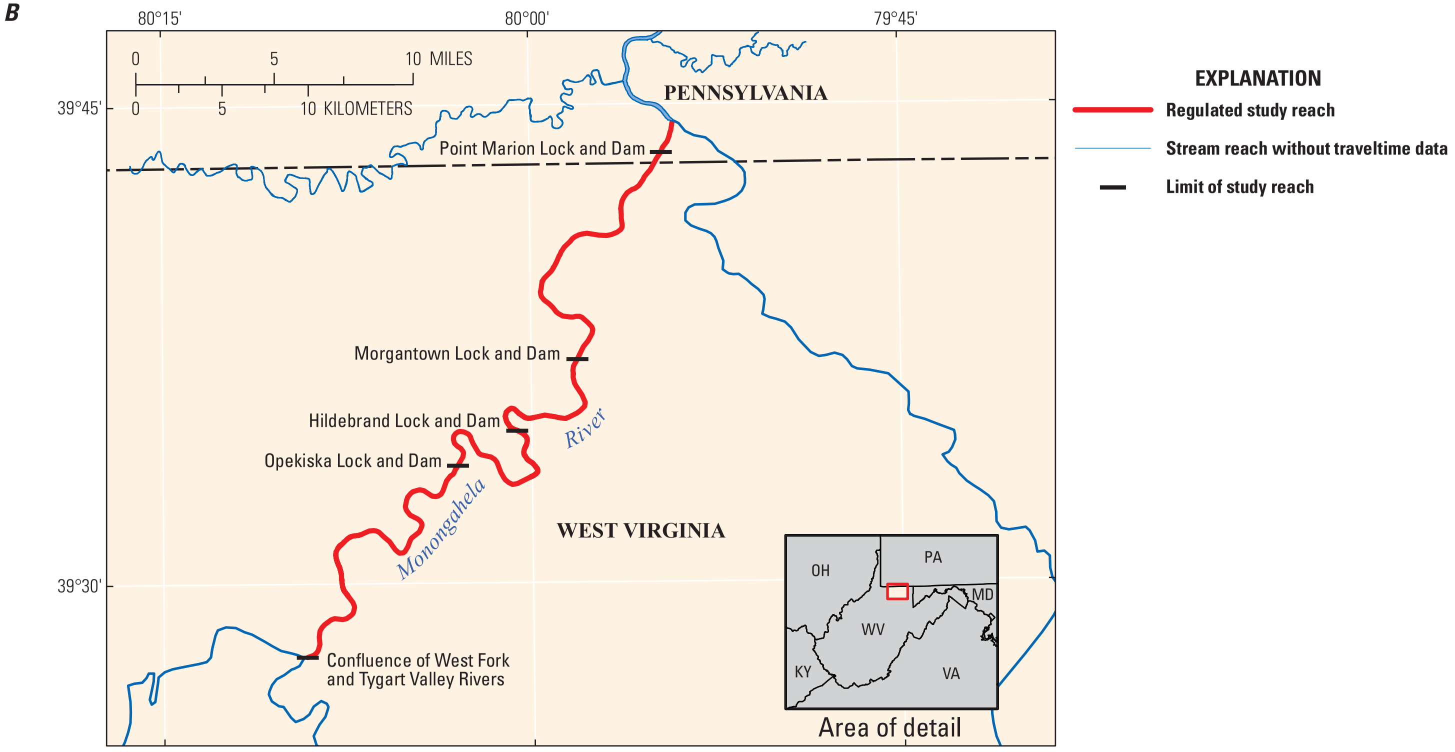


Figure 15. *A*, Traveltime characteristics of selected reaches, and *B*, location of the reaches of the Monongahela River, Pennsylvania and West Virginia.



Base from U.S. Geological Survey 1:24,000 digital line graphics
Streams from U.S. Geological Survey National Hydrography Dataset, 2012
Universal Transverse Mercator projection, Zone 17, North American Datum of 1983

Figure 15. *A*, Traveltime characteristics of selected reaches, and *B*, location of the reaches of the Monongahela River, Pennsylvania and West Virginia.—Continued

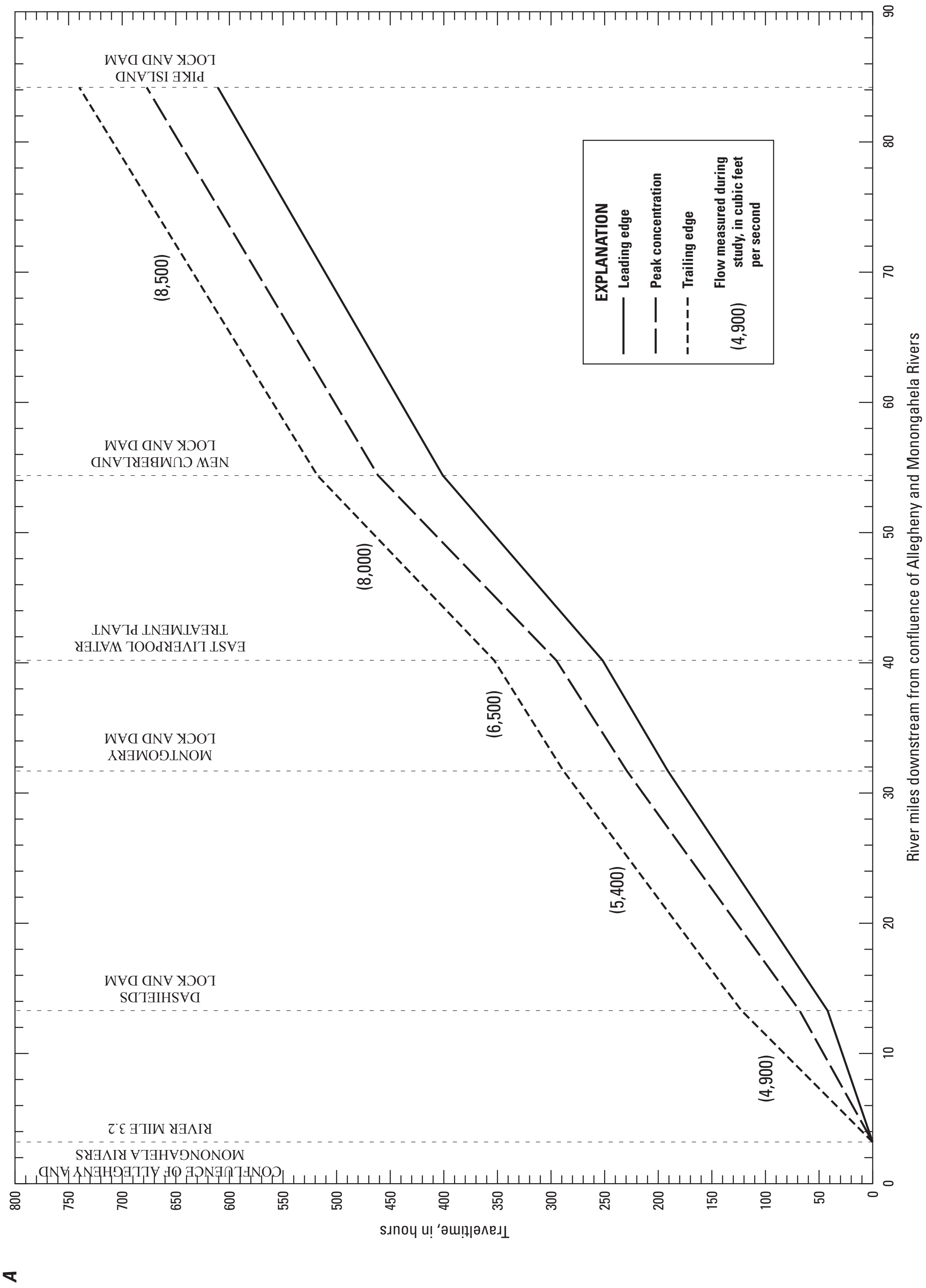
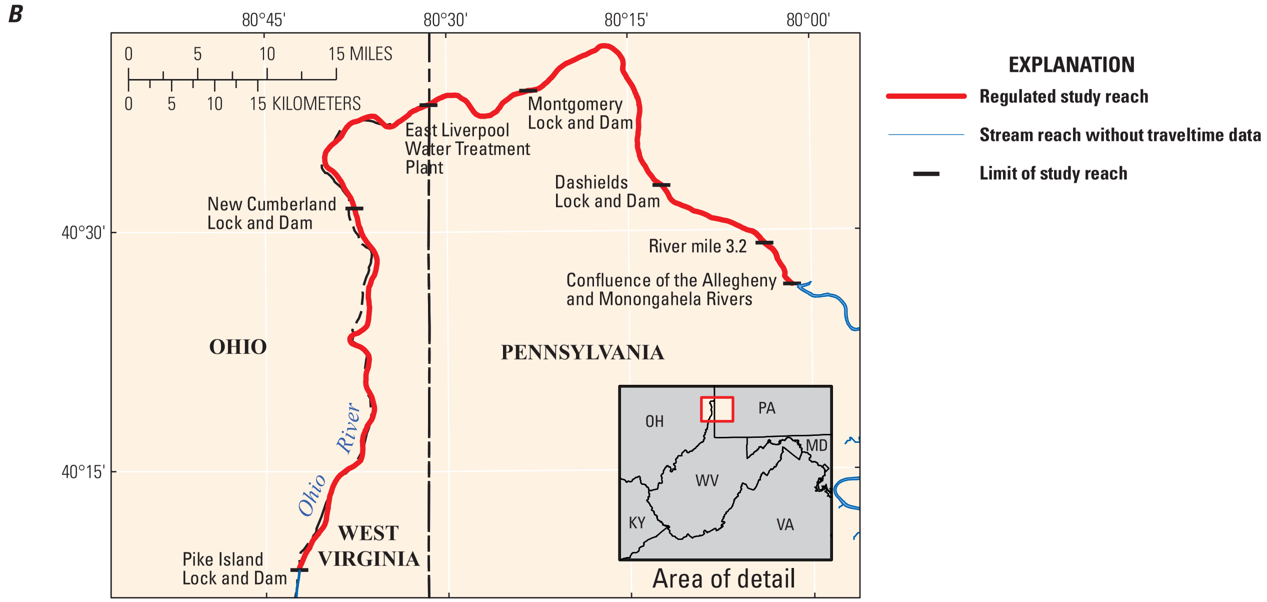


Figure 16. *A*, Traveltime and dispersion characteristics of selected reaches, and *B*, location of the reaches of the Ohio River, Pennsylvania, Ohio, and West Virginia.



Base from U.S. Geological Survey 1:24,000 digital line graphics
Streams from U.S. Geological Survey National Hydrography Dataset, 2012
Universal Transverse Mercator projection, Zone 17, North American Datum of 1983

Figure 16. *A*, Traveltime and dispersion characteristics of selected reaches, and *B*, location of the reaches of the Ohio River, Pennsylvania, Ohio, and West Virginia.—Continued

Appendix 1: Dye Injection, Traveltime, and Dispersion Data

The traveltime and dispersion data in tables 1-1 and 1-2 were obtained from reach-specific study documents, compiled by Jobson (1996), U.S. Geological Survey Annual Water Data Reports (*http://wdr.water.usgs.gov/*), and a summary of water-resources data prepared by Evaldi and others (2009) or were determined from 1:24,000 scale topographic or from the geographic information system interactive map available at *http://www.mapwv.gov/*. The data are presented in two tables containing abbreviated headings. Detailed descriptions of the table headings are provided below.

Inj No	is a unique number that identifies each injection.
Stream	is the name of the stream where tracer dye was injected.
Location	is the stream location where tracer dye was injected.
Date	is the date the tracer dye was injected.
Time	is the time of the injection in military time, where midnight is 2400 h.
Injection	is the amount of tracer dye injected, in either liters (L) or pounds (lb), including the percentage of dye in solution when reported.
Dye type	is the type of tracer dye injected.
Mass	is the mass of “pure” dye injected, in lb.
Reach	is the name that identifies each stream reach where traveltime and dispersion data are tabulated.
D_a	is the drainage area of the stream at the end of the reach, in square miles (mi^2).
Q	is the streamflow at the end of the stream reach (where dye samples were collected), in cubic feet per second (ft^3/s).
Len	is the length of the stream reach, in miles (mi).
Slope	is the slope of the stream reach, dimensionless (ft/ft, mi/mi, or kilometers per kilometers (km/km)).
Q_a	is the mean annual streamflow at the end of the stream reach, in ft^3/s.
T_l	is the traveltime of the leading edge of the dye cloud since injection, in hours (h).
T_p	is the traveltime of the peak concentration of the dye cloud since injection, in h.
T_t	is the traveltime of the trailing edge of the dye cloud (defined as when the concentration recedes to 10-percent of the peak concentration) since injection, in h.
T_d10	is the time of passage of the dye cloud (Td10 = Tl – Tt), in h.
C_p	is the observed peak concentration of the dye cloud collected at the end of the stream reach, in micrograms per liter (µg/L).
R_r	is the recovery ratio, equal to the mass of rhodamine dye injected divided by the mass recovered, unitless.
Cup_H	is the unit peak concentration defined by Hubbard and others (1982), in (µg/L)(ft^3/s)/lb.
C_{up}	is the unit peak concentration defined by Jobson (1996), in 1/s (inverse seconds).

Table 1–1. Dye injections for traveltime and dispersion studies in West Virginia and nearby states.

[---, not recorded; Inj no, injection number; lbs, pounds; B, rhodamine B; WT, rhodamine Wt; BA, rhodamine BA]

Inj No	Stream	Location	Date	Time	Injection	Dye type	Mass (lbs)
1	Tug Fork	Welch	---	---	---	---	---
2	Tug Fork	Iaeger	---	---	---	---	---
3	Tug Fork	Iaeger	---	---	---	---	---
4	Tug Fork	Matewan	---	---	---	---	---
5	Tug Fork	Matewan	---	---	---	---	---
6	Tug Fork	Kermit	---	---	---	---	---
7	Guyandotte River	Justice	9/19/1976	1300	---	---	---
8	Guyandotte River	Justice	3/27/1977	1600	---	---	---
9	Guyandotte River	Justice	5/15/1977	1200	---	---	---
10	Guyandotte River	Logan	9/21/1976	1600	---	---	---
11	Guyandotte River	Logan	3/27/1977	2300	---	---	---
12	Guyandotte River	Logan	5/15/1977	1700	---	---	---
13	Guyandotte River	Harts	9/19/1976	1800	---	---	---
14	Guyandotte River	Harts	3/27/1977	2200	---	---	---
15	Guyandotte River	Harts	5/15/1977	1800	---	---	---
16	Guyandotte River	Branchland	9/19/1976	1615	---	---	---
17	Guyandotte River	Branchland	3/27/1977	2100	---	---	---
18	Guyandotte River	Branchland	5/15/1977	1500	---	---	---
19	Little Coal River	Confluence of Pond Fork and Spruce Fork	7/30/1973	---	4.0 liters	---	---
20	Little Coal River	Confluence of Pond Fork and Spruce Fork	5/21/1974	---	0.6 liters	---	---
21	Little Coal River	Confluence of Pond Fork and Spruce Fork	4/2/1975	---	8.0 liters	---	---
22	Little Coal River	Julian	5/21/1974	---	0.9 liters	---	---
23	Big Coal River	Confluence of Clear Fork and Marsh Fork	7/22/1974	---	1.0 liters	---	---
24	Big Coal River	Confluence of Clear Fork and Marsh Fork	3/17/1975	---	8.0 liters	---	---
25	Big Coal River	Confluence of Clear Fork and Marsh Fork	4/7/1975	---	4.0 liters	---	---
26	Big Coal River	Seth	7/22/1974	---	0.5 liters	---	---
27	Big Coal River	Ashford	7/22/1974	---	1.0 liters	---	---
28	Coal River	Confluence of Little Coal River and Big Coal River	6/10/1974	---	1.5 liters	---	---
29	New River	Highway 3 bridge at Hinton	8/14/1985	2100	50 pounds of 20-percent	WT	10
30	New River	Highway 3 bridge at Hinton	11/8/1985	1200	150 pounds of 20-percent	WT	30
31	New River	Highway 3 bridge at Hinton	5/15/1986	1530	82.6 pounds of 20-percent	WT	16.52

Table 1–1. Dye injections for traveltime and dispersion studies in West Virginia and nearby states.—Continued

[---, not recorded; Inj no, injection number; lbs, pounds; B, rhodamine B; WT, rhodamine Wt; BA, rhodamine BA]

Inj No	Stream	Location	Date	Time	Injection	Dye type	Mass (lbs)
32	New River	Highway 41 bridge at Prince	8/15/1985	1345	50 pounds of 20-percent	WT	10
33	New River	Interstate 64 bridge near Sandstone	10/24/1985	1015	75 pounds of 20-percent	WT	15
34	Greenbrier River	Durbin	6/19/1972	1335	---	---	---
35	Greenbrier River	Durbin	10/1/1972	1840	---	---	---
36	Greenbrier River	Cloverlick	10/1/1972	1730	---	---	---
37	Greenbrier River	Clawson	10/25/1972	1730	---	---	---
38	South Branch Potomac River	Petersburg	11/18/1970	1023	29.6 pounds	B	29.6
39	South Branch Potomac River	Petersburg	9/20/1982	1240	1.048 pounds	B	1.048
40	South Branch Potomac River	U.S. Route 220 bridge downstream of Petersburg	9/20/1982	1410	1.572 pounds	WT	1.572
41	South Branch Potomac River	Railroad bridge at Romney	11/18/1970	0900	50 pounds	WT	50
42	South Branch Potomac River	U.S. 50 bridge upstream of Romney	9/20/1982	1525	2.096 pounds	WT	2.096
43	South Branch Potomac River	Springfield	9/20/1982	1600	1.572 pounds	WT	1.572
44	North Branch Potomac River	Cumberland	5/25/1964	1540	45.4 liters of 30-percent	BA	---
45	North Branch Potomac River	Cumberland (2.2 miles upstream)	10/10/1981	1135	24.8 liters of 20-percent	WT	---
46	Potomac River	Paw Paw	5/25/1964	1405	68.1 liters of 30-percent	BA	---
47	Potomac River	Hancock	5/25/1964	1305	64.4 liters of 30-percent	BA	---
48	Potomac River	Hancock (4.1 miles upstream)	10/10/1981	1230	15.2 liters of 20-percent	WT	---
49	Potomac River	Williamsport	5/25/1964	1540	132 liters of 30-percent	BA	---
50	Potomac River	Williamsport (6.0 miles upstream)	10/10/1981	1700	30.3 liters of 20-percent	WT	---
51	Potomac River	Shepherdstown	5/25/1964	1440	87.1 liters of 30-percent	BA	---
52	Potomac River	Shepherdstown (4.5 miles upstream)	9/26/1981	1150	50.0 liters of 20-percent	WT	---
53	Potomac River	Point of Rocks	5/25/1964	1205	288 liters of 30-percent	BA	---
54	Potomac River	Point of Rocks (5.4 miles upstream)	9/26/1981	1630	67.6 liters of 20-percent	WT	---
55	Shenandoah River	Waynesboro (1.4 miles upstream)	9/6/1983	1700	12 liters of 20-percent	WT	---
56	Shenandoah River	Waynesboro (1.4 miles upstream)	6/4/1984	1345	50 pounds of 20-percent	WT	---
57	Shenandoah River	Shenandoah	9/6/1983	1455	35 liters of 20-percent	WT	---
58	Shenandoah River	Shenandoah (7.0 miles upstream)	6/4/1984	1145	75 pounds of 20-percent	WT	---
59	Shenandoah River	Bixler Bridge	6/4/1984	1030	150 pounds of 20-percent	WT	---
60	Shenandoah River	Morgan Ford (4.9 miles upstream)	9/6/1983	1100	150 pounds of 20-percent	WT	---
61	Shenandoah River	Morgan Ford	6/4/1984	0905	100 pounds of 20-percent	WT	---

Table 1–1. Dye injections for traveltime and dispersion studies in West Virginia and nearby states.—Continued

[---, not recorded; Inj no, injection number; lbs, pounds; B, rhodamine B; WT, rhodamine Wt; BA, rhodamine BA]

Inj No	Stream	Location	Date	Time	Injection	Dye type	Mass (lbs)
62	Monocacy River	Harney Bridge	11/13/1967	1345	2.0 liters of 30-percent	BA	---
63	Monocacy River	Harney Bridge	6/7/1968	1139	1.5 liters of 20-percent	WT	---
64	Monocacy River	State Route 97	11/14/1967	1335	3.0 liters of 30-percent	BA	---
65	Monocacy River	State Route 97	6/7/1968	1232	7.0 liters of 30-percent	BA	---
66	Monocacy River	Le Gore Bridge	11/14/1967	0600	3.0 liters of 20-percent	WT	---
67	Monocacy River	Le Gore Bridge	6/7/1968	1626	8.0 liters of 20-percent	WT	---
68	Monocacy River	Le Gore Bridge	9/25/1968	1200	4.0 liters of 30-percent	BA	---
69	Monocacy River	Filtration Plant	11/14/1967	0510	5.0 liters of 30-percent	BA	---
70	Monocacy River	Filtration Plant (0.1 miles downstream)	6/7/1968	1445	12 liters of 30-percent	BA	---
71	Monocacy River	Filtration Plant (0.1 miles downstream)	9/25/1968	1035	6.0 liters of 30-percent	BA	---
72	Antietam Creek	County Road Bridge (1.6 miles upstream)	5/27/1969	1100	1.5 liters of 30-percent	BA	---
73	Antietam Creek	County Road Bridge (1.6 miles upstream)	3/24/1970	1230	8.0 liters of 30-percent	BA	---
74	Antietam Creek	County Road Bridge (1.6 miles upstream)	8/18/1970	1030	3.0 liters of 30-percent	BA	---
75	Antietam Creek	West Baltimore Street	8/18/1970	0010	5.0 liters of 30-percent	BA	---
76	Antietam Creek	West Baltimore Street	5/27/1969	1242	2.5 liters of 30-percent	BA	---
77	Antietam Creek	Monroe Road	5/28/1969	0950	2.0 liters of 30-percent	BA	---
78	Conococheague Creek	State Highway 494 (2.75 miles upstream)	4/30/1970	1015	6.0 liters of 30-percent	BA	---
79	Conococheague Creek	State Highway 494 (2.75 miles upstream)	5/6/1969	1040	5.0 liters of 30-percent	BA	---
80	Conococheague Creek	State Highway 494 (2.75 miles upstream)	9/30/1969	1140	6.0 liters of 20-percent	WT	---
81	Conococheague Creek	U.S. Highway 40	9/30/1969	1655	4.0 liters of 20-percent	WT	---

Table 1–2. Traveltime and dispersion data for studies in West Virginia and nearby states.

[---, not recorded; inj no, injection number; D_a, drainage area; Q, flow; Len, length; Q_a, mean annual streamflow; T_l, traveltime of the leading edge of the dye cloud; T_p, traveltime of the peak concentration of the dye cloud; T_t, traveltime of the trailing edge of the dye cloud; T_d10; time of passage of the dye cloud; C_p, observed peak concentration; R_r, recovery ratio; Cup_H, unit peak concentration as defined by Hubbard and others, 1982; C_{up}, unit peak concentration as defined by Jobson, 1996; mi, miles; ft, feet; s, seconds; h, hours; µg/L, micrograms per liter]

Inj No	Reach	D_a (mi²)	Q (ft³/s)	Len (mi)	Slope (ft/ft)	Q_a (ft³/s)	T_l (h)	T_p (h)	T_t (h)	T_d10 (h)	C_p (µg/L)	R_r	Cup_H ((µg/L) (ft³/s)/lb)	C_{up} (1/s)	Comment
Tug Fork															
1	Welch to Iaeger	264	200	23.5	0.002538	301	29.4	33.6	---	---	---	---	---	---	Injection reach
2	Iaeger to Matewan	855	350	39.5	0.001364	1,015	79.0	87.8	---	---	---	---	---	---	Injection reach
3	Iaeger to Matewan	855	1,250	39.5	0.001364	1,015	31.6	35.9	---	---	---	---	---	---	Injection reach
4	Matewan to Kermit	1,188	650	35	0.000492	1,411	35.0	38.9	---	---	---	---	---	---	Injection reach
5	Matewan to Kermit	1,188	1,800	35	0.000492	1,411	19.4	21.9	---	---	---	---	---	---	Injection reach
6	Kermit to Louisa, KY	1,559	550	35	0.000265	1,852	70.0	79.5	---	---	---	---	---	---	Injection reach
Guyandotte River															
7	Justice to Logan	833	135	30	0.001515	1,217	91	112	139	48	---	---	---	---	Injection reach
8	Justice to Logan	833	1,080	30	0.001515	1,217	21	25	29	8	---	---	---	---	Injection reach
9	Justice to Logan	833	490	30	0.001515	1,217	36	42	51	15	---	---	---	---	Injection reach
10	Logan to Harts	1,080	120	24.1	0.000398	1,468	49	59	75	26	---	---	---	---	Injection reach
11	Logan to Harts	1,080	1,070	24.1	0.000398	1,468	14	16.5	19	5	---	---	---	---	Injection reach
12	Logan to Harts	1,080	505	24.1	0.000398	1,468	21	24	29.5	8.5	---	---	---	---	Injection reach
13	Harts to Branchland	1,224	250	21.7	0.000341	1,615	32.5	40	51	18.5	---	---	---	---	Injection reach
14	Harts to Branchland	1,224	1,730	21.7	0.000341	1,615	12.5	14	17	4.5	---	---	---	---	Injection reach
15	Harts to Branchland	1,224	720	21.7	0.000341	1,615	17.5	21	26	8.5	---	---	---	---	Injection reach
16	Branchland to Barboursville	1,308	260	28.1	0.00017	1,726	27	33	43.5	16.5	---	---	---	---	Injection reach
17	Branchland to Barboursville	1,308	1,710	28.1	0.00017	1,726	15	17.5	20.5	5.5	---	---	---	---	Injection reach
18	Branchland to Barboursville	1,308	720	28.1	0.00017	1,726	20.5	23.5	28.5	8	---	---	---	---	Injection reach
Little Coal River															
19	Confluence of Pond Fork and Spruce Fork to Danville	269	102	2.5	0.00065	356	2.4	2.85	4.3	1.9	114	---	---	---	Injection reach
19	Danville to Julian	318	101	7.3	0.000756	421	12.2	15.1	20.8	8.6	21.2	---	---	---	---
19	Julian to mouth of Little Coal River	384	100	20.2	0.000539	508	45.3	52.8	78.8	33.5	3.9	---	---	---	---
19	Confluence of Little Coal River and Big Coal River to Tornado	862	225	7.1	0.000126	862	72	82	130	58	0.875	---	---	---	Dam reach
20	Confluence of Pond Fork and Spruce Fork to Danville	269	240	2.5	0.00065	356	1.9	2.1	3.3	1.4	7.1	---	---	---	Injection reach

Table 1–2. Traveltime and dispersion data for studies in West Virginia and nearby states.—Continued

[---, not recorded; inj no, injection number; D_a, drainage area; Q, flow; Len, length; Q_a, mean annual streamflow; T_l, traveltime of the leading edge of the dye cloud; T_p, traveltime of the peak concentration of the dye cloud; T_t, traveltime of the trailing edge of the dye cloud; T_d10; time of passage of the dye cloud; C_p, observed peak concentration; R_r, recovery ratio; Cup_H, unit peak concentration as defined by Hubbard and others, 1982; C_{up}, unit peak concentration as defined by Jobson, 1996; mi, miles; ft, feet; s, seconds; h, hours; µg/L, micrograms per liter]

Inj No	Reach	D_a (mi^2)	Q (ft^3/s)	Len (mi)	Slope (ft/ft)	Q_a (ft^3/s)	T_l (h)	T_p (h)	T_t (h)	T_d10 (h)	C_p (µg/L)	R_r	Cup_H ((µg/L)(ft^3/s)/lb)	C_{up} (1/s)	Comment
20	Danville to Julian	318	235	7.3	0.000756	421	8	9.8	12.5	4.5	1.9	---	---	---	---
21	Confluence of Pond Fork and Spruce Fork to Julian	318	1,020	9.8	0.000189	421	4.5	5.2	6.4	1.9	17	---	---	---	Injection reach
21	Julian to mouth of Little Coal River	384	1,360	20.2	0.000539	508	13.8	15.5	18.5	4.7	5.4	---	---	---	---
21	Confluence of Little Coal River and Big Coal River to Tornado	862	2,940	7.1	0.000126	862	17.8	20.2	24.5	6.7	1.8	---	---	---	Dam reach
22	Julian to mouth of Little Coal River	384	253	20.2	0.000539	508	18	20.8	26.8	8.8	1.43	---	---	---	Injection reach
						Big Coal River									
23	Confluence of Clear Fork and Marsh Fork to Seth	282	114	15.6	0.00179	379	26	30.3	35.3	9.3	3	---	---	---	Injection reach
24	Confluence of Clear Fork and Marsh Fork to Seth	282	1,090	15.6	0.00179	379	7.9	9	10.2	2.3	14.4	---	---	---	Injection reach
24	Seth to Ashford	391	1,350	12.4	0.000797	525	12.8	14.5	16.6	3.8	5.2	---	---	---	---
24	Ashford to mouth of Big Coal River	446	1,550	9.1	0.000581	599	18.6	20.5	24.2	5.6	3.2	---	---	---	---
25	Confluence of Clear Fork and Marsh Fork to Seth	282	422	15.6	0.00179	379	10.4	12.7	15	4.6	10.6	---	---	---	Injection reach
25	Seth to Ashford	391	698	12.4	0.000797	525	20.5	23.8	27.8	7.3	4.22	---	---	---	---
25	Ashford to mouth of Big Coal River	446	745	9.1	0.000581	599	29.2	32.2	38	8.8	2.55	---	---	---	---
26	Seth to Ashford	391	130	12.4	0.000797	525	24.6	28.8	35.4	10.8	1.25	---	---	---	Injection reach
27	Ashford to mouth of Big Coal River	446	136	9.1	0.000581	599	15.6	19.2	24	8.4	3.3	---	---	---	Injection reach
						Coal River									
28	Confluence of Little Coal River and Big Coal River to Tornado	862	755	7.1	0.000126	862	8.1	10.3	13.5	5.4	1.6	---	---	---	Injection reach, dam reach

Table 1–2. Traveltime and dispersion data for studies in West Virginia and nearby states.—Continued

[---, not recorded; inj no, injection number; D_a, drainage area; Q, flow; Len, length; Q_a, mean annual streamflow; T_l, traveltime of the leading edge of the dye cloud; T_p, traveltime of the peak concentration of the dye cloud; T_t, traveltime of the trailing edge of the dye cloud; T_d10; time of passage of the dye cloud; C_p, observed peak concentration; R_r, recovery ratio; Cup_H, unit peak concentration as defined by Hubbard and others, 1982; C_{up}, unit peak concentration as defined by Jobson, 1996; mi, miles; ft, feet; s, seconds; h, hours; µg/L, micrograms per liter]

Inj No	Reach	D_a (mi²)	Q (ft³/s)	Len (mi)	Slope (ft/ft)	Q_a (ft³/s)	T_l (h)	T_p (h)	T_t (h)	T_d10 (h)	C_p (µg/L)	R_r	Cup_H ((µg/L)(ft³/s)/lb)	C_{up} (1/s)	Comment
						New River									
29	Hinton to Interstate 64 bridge near Sandstone	6,363	2,200	11.9	0.001803	8,068	14	16	30	16	4.18	0.91	920	57.4	Injection reach
29	Interstate 64 bridge near Sandstone to Prince	6,517	2,200	13.5	0.001527	8,264	29.5	36	51	21.5	2.13	0.87	469	29.3	---
30	Hinton to Interstate 64 bridge near Sandstone	6,363	18,150	11.9	0.001803	8,068	4.2	4.4	7.2	3	11.9	1.23	7259	453.2	Injection reach
30	Interstate 64 bridge near Sandstone to Prince	6,517	18,450	13.5	0.001527	8,264	8.2	9.2	12.2	4	4.75	1.09	2945	183.9	---
30	Prince to Stone Cliff	6,687	18,800	12.4	0.001708	8,479	11.8	13.2	16.5	4.7	3.2	1.02	2027	126.5	---
30	Stone Cliff to Fayette Station	6,850	19,000	15.1	0.002462	8,686	16.7	18.8	22.7	6	---	---	---	---	---
30	Fayette Station to Hawks Nest	6,876	19,000	4.7	0.001208	8,719	20.3	22.3	26.5	6.2	2.22	0.99	1406	87.8	Dam reach
30	Hawks Nest to Gauley Bridge	6,942	19,000	6.4	0.005114	8,802	22.7	25.5	29	6.3	---	0.89	---	---	Dam reach
31	Hinton to Interstate 64 bridge near Sandstone	6,363	9,250	11.9	0.001803	8,068	5.5	6	10.5	5	8.1	1.05	4560	284.7	Injection reach
31	Interstate 64 bridge near Sandstone to Prince	6,517	9,600	13.5	0.001527	8,264	11.4	13	17.7	6.3	2.78	1.02	1666	104.0	---
31	Prince to Stone Cliff	6,687	10,200	12.4	0.001708	8,479	16	19.4	26.7	10.7	1.87	1.02	1189	74.2	---
31	Stone Cliff to Fayette Station	6,850	10,500	15.1	0.002462	8,686	23.6	27.6	34.3	10.7	1.47	0.98	934	58.3	---
31	Fayette Station to Hawks Nest	6,876	10,500	4.7	0.001208	8,719	29.1	33.8	40.8	11.7	1.31	0.96	833	52.0	Dam reach
31	Hawks Nest to Gauley Bridge	6,942	10,500	6.4	0.005114	8,802	33.6	37.4	47.8	14.2	1.22	0.93	775	48.4	Dam reach
32	Prince to Stone Cliff	6,687	2,200	12.4	0.001708	8,479	12.5	15.5	25	12.5	3.96	0.96	871	54.4	Injection reach
32	Stone Cliff to Fayette Station	6,850	2,200	15.1	0.002462	8,686	33	39.5	55	22	2.13	0.94	469	29.3	---
33	Interstate 64 bridge near Sandstone to Prince	6,517	3,200	13.5	0.001527	8,264	10.5	13	21.5	11	5.55	1.04	1184	73.9	Injection reach
33	Prince to Stone Cliff	6,687	3,200	12.4	0.001708	8,479	21.5	26	39	17.5	3.32	0.98	708	44.2	---
33	Stone Cliff to Fayette Station	6,850	3,200	15.1	0.002462	8,686	37.5	44.5	56.5	19	2.84	0.88	606	37.8	---

Table 1–2. Traveltime and dispersion data for studies in West Virginia and nearby states.—Continued

[---, not recorded; inj no, injection number; D_a, drainage area; Q, flow; Len, length; Q_a, mean annual streamflow; T_l, traveltime of the leading edge of the dye cloud; T_p, traveltime of the peak concentration of the dye cloud; T_t, traveltime of the trailing edge of the dye cloud; T_d10; time of passage of the dye cloud; C_p, observed peak concentration; R_r, recovery ratio; Cup_H, unit peak concentration as defined by Hubbard and others, 1982; C_{up}, unit peak concentration as defined by Jobson, 1996; mi, miles; ft, feet; s, seconds; h, hours; µg/L, micrograms per liter]

Inj No	Reach	D_a (mi²)	Q (ft³/s)	Len (mi)	Slope (ft/ft)	Q_a (ft³/s)	T_l (h)	T_p (h)	T_t (h)	T_d10 (h)	C_p (µg/L)	R_r	Cup_H ((µg/L) (ft³/s)/lb)	C_{up} (1/s)	Comment
						Greenbrier River									
34	Durbin to Hosterman	150	324	7	0.003125	293	---	6.3	---	---	---	---	---	---	Injection reach
34	Hosterman to Cass	180	340	8	0.003258	339	---	13.1	---	---	---	---	---	---	---
34	Cass to Cloverlick	335	356	9	0.003087	578	---	21.9	---	---	---	---	---	---	---
34	Cloverlick to Clawson	346	367	11	0.001913	595	---	34.4	---	---	---	---	---	---	---
35	Durbin to Cass	180	62	15	0.003201	339	---	53.3	---	---	---	---	---	---	Injection reach
35	Cass to Cloverlick	335	74	9	0.003087	578	---	80.8	---	---	---	---	---	---	---
36	Cloverlick to Clawson	346	77	11	0.001913	595	---	21.5	---	---	---	---	---	---	Injection reach
36	Clawson to Buckeye	540	120	12	0.001294	893	---	45	---	---	---	---	---	---	---
37	Clawson to Buckeye	540	302	12	0.001294	893	---	11.5	---	---	---	---	---	---	Injection reach
						South Branch Potomac River									
38	Petersburg to U.S. Route 220 bridge downstream of Petersburg	850	700	2.8	0.0025	943	1.6	1.9	3.3	1.7	86	0.84	6030	376.4	Injection reach
38	U.S. Route 220 bridge downstream of Petersburg to WV Secondary Route 220/3 bridge upstream of Moorefield	888	800	7.6	0.001742	980	7.6	9.1	12.8	5.2	25	0.83	2020	126.1	---
38	WV Secondary Route 220/3 bridge upstream of Moorefield to U.S. 220 bridge downstream of Moorefield	1,216	850	4.6	0.001443	1,299	10.8	13.1	18.1	7.3	15	0.69	1580	98.6	---
38	U.S. 220 bridge downstream of Moorefield to Sector	1,310	880	11.8	0.001157	1,320	21.1	24.4	30.2	9.1	6.7	0.6	820	51.2	---
38	Sector to U.S. 50 bridge upstream of Romney	1,400	900	10.4	0.001072	1,340	32.4	35.9	47.8	15.4	5.2	0.63	630	39.3	---
38	U.S. 50 bridge upstream of Romney to railroad bridge at Romney	1,402	900	1.1	0.000118	1,341	33.6	37.8	49	15.4	---	---	---	---	---
39	Petersburg to U.S. Route 220 bridge downstream of Petersburg	850	75	2.8	0.0025	943	7.1	8.8	18.3	11.2	12	0.634	1340	83.7	Injection reach

Table 1–2. Traveltime and dispersion data for studies in West Virginia and nearby states.—Continued

[---, not recorded; inj no, injection number; D_a, drainage area; Q, flow; Len, length; Q_a, mean annual streamflow; T_l, traveltime of the leading edge of the dye cloud; T_p, traveltime of the peak concentration of the dye cloud; T_t, traveltime of the trailing edge of the dye cloud; T_d10; time of passage of the dye cloud; C_p, observed peak concentration; R_r, recovery ratio; Cup_H, unit peak concentration as defined by Hubbard and others, 1982; C_{up}, unit peak concentration as defined by Jobson, 1996; mi, miles; ft, feet; s, seconds; h, hours; µg/L, micrograms per liter]

Inj No	Reach	D_a (mi²)	Q (ft³/s)	Len (mi)	Slope (ft/ft)	Q_a (ft³/s)	T_l (h)	T_p (h)	T_t (h)	T_d10 (h)	C_p (µg/L)	R_r	Cup_H ((µg/L)(ft³/s)/lb)	C_{up} (1/s)	Comment
39	U.S. Route 220 bridge downstream of Petersburg to WV Secondary Route 220/3 bridge upstream of Moorefield	888	105	7.6	0.001742	980	34.8	40.1	58.3	23.5	2.7	0.575	470	29.3	---
39	WV Secondary Route 220/3 bridge upstream of Moorefield to U.S. 220 bridge downstream of Moorefield	1,216	150	4.6	0.001443	1,299	48.3	56.3	70.3	22	1.7	0.539	452	28.2	---
40	U.S. 220 bridge downstream of Moorefield to Sector	1,310	115	11.8	0.001157	1,320	36.6	43.3	57	20.4	3.9	0.646	442	27.6	Injection reach
40	Sector to U.S. 50 bridge upstream of Romney	1,400	165	10.4	0.001072	1,340	78.3	87.8	111.8	33.5	1.9	0.6	335	20.9	---
41	Railroad bridge at Romney to Wapocomo	1,420	1,180	3.6	0.000758	1,345	2.2	3	4.4	2.2	53	0.69	4540	283.4	Injection reach
41	Wapocomo to Grace	1,440	1,150	3.7	0.00079	1,349	6	7	10	4	33	0.68	2820	176.0	---
41	Grace to Springfield	1,461	1,000	10	0.00078	1,354	14	16	22	8	14	0.57	1250	78.0	---
41	Springfield to 0.6 mi upstream of mouth	1,479	985	12.8	0.000591	1,371	25.2	30	40	14.8	8.4	0.58	690	43.1	---
42	U.S. 50 bridge upstream of Romney to Wapocomo	1,420	105	4.7	0.000557	1,345	13.3	17.1	31.8	18.5	9.1	0.717	636	39.7	Injection reach
42	Wapocomo to Grace	1,440	120	3.7	0.00079	1,349	36	43.6	69.1	33.1	4.2	0.603	400	25.0	---
42	Grace to Springfield	1,461	145	10	0.00078	1,354	70.6	81.6	99.6	29	2.6	0.565	318	19.9	---
43	Springfield to 0.6 mi upstream of mouth	1,479	150	12.8	0.000591	1,371	75.3	83	104	28.7	3.3	0.852	369	23.0	Injection reach
						North Branch Potomac River									
44	Cumberland to North Branch	875	410	8.7	0.000663	1,278	15	19	26	11	58	0.92	835	52.1	Injection reach
44	North Branch to Oldtown	875	585	8.7	0.000663	1,278	28	33	43.5	15.5	33	1.08	575	35.9	---
44	Oldtown to Paw Paw	3,108	870	10.7	0.000663	3,298	43.5	50.5	64	20.5	12	0.8	410	25.6	---
44	Paw Paw to Doe Gully	3,578	860	19.8	0.000511	3,641	70	80.5	96	26	7.5	0.58	360	22.5	---
44	Doe Gully to Hancock	4,071	990	18.1	0.00036	4,142	92.5	106	129	36.5	4.2	0.54	250	15.6	---
45	2.2 miles upstream from Cumberland to Cumberland	875	245	2.2	0.000663	1,278	4	4.8	6.3	2.3	223	0.93	4580	285.9	Injection reach

Table 1–2. Traveltime and dispersion data for studies in West Virginia and nearby states.—Continued

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Inj No	Reach	D_a (mi^2)	Q (ft^3/s)	Len (mi)	Slope (ft/ft)	Q_a (ft^3/s)	T_l (h)	T_p (h)	T_t (h)	T_d10 (h)	C_p (µg/L)	R_r	Cup_H ((µg/L)(ft^3/s)/lb)	C_{up} (1/s)	Comment
45	Cumberland to North Branch	875	255	8.7	0.000663	1,278	25	31.5	43	18	20	0.76	516	32.2	---
45	North Branch to Oldtown	875	280	8.7	0.000663	1,278	41	50.5	67	26	14	0.81	367	22.9	---
45	Oldtown to Paw Paw	3,108	460	10.7	0.000663	3,298	63	74.5	93.5	30.5	6.8	0.79	302	18.9	---
45	Paw Paw to Doe Gully	3,578	430	19.8	0.000511	3,641	104	119	148	44	4.7	0.74	209	13.0	---
45	Doe Gully to Hancock	4,071	525	18.1	0.00036	4,142	138	158	195	57	3.4	0.77	177	11.0	---
						Potomac River									
46	Paw Paw to Doe Gully	3,578	1,010	19.8	0.000511	3,641	22	25	32	10	52	1.09	1010	63.1	Injection reach
46	Doe Gully to Hancock	4,071	1,200	18.1	0.00036	4,142	44.5	48.5	63.5	19	14	0.68	545	34.0	---
46	Hancock to Fort Frederick	7,090	1,280	11.5	0.00036	4,471	58.5	64	---	---	11	0.72	405	25.3	---
47	Hancock to Fort Frederick	7,090	1,530	11.5	0.00036	4,471	12	14	15.5	3.5	96	1.31	2540	158.6	Injection reach
47	Fort Frederick to Dam Number 5	4,707	1,200	9.7	0.00036	4,767	48	64	100	52	5.7	0.77	205	12.8	Dam reach
47	Dam Number 5 to Williamsport	4,925	1,500	6.6	0.00036	4,979	61	79	120	59	4.5	0.99	155	9.7	---
48	4.1 miles upstream of Hancock to Hancock	4,071	570	4.1	0.00036	4,142	7.5	9	12	4.5	36	1.15	2220	138.6	Injection reach
48	Hancock to Fort Frederick	4,405	610	11.5	0.00036	4,471	30	33.5	44.5	14.5	8	0.91	668	41.7	---
48	Fort Frederick to Dam Number 5	4,707	550	9.7	0.00036	4,767	104	135	218	114	1.2	1.03	80	5.0	Dam reach
48	Dam Number 5 to Williamsport	4,925	620	6.6	0.00036	4,979	130	166	259	129	0.9	1.02	70	4.4	---
49	Williamsport to Dam Number 4	5,476	1,840	15.5	0.00036	5,520	44	48	91	47	8.7	0.91	195	12.2	Injection reach, dam reach
49	Dam Number 4 to Shepherdstown	5,934	1,740	11.7	0.00036	5,968	58	65	106	48	7.2	0.73	190	11.9	---
50	6.0 miles upstream of Williamsport to Williamsport	4,925	690	6	0.00036	4,979	21.5	24	29.5	8	32	1.08	1300	81.2	Injection reach
50	Williamsport to Dam Number 4	5,476	690	15.5	0.00036	5,520	120	167	261	141	1.3	0.84	67	4.2	Dam reach
50	Dam Number 4 to Shepherdstown	5,934	710	11.7	0.00036	5,968	150	203	304	154	1.1	0.82	60	3.7	---
51	Shepherdstown to Dam Number 3	6,214	2,270	10.5	0.000455	6,251	28.5	32	39	10.5	24	0.9	1010	63.1	Injection reach, dam reach
51	Dam Number 3 to Brunswick	9,253	3,670	7.3	0.000568	8,935	36.5	40.5	50.5	14	16	1.31	760	47.4	---
51	Brunswick to Point of Rocks	9,647	3,790	6.3	0.000663	9,365	44	48.5	60.5	16.5	9.3	0.99	600	37.5	---
51	Point of Rocks to Whites Ferry	10,495	3,960	12.4	0.000663	10,125	59	63	77.5	18.5	3.6	0.52	465	29.0	---

Table 1–2. Traveltime and dispersion data for studies in West Virginia and nearby states.—Continued

[---, not recorded; inj no, injection number; D_a, drainage area; Q, flow; Len, length; Q_a, mean annual streamflow; T_l, traveltime of the leading edge of the dye cloud; T_p, traveltime of the peak concentration of the dye cloud; T_t, traveltime of the trailing edge of the dye cloud; T_d10; time of passage of the dye cloud; C_p, observed peak concentration; R_r, recovery ratio; Cup_H, unit peak concentration as defined by Hubbard and others, 1982; C_{up}, unit peak concentration as defined by Jobson, 1996; mi, miles; ft, feet; s, seconds; h, hours; µg/L, micrograms per liter]

Inj No	Reach	D_a (mi²)	Q (ft³/s)	Len (mi)	Slope (ft/ft)	Q_a (ft³/s)	T_l (h)	T_p (h)	T_t (h)	T_d10 (h)	C_p (µg/L)	R_r	Cup_H ((µg/L)(ft³/s)/lb)	C_{up} (1/s)	Comment
52	4.5 miles upstream of Shepherdstown to Shepherdstown	5,934	1,120	4.5	0.00036	5,968	12.5	14.5	21	8.5	31	0.99	1350	84.3	Injection reach
52	Shepherdstown to Dam Number 3	6,214	1,140	10.5	0.000455	6,251	59	66.5	89	30	7.3	1	318	19.9	---
52	Dam Number 3 to Brunswick	9,253	1,440	7.3	0.000568	8,935	70	79	103	33	6	1.14	287	17.9	Dam reach
52	Brunswick to Point of Rocks	9,647	1,420	6.3	0.000663	9,365	79	90.5	114.5	35.5	5.4	1.1	266	16.6	---
53	Point of Rocks to Whites Ferry	10,495	4,680	12.4	0.000663	10,125	12.5	14	15.5	3	28	0.19	3530	220.4	Injection reach
53	Whites Ferry to Seneca	10,995	4,520	13.2	0.000663	10,570	31	34	37	6	36	0.46	1810	113.0	---
53	Seneca to Little Falls Dam	11,555	4,530	16.8	0.000663	11,071	61	68	84	23	---	---	---	---	Dam reach
54	5.4 miles upstream of Point of Rocks to Point of Rocks	9,647	1,680	8.5	0.000663	9,365	8	9.5	11	3	50	0.74	3180	198.5	Injection reach
54	Point of Rocks to Whites Ferry	10,495	1,800	12.4	0.000663	10,125	29	31.5	35.5	6.5	30	1.02	1490	93.0	---
54	Whites Ferry to Seneca	10,995	1,770	13.2	0.000663	10,570	63	67	76	13	14	0.85	823	51.4	---
54	Seneca to Little Falls Dam	11,555	1,800	16.8	0.000663	11,071	130	144	184	54	1.9	0.6	159	9.9	Dam reach
Shenandoah River															
55	1.4 miles upstream of Waynesboro to Waynesboro	127	36	1.4	0.001705	141	3	4	6	3	535	1.07	2870	179.2	Injection reach
55	Waynesboro to Hopeman Parkway	148	56	5.3	0.001705	201	21	26	34	13	67	0.82	729	45.5	---
55	Hopeman Parkway to Crimora	184	62	7.4	0.001705	251	44	52	66	22	34.5	0.76	448	28.0	---
55	Crimora to Harriston	212	68	6.4	0.001705	254	64	75	91	27	21.5	0.67	347	21.7	---
55	Harriston to Island Ford	1,149	272	16.8	0.001705	1,059	116	131	158	42	2.5	0.5	214	13.4	---
55	Island Ford to Shenandoah	1,278	327	13.5	0.001136	1,180	156	173	210	54	1.5	0.46	170	10.6	---
55	Shenandoah to Grove Hill	1,290	376	7.9	0.001136	1,190	174	193	236	62	1.4	0.52	162	10.1	---
56	1.4 miles upstream of Waynesboro to Waynesboro	127	110	1.4	0.001705	141	1.3	1.8	3.1	1.8	455	0.99	5070	316.5	Injection reach
56	Waynesboro to Hopeman Parkway	148	130	5.3	0.001705	201	10	13	18.5	8.5	74	0.88	1090	68.0	---
56	Hopeman Parkway to Crimora	184	160	7.4	0.001705	251	22.2	27.3	34.2	12	42	0.89	757	47.3	---
56	Crimora to Harriston	212	170	6.4	0.001705	254	32.5	38.8	47.5	15	29	0.83	597	37.3	---

Table 1–2. Traveltime and dispersion data for studies in West Virginia and nearby states.—Continued

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Inj No	Reach	D_a (mi²)	Q (ft³/s)	Len (mi)	Slope (ft/ft)	Q_a (ft³/s)	T_l (h)	T_p (h)	T_t (h)	T_d10 (h)	C_p (µg/L)	R_r	Cup_H ((µg/L) (ft³/s)/lb)	C_{up} (1/s)	Comment
56	Harriston to Island Ford	1,149	680	16.8	0.001705	1,059	58	66.3	80.5	22.5	3.9	0.68	391	24.4	---
56	Island Ford to Shenandoah	1,278	730	13.5	0.001136	1,180	79.5	90.3	106	26.5	2.8	0.59	347	21.7	---
57	Shenandoah to Grove Hill	1,290	334	7.9	0.001136	1,190	14	17	24	10	52	1.12	848	52.9	Injection reach
57	Grove Hill to U.S. Highway 211	1,376	379	15	0.001136	1,314	50	63	87	37	11.4	0.91	259	16.2	Dam reach
57	U.S. Highway 211 to Bixler Bridge	1,398	396	7	0.001136	1,360	84	115	163	79	5.3	0.95	120	7.5	Dam reach
57	Bixler Bridge to Bentonville	1,576	452	26.1	0.001136	1,533	162	196	248	86	4.8	0.98	120	7.5	---
57	Bentonville to Front Royal	1,641	460	15.4	0.001136	1,596	208	246	305	97	4	1.02	98.3	6.1	---
57	Front Royal to Morgan Ford	2,770	640	10.2	0.001136	2,514	256	292	378	122	1.6	0.72	77.8	4.9	Dam reach
58	7.0 miles upstream from Shenandoah to Shenandoah	1,278	850	7	0.001136	1,180	8.8	10.8	14	5.2	31.9	1.08	1670	104.3	Injection reach
58	Shenandoah to Grove Hill	1,290	820	7.9	0.001136	1,190	17.5	21	26	8.5	16.8	0.91	1010	63.1	---
58	Grove Hill to U.S. Highway 211	1,376	850	15	0.001136	1,314	37	42.5	51.2	14.2	8.4	0.74	640	40.0	Dam reach
58	U.S. Highway 211 to Bixler Bridge	1,398	820	7	0.001136	1,360	53	60	76.5	23.5	4.7	0.77	335	20.9	Dam reach
58	Bixler Bridge to Bentonville	1,576	870	26.1	0.001136	1,533	85	98.5	123.5	38.5	3	0.75	232	14.5	---
59	Bixler Bridge to Bentonville	1,576	1,020	26.1	0.001136	1,596	30	33.5	39	9	28.2	0.96	1000	62.4	Injection reach
59	Bentonville to Front Royal	1,641	1,040	15.4	0.001136	1,596	51	56	64	13	15.8	0.76	676	42.2	---
59	Front Royal to Morgan Ford	2,770	1,520	10.2	0.001136	2,514	71.5	76.5	86	14.5	9.1	0.77	599	37.4	Dam reach
59	Morgan Ford to U.S. Highway 17 and 50	2,794	1,520	10.9	0.000568	2,536	84	90.5	102	18	7.1	0.77	467	29.2	---
60	4.9 miles upstream of Morgan Ford to Morgan Ford	2,770	590	4.9	0.001136	2,514	13	23	111	98	4.8	1.01	93.3	5.8	Injection reach, double peak
60	Morgan Ford to U.S. Highway 17 and 50	2,794	545	10.9	0.000568	2,536	36	58	143	107	3.8	0.89	77.9	4.9	Double peak
60	U.S. Highway 17 and 50 to State Highway 7	2,939	563	14.5	0.000568	2,666	64	89	176	112	3.1	0.83	70	4.4	Double peak
60	State Highway 7 to State Highway 9	3,011	597	13.7	0.000568	2,730	99	127	219	120	2.2	0.78	55.9	3.5	Double peak
60	State Highway 9 to Harpers Ferry	3,059	570	7.6	0.002178	2,776	131	165	262	131	1.7	0.63	51.1	3.2	Dam reach, double peak

Table 1–2. Traveltime and dispersion data for studies in West Virginia and nearby states.—Continued

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Inj No	Reach	D_a (mi²)	Q (ft³/s)	Len (mi)	Slope (ft/ft)	Q_a (ft³/s)	T_l (h)	T_p (h)	T_t (h)	T_d10 (h)	C_p (µg/L)	R_r	Cup_H ((µg/L)(ft³/s)/lb)	C_{up} (1/s)	Comment
61	Morgan Ford to U.S. Highway 17 and 50	2,794	1,720	10.9	0.000568	2,536	11.2	12.7	16.5	5.3	18.7	0.94	1710	106.8	Injection reach
61	U.S. Highway 17 and 50 to State Highway 7	2,939	1,720	14.5	0.000568	2,666	25.3	27.7	34.3	9	9.9	0.92	924	57.7	---
61	State Highway 7 to State Highway 9	3,011	1,700	13.7	0.000568	2,730	40.7	47.5	56.3	15.6	5.6	0.88	539	33.6	---
61	State Highway 9 to Harpers Ferry	3,059	1,730	7.6	0.002178	2,776	54.7	62	74.5	19.8	4.1	0.84	424	26.5	Dam reach
						Monocacy River									
62	Harney Bridge to Starners Dam	150	38	1.75	0.0007	177	26.5	35.5	57	30.5	16.2	---	---	---	Injection reach, dam reach
62	Starners Dam to State Route 97	173	42	2.95	0.0007	201	39	51	81	42	10.3	---	---	---	---
63	Harney Bridge to Starners Dam	150	94	1.75	0.0007	177	8.6	10.9	25	16.4	6.8	---	---	---	Injection reach, dam reach
63	Starners Dam to State Route 97	173	92	2.95	0.0007	201	14.8	19	33	18.2	4.8	---	---	---	---
64	State Route 97 to Sixes Bridge	270	88	5.8	0.0007	314	21.8	27.2	45	23.2	12.8	---	480	30.0	Injection reach
64	Sixes Bridge to Le Gore Bridge	515	140	8.35	0.0008	583	48.2	57	82	33.8	3.4	---	330	20.6	---
64	Le Gore Bridge to Links Bridge	612	165	6.4	0.0006	696	62.2	72.5	98	35.8	2	---	310	19.4	---
65	State Route 97 to Sixes Bridge	270	195	5.8	0.0007	314	10.4	13.3	19	8.6	27	---	1140	71.2	Injection reach
65	Sixes Bridge to Le Gore Bridge	515	405	8.35	0.0008	583	24	28.5	39	15	6	---	690	43.1	---
65	Le Gore Bridge to Links Bridge	612	445	6.4	0.0006	696	32	37.2	50	18	4	---	610	38.1	---
66	Le Gore Bridge to Links Bridge	612	190	6.4	0.0006	696	11	12.6	17	6	9.6	---	1450	90.5	Injection reach
66	Links Bridge to Biggs Ford Bridge	637	200	5	0.0006	724	20.4	23	32	11.6	6.1	---	920	57.4	---
66	Biggs Ford Bridge to Filtration Plant	702	225	5.25	0.0005	798	28.8	33.5	45	16.2	4	---	620	38.7	---
66	Filtration Plant to U.S. Route 40 Bridge	817	270	4.65	0.0003	925	37.4	43.8	60	22.6	2.9	---	490	30.6	---
67	Le Gore Bridge to Links Bridge	612	505	6.4	0.0006	696	6.3	7.1	10.5	4.2	20.6	---	2600	162.3	Injection reach
67	Links Bridge to Biggs Ford Bridge	637	535	5	0.0006	724	11.8	13.5	18	6.2	12.1	---	1540	96.1	---

Table 1–2. Traveltime and dispersion data for studies in West Virginia and nearby states.—Continued

[---, not recorded; inj no, injection number; D_a, drainage area; Q, flow; Len, length; Q_a, mean annual streamflow; T_l, traveltime of the leading edge of the dye cloud; T_p, traveltime of the peak concentration of the dye cloud; T_t, traveltime of the trailing edge of the dye cloud; T_d10; time of passage of the dye cloud; C_p, observed peak concentration; R_r, recovery ratio; Cup_H, unit peak concentration as defined by Hubbard and others, 1982; C_{up}, unit peak concentration as defined by Jobson, 1996; mi, miles; ft, feet; s, seconds; h, hours; µg/L, micrograms per liter]

Inj No	Reach	D_a (mi^2)	Q (ft^3/s)	Len (mi)	Slope (ft/ft)	Q_a (ft^3/s)	T_l (h)	T_p (h)	T_t (h)	T_d10 (h)	C_p (µg/L)	R_r	Cup_H ((µg/L)(ft^3/s)/lb)	C_{up} (1/s)	Comment
67	Biggs Ford Bridge to Filtration Plant	702	560	5.25	0.0005	798	17	19.6	25	8	8.1	---	1260	78.7	---
67	Filtration Plant to U.S. Route 40 Bridge	817	655	4.65	0.0003	925	22	25.6	34	12	6.2	---	970	60.6	---
68	Le Gore Bridge to Links Bridge	612	71	6.4	0.0006	696	22	27	41	19	17.9	0.83	568	35.5	Injection reach
68	Links Bridge to Biggs Ford Bridge	637	71	5	0.0006	724	45.5	54	80	34.5	9.4	0.75	332	20.7	---
68	Biggs Ford Bridge to Filtration Plant	702	81	5.25	0.0005	798	64.5	76	115	50.5	4.8	0.61	234	14.6	---
69	Filtration Plant to U.S. Route 40 Bridge	817	286	4.65	0.0003	925	7.2	8.6	15	7.8	20.5	---	1260	78.7	Injection reach
69	U.S. Route 40 Bridge to State Route 80	858	295	7.15	0.0003	975	25.5	29	43	17.5	6	---	640	40.0	---
69	State Route 80 to Greenfield Mills Bridge	947	330	5.45	0.0006	1,074	35	40.5	56	21	3.6	---	470	29.3	---
69	Greenfield Mills Bridge to Monocacy Aqueduct	972	335	3.85	0.0003	1,102	42.5	48.8	67	24.5	3	---	430	26.8	---
70	Filtration Plant to U.S. Route 40 Bridge	817	720	4.55	0.0003	925	4.2	5.1	7.7	3.5	37.8	---	2640	164.8	Injection reach
70	U.S. Route 40 Bridge to State Route 80	858	720	7.15	0.0003	975	13.4	15.7	21	7.6	17.5	---	1580	98.6	---
70	State Route 80 to Greenfield Mills Bridge	947	780	5.45	0.0006	1,074	19.3	22	29	9.7	8.8	---	1020	63.7	---
70	Greenfield Mills Bridge to Monocacy Aqueduct	972	780	3.85	0.0003	1,102	24.3	27.7	36	11.7	---	---	920	57.4	---
71	Filtration Plant to U.S. Route 40 Bridge	817	108	4.55	0.0003	925	13.5	17.5	32	18.5	19.9	---	660	41.2	Injection reach
71	U.S. Route 40 Bridge to State Route 80	858	113	7.15	0.0003	975	52	63	103	51	4.6	---	226	14.1	---
71	State Route 80 to Greenfield Mills Bridge	947	122	5.45	0.0006	1,074	70.5	85	135	64.5	2.6	---	168	10.5	---
71	Greenfield Mills Bridge to Monocacy Aqueduct	972	124	3.85	0.0003	1,102	83	100	155	72	2	---	146	9.1	---

Table 1–2. Traveltime and dispersion data for studies in West Virginia and nearby states.—Continued

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Inj No	Reach	D_a (mi²)	Q (ft³/s)	Len (mi)	Slope (ft/ft)	Q_a (ft³/s)	T_l (h)	T_p (h)	T_t (h)	T_d10 (h)	C_p (µg/L)	R_r	Cup_H ((µg/L) (ft³/s)/lb)	C_{up} (1/s)	Comment
						Antietam Creek									
72	County Road Bridge (1.6 miles upstream) to County Road Bridge	92.7	41	1.6	0.0027	92	2.4	3.4	5.1	2.7	92.5	---	4100	256.0	Injection reach
72	County Road Bridge to State Highway 60	98.5	42	4.35	0.0011	95	10.5	12.8	18	7.5	30.5	---	1640	102.4	---
72	State Highway 60 to State Highway 64	166	58	7.4	0.0011	162	37	43.2	57	20	4.9	---	660	41.2	Dam reach
72	State Highway 64 to West Baltimore Street	180	63	5.05	0.0008	173	57.5	67	86	28.5	2.2	---	440	27.5	Dam reach
73	County Road Bridge (1.6 miles upstream) to County Road Bridge	92.7	180	1.6	0.0027	92	1	1.4	1.9	0.9	350	---	11300	705.4	Injection reach
73	County Road Bridge to State Highway 60	98.5	185	4.35	0.0011	95	4.7	5.5	6.7	2	150	---	4920	307.1	---
73	State Highway 60 to State Highway 64	166	260	7.4	0.0011	162	14	15.9	18.2	4.2	50	---	2660	166.1	Dam reach
73	State Highway 64 to West Baltimore Street	180	275	5.05	0.0008	173	21	23.4	27	6	24.5	---	1880	117.4	Dam reach
73	West Baltimore Street to Roxbury Road	197	300	7.85	0.0015	191	30	33.2	38.5	8.5	13.5	---	1280	79.9	Dam reach
73	Roxbury Road to Monroe Road	233	360	4.3	0.0017	226	34.2	38	44	9.8	8.5	---	1160	72.4	---
73	Monroe Road to New Burnside Bridge Road	42.9	430	6.25	0.001	272	39.3	43.3	51	11.7	6	---	1040	64.9	---
73	New Burnside Bridge Road to Harpers Ferry Road	292	450	4.65	0.001	283	43.3	47.5	56.5	13.2	5	---	950	59.3	---
74	County Road Bridge (1.6 miles upstream) to County Road Bridge	92.7	85	1.6	0.0027	92	2	2.6	4.2	2.2	110	---	4500	280.9	Injection reach
74	County Road Bridge to State Highway 60	98.5	86	4.35	0.0011	95	7.9	9.5	12.8	4.9	49	---	2240	139.8	---
74	State Highway 60 to State Highway 64	166	120	7.4	0.0011	162	24	27.4	35	11	11.4	---	1080	67.4	Dam reach

Table 1–2. Traveltime and dispersion data for studies in West Virginia and nearby states.—Continued

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Inj No	Reach	D_a (mi^2)	Q (ft^3/s)	Len (mi)	Slope (ft/ft)	Q_a (ft^3/s)	T_l (h)	T_p (h)	T_t (h)	T_d10 (h)	C_p (µg/L)	R_r	Cup_H ((µg/L) (ft^3/s)/lb)	C_{up} (1/s)	Comment
74	State Highway 64 to West Baltimore Street	180	140	5.05	0.0008	173	36.4	40.2	48.6	12.2	6.6	---	980	61.2	Dam reach
75	West Baltimore Street to Roxbury Road	197	160	7.85	0.0015	191	11.8	13.8	19.2	7.4	22	---	1500	93.6	Injection reach, dam reach
75	Roxbury Road to Monroe Road	233	188	4.3	0.0017	226	18.5	21.1	28.6	10.1	13.3	---	1160	72.4	---
75	Monroe Road to New Burnside Bridge Road	281	225	6.25	0.001	272	26	29	37.5	11.5	8.4	---	1030	64.3	---
75	New Burnside Bridge Road to Harpers Ferry Road	292	230	4.65	0.001	283	31	34.2	44	13	7.8	---	980	61.2	---
76	West Baltimore Street to Roxbury Road	197	72	7.85	0.0015	191	19.8	25	43.8	24	8.6	---	590	36.8	Injection reach, dam reach
76	Roxbury Road to Monroe Road	233	101	4.3	0.0017	226	31.5	37.2	65	33.5	3.5	---	450	28.1	---
76	Monroe Road to New Burnside Bridge Road	281	110	6.25	0.001	272	43.6	50	82	38.4	2.4	---	380	23.7	---
77	Monroe Road to New Burnside Bridge Road	281	112	6.25	0.001	272	10.1	12.8	17.6	7.5	14	---	1490	93.0	Injection reach
77	New Burnside Bridge Road to Harpers Ferry Road	292	114	4.65	0.001	283	17.7	21.3	28	10.3	8.1	---	1050	65.5	---
						Conococheague Creek									
78	State Highway 58 (2.75 miles upstream) to State Highway 494	494	1,040	2.75	0.0005	583	1.25	1.35	1.8	0.55	87	---	23200	1448.3	Injection reach
78	State Highway 494 to Broadfording Road	514	1,040	2.65	0.0007	607	2.8	3.15	4.35	1.55	26.5	---	7300	455.7	---
78	Broadfording Road to Mouth of Rush Run	524	1,050	2.95	0.0007	618	4.6	5	6.8	2.2	17.5	---	4900	305.9	---
78	Mouth of Rush Run to U.S. Highway 40	533	1,060	4	0.0006	632	7	7.65	9.9	2.9	13	---	3900	243.5	---
78	U.S. Highway 40 to Kemps Mill Road	533	1,070	3.8	0.0006	632	9.5	10.4	13.5	4	7.5	---	2440	152.3	---
78	Kamps Mill Road to C&O Canal Aqueduct	563	1,080	4.9	0.0005	667	13.3	14.8	19.5	6.2	5.2	---	1750	109.2	Dam reach

Table 1–2. Traveltime and dispersion data for studies in West Virginia and nearby states.—Continued

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Inj No	Reach	D_a (mi²)	Q (ft³/s)	Len (mi)	Slope (ft/ft)	Q_a (ft³/s)	T_l (h)	T_p (h)	T_t (h)	T_d10 (h)	C_p (µg/L)	R_r	Cup_H ((µg/L) (ft³/s)/lb)	C_{up} (1/s)	Comment
79	State Highway 494 (2.75 miles upstream) to State Highway 494	494	241	2.75	0.0005	583	2.6	3	3.8	1.2	155	---	9800	611.8	Injection reach
79	State Highway 494 to Broadfording Road	514	242	2.65	0.0007	607	6	6.6	8.9	2.9	67	---	4220	263.4	---
79	Broadfording Road to Mouth of Rush Run	524	243	2.95	0.0007	618	9.6	10.3	14.2	4.6	41	---	2840	177.3	---
79	Mouth of Rush Run to U.S. Highway 40	533	245	4	0.0006	632	14.6	15.5	20.8	6.2	24.5	---	2060	128.6	---
79	U.S. Highway 40 to Kemps Mill Road	533	245	3.8	0.0006	632	19.8	21.3	28.6	8.8	14	---	1240	77.4	---
79	Kamps Mill Road to C&O Canal Aqueduct	563	250	4.9	0.0007	667	30.1	33.8	45.5	15.4	5.5	---	830	51.8	Dam reach
80	State Highway 58 (2.75 miles upstream) to State Highway 494	494	91	2.75	0.0005	583	4.7	5.4	8.4	3.7	86	---	2300	143.6	Injection reach
80	State Highway 494 to Broadfording Road	514	100	2.65	0.0007	607	11.4	14	21.2	9.8	35	---	1130	70.5	---
80	Broadfording Road to Mouth of Rush Run	524	102	2.95	0.0007	618	19	24.6	38	19	14.8	---	480	30.0	---
80	Mouth of Rush Run to U.S. Highway 40	533	102	4	0.0007	632	31.3	37.5	55	23.7	14	---	480	30.0	---
81	U.S. Highway 40 to Kemps Mill Road	533	105	3.8	0.0006	632	12.2	17	20	7.8	27.5	---	1400	87.4	Injection reach
81	Kamps Mill Road to C&O Canal Aqueduct	563	105	4.9	0.0006	667	35	42	52.5	17.5	7.5	---	490	30.6	Dam reach

For additional information call or write to:

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