USGS
science for a changing world

Development of a Traveltime Prediction Equation for Streams in Arkansas

Prepared in cooperation with the
ARKANSAS DEPARTMENT OF HEALTH

Scientific Investigations Report 2004-5064

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

Front Cover: Photograph of Rhodamine WT dye in the Cossatot River 3 miles upstream from the U.S. Geological Survey streamgaging station 07340300 Cossatot River near Vandervoort, Arkansas, February 2002 (photograph by U.S. Geological Survey).

Development of a Traveltime Prediction Equation for Streams in Arkansas

By Jaysson E. Funkhouser and C. Shane Barks

Prepared in cooperation with the
ARKANSAS DEPARTMENT OF HEALTH

Scientific Investigations Report 2004-5064

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

U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

U.S. Geological Survey, Reston, Virginia: 2004
For sale by U.S. Geological Survey, Information Services
Box 25286, Denver Federal Center
Denver, CO 80225

For more information about the USGS and its products:
Telephone: 1-888-ASK-USGS
World Wide Web: http://www.usgs.gov/

CONTENTS

ILLUSTRATIONS

TABLES

Development of a Traveltime Prediction Equation for Streams in Arkansas

By Jaysson E. Funkhouser and C. Shane Barks

Abstract

During 1971 and 1981 and 2001 and 2003, traveltime measurements were made at 33 sample sites on 18 streams throughout northern and western Arkansas using fluorescent dye. Most measurements were made during steady-state base-flow conditions with the exception of three measurements made during near steady-state medium-flow conditions (for the study described in this report, medium-flow is approximately 100-150 percent of the mean monthly streamflow during the month the dye trace was conducted). These traveltime data were compared to the U.S. Geological Survey's national traveltime prediction equation and used to develop a specific traveltime prediction equation for Arkansas streams.

In general, the national traveltime prediction equation yielded results that over-predicted the velocity of the streams for 29 of the 33 sites measured. The standard error for the national traveltime prediction equation was 105 percent. The coefficient of determination was 0.78.

The Arkansas prediction equation developed from a regression analysis of dye-tracing results was a significant improvement over the national prediction equation. This regression analysis yielded a standard error of 46 percent and a coefficient of determination of 0.74. The predicted velocities using this equation compared better to measured velocities.

Using the variables in a regression analysis, the Arkansas prediction equation derived for the peak velocity in feet per second was:

$$V_p = 0.0731 \times \left(\frac{Q}{D_a}\right)^{0.664} \times S^{-0.377} \times 1.074$$

where,

Q is discharge at point of interest, in cubic feet per second;

D_a is drainage area at point of interest, in square miles; and

S is slope from point of injection of point of interest, in foot per foot.

In addition to knowing when the peak concentration will arrive at a site, it is of great interest to know when the leading edge of a contaminant plume will arrive. The traveltime of the leading edge of a contaminant plume indicates when a potential problem might first develop and also defines the overall shape of the concentration response function.

Previous USGS reports have shown no significant relation between any of the variables and the time from injection to the arrival of the leading edge of the dye plume. For this report, the analysis of the dye-tracing data yielded a significant correlation between traveltime of the leading edge and traveltime of the peak concentration with an R^2 value of 0.99. These data indicate that the traveltime of the leading edge can be estimated from:

$$T_l = 0.79 \times T_p$$

where,

T_l is traveltime of the leading edge, in hours, and

T_p is traveltime of peak concentration, in hours.

Introduction

The 1996 Amendments to the Safe Drinking-Water Act require that each state prepare a source-water assessment for all public water supplies. States are required to determine the sources of drinking water, the origin of contaminants monitored, or the identification of the potential contaminants to be monitored, and the intrinsic susceptibility of the water supplies to these contaminants (Arkansas Department of Health, 2002). In Arkansas, source-water protection is the responsibility of the Arkansas Department of Health (ADH).

There are more than 1,500 public drinking-water sources in Arkansas (T.W. Holland, U.S. Geological Survey, oral commun., 2001). Of these, more than 100 use surface-water sources that serve nearly one million people. These surface-water sources include free-flowing rivers, reservoirs, and springs that are susceptible to potential sources of contamination (PSOC's) that may be located within or near the area influencing the water source. Nearly half of the population served by these surface-water sources are located within rural and undeveloped areas of the State.

An important aspect of PSOC's for surface-water sources is the time it takes for a contaminant to reach the intake structure of a drinking-water supply from the point of input (spill or leak). Public-health officials often need to decide when and how long to suspend operations of public water-supply intakes in the reach downstream from a spill or leak. Stream velocity, which can be obtained from traveltime data, is a streamflow characteristic that water-resource managers and planners can use to predict the rate of movement of contaminants that may be introduced into the stream (Jobson, 1996). Fluorescent dyes can be used to measure a stream's velocity and gain a better understanding of the potential rate of movement of contaminants.

To address the need for traveltime data to estimate rate of movement of contaminants in Arkansas streams, the U.S. Geological Survey (USGS) conducted a study in cooperation with the ADH during 2001 and 2003. These data, along with data collected during Lamb's (1983) study, were combined to develop an equation that can be used to estimate the average velocity of an Arkansas stream.

Purpose and Scope

This report presents traveltime data collected at 33 sample sites on 18 different streams in Arkansas during two studies based on dye-tracing techniques. The first study was conducted between 1971 and 1981 (Lamb, 1983). The present (2003) study was conducted between 2001 and 2003 by the USGS in cooperation with the ADH. The data collected from both of these studies has been combined for this report and are hereafter referred to as the Arkansas data set.

The Arkansas data set was used to evaluate the USGS national traveltime prediction equation (hereafter referred to as the national traveltime prediction equation) (Jobson, 1996) for use in Arkansas and to develop a traveltime prediction equation specific to Arkansas streams. Verification and calibration error statistics are presented for the national traveltime equation. Calibration coefficients are presented for a traveltime prediction equation using only the Arkansas data set. An example demonstrating the traveltime prediction equation for Arkansas is presented in this report.

Location of Study Sites

Eighteen stream reaches were chosen for this study that are located in the northern and western areas of Arkansas (fig. 1, table 1). The boundary for the study area extended from Randolph County in northern Arkansas to Benton County in northwestern Arkansas and to Polk County in western Arkansas (fig. 1).

Acknowledgments

Gratitude is expressed to the residents and water-treatment plant managers that allowed the USGS to access the streams for data-collection purposes. Gratitude also is expressed to the ADH for their assistance in helping the USGS identify the streams in Arkansas to be studied.

Dye-Cloud Dispersion Theory

The traveltime and longitudinal-dispersion of chemical constituents in a stream vary with flow conditions. Therefore, developing accurate traveltime and longitudinal-dispersion characteristics over a range of flow conditions is critical to understanding the transport of chemicals in a stream reach. Dye tracing provides one of the best methods of predicting stream traveltimes and what may happen to conservative contaminants that are introduced into a stream reach.

Longitudinal Dispersion

Longitudinal dispersion is the process whereby a mass of solute introduced into a flowing stream is mixed and diluted in the longitudinal, or downstream direction (Nordin and Sabol, 1974; Gurdak and others, 2002). The response to the slug injection of a soluble tracer is assumed to imitate the characteristics of a soluble contaminant. An understanding of how tracers mix and disperse in a stream is essential to understanding their application in simulating contaminant transport. This report will provide a brief description on the theory of dye-cloud dispersion (traveltime) for instantaneous sources, but a detailed description of this theory can be found in Hubbard and others (1982), Kilpatrick (1993) and Kilpatrick and Wilson (1989).

The dispersion and mixing of a tracer in a receiving stream take place in all three dimensions of the channel (fig. 2)—vertical, lateral, and longitudinal. Vertical mixing (throughout the depth of the stream) is normally completed rather rapidly, within a distance of a few river depths. Lateral mixing is much slower, but is usually completed within a few miles downstream. Longitudinal dispersion continues indefinitely because there are no physical boundaries (Hubbard and others, 1982; Lamb, 1983; Jobson, 1996). Longitudinal dispersion is the dispersion component of primary interest in this report.

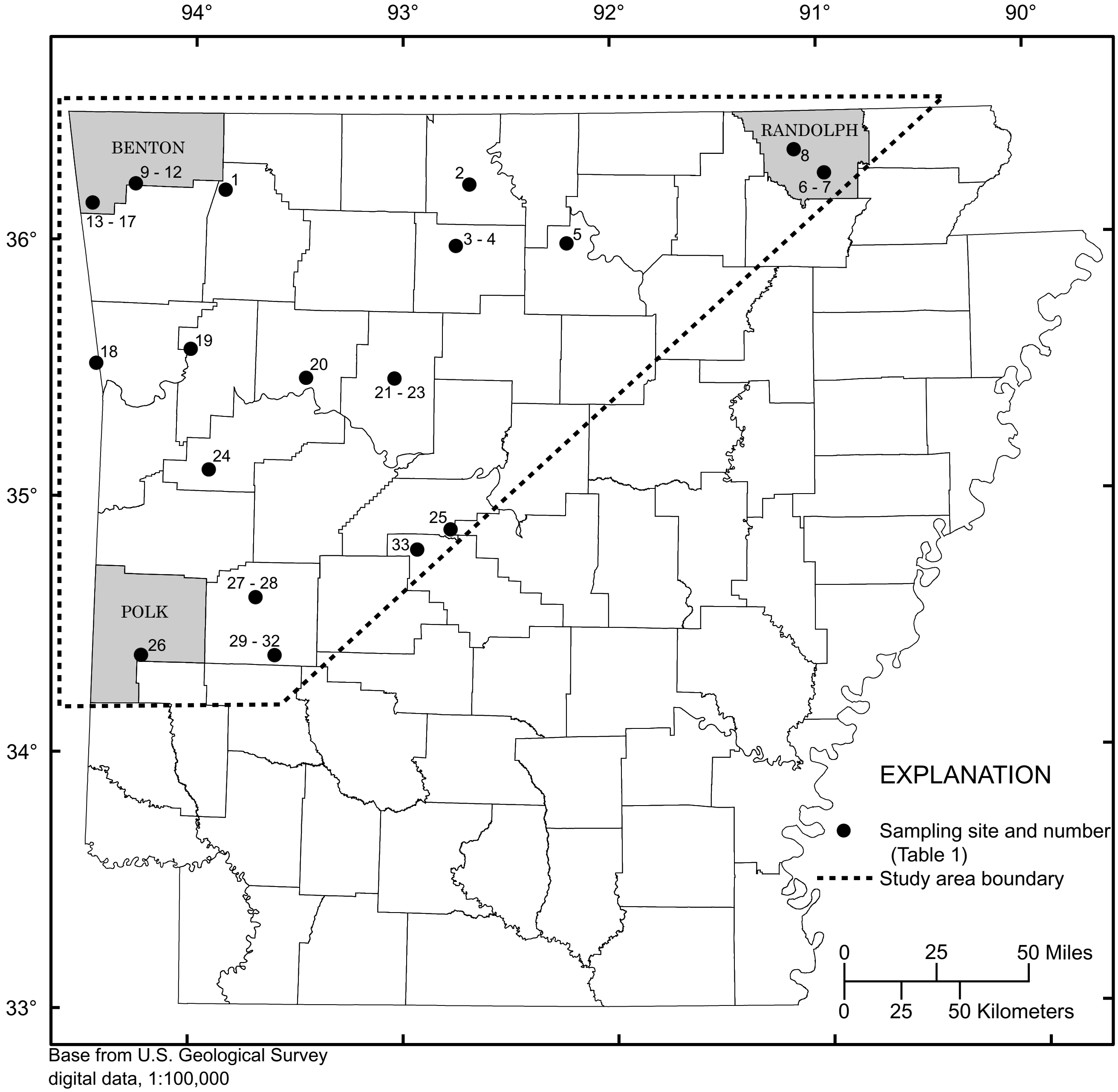


Figure 1. General location of sampling sites.

Table 1. Sample sites and stream reaches used for traveltime study and their approximate locations in Arkansas.

[Numbers in parentheses indicate the stream reach relative to a reference gage. Negative numbers in parentheses represent distance upstream from the reference gage on the stream, in miles; positive numbers in parentheses represent distance downstream from the reference gage on the stream, in miles; Reference gage is a U.S. Geological Survey streamflow gaging station with the associated station identification number]

Sample site number (fig. 1)	Stream name	Location of nearest town	Location of stream reach with respect to reference gage	Station identification number
1	War Eagle Creek	Hindsville, Arkansas	(-12.8, -9.9) War Eagle Creek near Hindsville	07049000
2	Crooked Creek	Yellville, Arkansas	(-3.9, 0.0) Crooked Creek at Yellville	07055608
3	Buffalo River	St. Joe, Arkansas	(-8.3, 4.2) Buffalo River near St. Joe	07056000
4	Buffalo River	St. Joe, Arkansas	(-8.3, 4.2) Buffalo River near St. Joe	07056000
5	North Sylamore Creek	Fifty Six, Arkansas	(-4.2, 4.8) North Sylamore Creek near Fifty Six	07060710
6	Black River	Pocahontas, Arkansas	(0.0, -15.9) Black River at Pocahontas	07069000
7	Black River	Pocahontas, Arkansas	(0.0, -15.9) Black River at Pocahontas	07069000
8	Eleven Point River	Ravenden Springs, Arkansas	(-8.9, 0.0) Eleven Point River near Ravenden Springs	07072000
9	Osage Creek	Elm Springs, Arkansas	(4.0, 8.4) Osage Creek near Elm Springs	07195000
10	Osage Creek	Elm Springs, Arkansas	(-5.2., 0.0) Osage Creek near Elm Springs	07195000
11	Osage Creek	Elm Springs, Arkansas	(0.0, 8.4) Osage Creek near Elm Springs	07195000
12	Osage Creek	Elm Springs, Arkansas	(-11.1, -7.0) Osage Creek near Elm Springs	07195000
13	Illinois River	Siloam Springs, Arkansas	(-6.9, 0.0) Illinois River near Siloam Springs	07195400
14	Illinois River	Siloam Springs, Arkansas	(-18.1, -14.1) Illinois River near Siloam Springs	07195400
15	Illinois River	Siloam Springs, Arkansas	(-25.2, -22.6) Illinois River near Siloam Springs	07195400
16	Illinois River	Siloam Springs, Arkansas	(-6.0, 2.2) Illinois River near Siloam Springs	07195400
17	Illinois River	Siloam Springs, Arkansas	(-14.1, -9.1) Illinois River near Siloam Springs	07195400
18	Lee Creek	Short, Oklahoma	(-8.5, 0.0) Lee Creek near Short	07249985
19	Mulberry River	Mulberry, Arkansas	(-14.1, 0.0) Mulberry River near Mulberry	07252000
20	Spadra Creek	Clarksville, Arkansas	(-9.0, 0.0) Spadra Creek at Clarksville	07256500
21	Illinois Bayou	Scottsville, Arkansas	(0.0, 9.0) Illinois Bayou near Scottsville	07257500
22	Illinois Bayou	Scottsville, Arkansas	(-7.4, 0.0) Illinois Bayou near Scottsville	07257500
23	Illinois Bayou	Scottsville, Arkansas	(-7.4, 9.0) Illinois Bayou near Scottsville	07257500
24	Petit Jean River	Booneville, Arkansas	(-1.1, 9.8) Petit Jean River near Booneville	07258500
25	Maumelle River	Williams Junction, Arkansas	(-6.0, 0.0) Maumelle River at William’s Junction	07263295
26	Cossatot River	Vandervoort, Arkansas	(-3.4, 9.4) Cossatot River near Vandervoort	07340300
27	Ouachita River	Mount Ida, Arkansas	(-9.6, 0) Ouachita River near Mount Ida	07356000
28	Ouachita River	Mount Ida, Arkansas	(-9.6, 0) Ouachita River near Mount Ida	07356000
29	Caddo River	Caddo Gap, Arkansas	(7.8, 19.8) Caddo River at Caddo Gap	07359610
30	Caddo River	Caddo Gap, Arkansas	(-8.0, 7.8) Caddo River at Caddo Gap	07359610
31	Caddo River	Caddo Gap, Arkansas	(7.8, 19.8) Caddo River at Caddo Gap	07359610
32	Caddo River	Caddo Gap, Arkansas	(-8.0, 15.0) Caddo River at Caddo Gap	07359610
33	Alum Fork Saline River	Reform, Arkansas	(-6.0, -5.3) Alum Fork Saline River near Reform	07362587

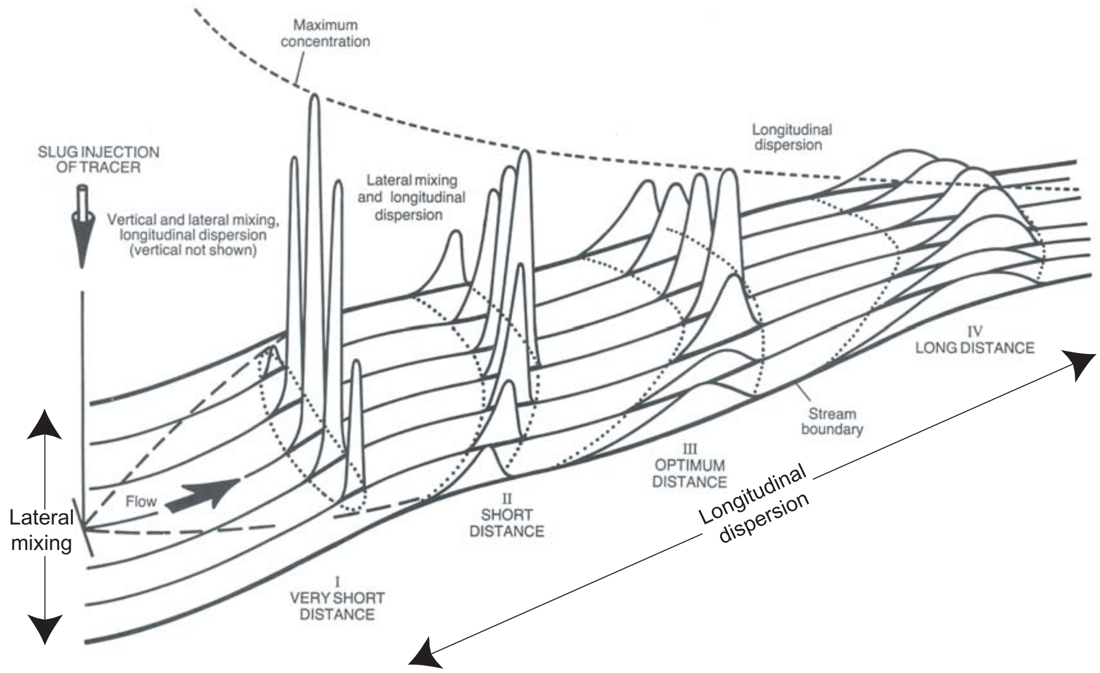


Figure 2. Lateral mixing and longitudinal dispersion patterns and changes of concentration downstream from a single, midpoint, slug injection of tracer (modified from Kilpatrick and Wilson, 1989, p. 2).

Theory of Dye-Cloud Dispersion for Instantaneous Sources

Figure 2 shows that for a midpoint slug injection, the tracer cloud typically moves faster than the mean stream velocity upstream from an optimum section distance (section III in fig. 2) because the bulk of the tracer is injected in the high velocity part of the cross section. For the present (2003) study, all of the measurement cross sections were located at least as far downstream as the optimum distance (explanation included later in report) (section III in fig. 2) so that longitudinal dispersion was the dominant mixing process.

The response curve at any point downstream from an instantaneous dye injection is normally represented by plotting concentration in relation to elapsed time (fig. 3). The response curves, defined by the analysis of water samples taken at selected time intervals during the dye-cloud passage, are the basis for determining traveltime and dispersion characteristics of streams (Kilpatrick and Wilson, 1989).

Previous USGS Traveltime Studies

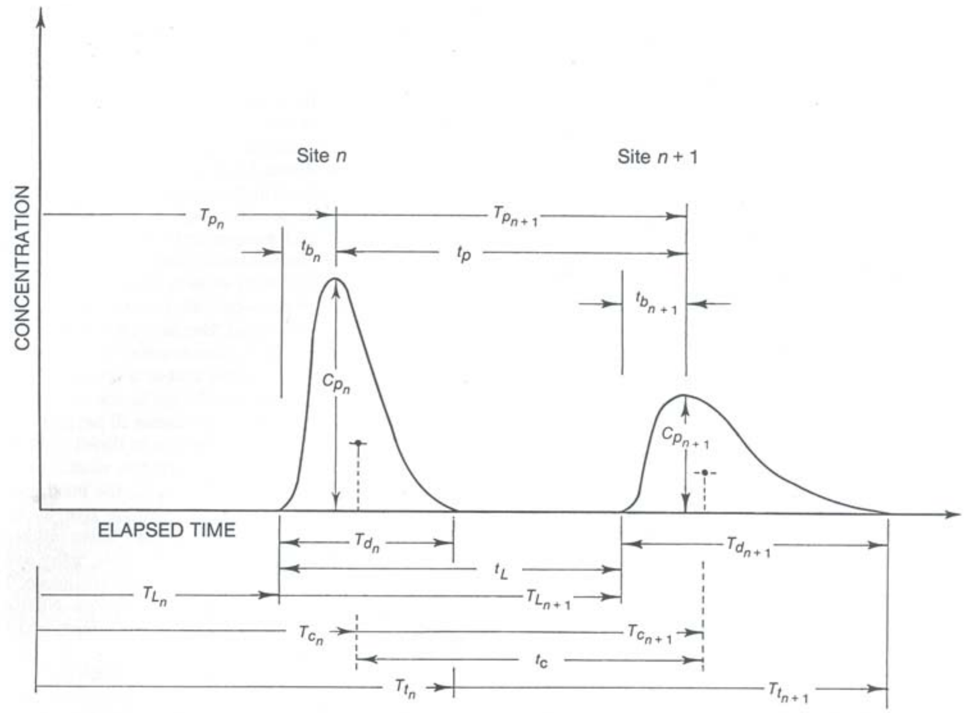
Extensive use of fluorescent dyes as water tracers to quantify transport in streams and rivers began in the United States in the early to mid-1960's (Wilson and others, 1986). Traveltime data collected using the dye-tracing techniques by the USGS have been used to develop national prediction equations that can provide guidance to water-resources managers and planners responding to spills.

Traveltime Studies on Arkansas Streams

Traveltime studies have been conducted on several streams in Arkansas. The USGS conducted a series of traveltime studies on streams in Arkansas between 1971 and 1981 using fluorescent dyes (Lamb, 1983). These studies demonstrated that traveltime could fluctuate greatly depending upon streamflow and the stream's basin characteristics. Other traveltime studies have been conducted sporadically over a period of years by universities and local government entities but none has been used to derive a specific traveltime equation for Arkansas streams.

National Traveltime Studies

Several national traveltime studies have been conducted by the USGS since 1974. A national traveltime study was completed in 1974 (Boning, 1974) using 873 individual dye-tracing measurements on more than 300 streams. These data were used



EXPLANATION

C_p is peak concentration of the dye cloud;

T_L is elapsed time to the arrival of the leading edge of a sampling location;

T_p is elapsed time to the peak concentration of the dye cloud;

T_t is elapsed time to the trailing edge of the tracer cloud;

T_d is duration of the dye cloud (T_t-T_L);

T_c is elapsed time to the centroid of the response curve;

t_b is the time from the arrival of the leading edge to the peak concentration;

t_p is the time it takes for the peak concentration to travel from site *n* to site *n* + 1;

t_L is the time it takes for the leading edge to travel from site *n* to site *n* + 1;

t_c is the time it takes for the centroid of the response curve to travel from site *n* to site *n* + 1;

n the number of sampling sites downstream from injection

Figure 3. Definition sketch of time-concentration curves along a selected streamline resulting from an instantaneous dye injection (modified from Kilpatrick and Wilson, 1989).

to develop a linear regression model that described travel rates of dye clouds for various streams. This model illustrated that discharge, slope, and duration frequency were related to traveltime. Kilpatrick (1993), using the concept of unit-peak concentration and the superposition principle, illustrated how traveltime data could be generalized for a wide range of flow conditions. Elaborating on Boning's (1974) study, Jobson (1996) used traveltime data from approximately 939 subreaches for about 90 different streams throughout the United States and developed a set of national traveltime prediction equations that were based on the size of the drainage area, the slope of the stream reach, the mean annual discharge of the stream, and the discharge of the stream at the point of interest.

Methods

The methods described in this report describe the techniques used during the field data-collection process for dye tracing and the statistical approach used to analyze the traveltime data. A description of the methods used in the evaluation of the national traveltime prediction equation for use in describing Arkansas streams also is provided.

Site Selection

Selecting the 18 streams used in this investigation was an important component of the study. Because northern and western Arkansas are the most populous areas of the State and rely on surface water as their primary source of drinking water, the risk can be high for having their drinking water supplies contaminated from a spill. For this reason, the selection of these streams had a higher priority than other streams in the State.

Other factors were important in selecting the study sites. The 18 selected streams (table 1) have little or no flow regulation (dams or other restrictions) and have an established streamflow gaging station with at least 10 consecutive years of streamflow data available. The 18 streams had a wide range of drainage areas, stream slopes, and geomorphic characteristics. All of these factors contributed to the range in variability of data which is important when performing a regression analysis and developing a locally based traveltime prediction equation. Of the 18 streams, 15 were flowing at steady-state base-flow conditions and 3 were flowing at near steady-state medium-flow conditions at the time of data collection (for this study, medium-flow is approximately 100-150 percent of the mean monthly streamflow during the month the dye trace was conducted).

Fluorescent Dye Concentration Determination

For the Lamb (1983) and the present (2003) study, Rhodamine WT 20 percent stock solution (RWT), a fluorescent dye, was used as the tracer. Dye concentrations were measured using a fluorometer, which is an instrument that measures fluorescence. Fluorescence readings, when calibrated to known concentrations, can be used to measure the concentration of dye in the water. Fluorescence concentrations in samples also need to be compared to known concentrations (standards) using the same fluorometer under the same environmental conditions (Wilson and others, 1986). Otherwise comparisons of fluorescence concentrations will not be meaningful. Because the fluorescence measured in a stream sample is proportional to the concentration of dye in the water, standard solutions—which compare fluorescence to dye concentration—can be mixed to properly calibrate a fluorometer to relate fluorescence to dye concentration.

Prior to each dye trace conducted during the present (2003) study, the fluorometer was calibrated to a set of known RWT concentrations, usually 10, 25, and 100 micrograms per liter (µg/L). The concentrations of the samples used for calibrating the fluorometer were mixed using water collected at each stream. Stream water was used in an effort to account for the natural fluorescence effects that might occur for a particular stream's water. For quality assurance, the calibration of the fluorometer was checked after each dye trace to ensure "drifting" of the fluorometer did not occur during the dye trace. See Lamb (1983) for a description of quality-assurance practices used in Lamb's study.

Field Methods

Several steps were followed during the field data-collection period for Lamb's (1983) study and for the present study. A brief description of Lamb's (1983) study is described in this report. A detailed description of the field methods used for data collection during Lamb's study can be found in Lamb (1983).

Previous Studies on Arkansas Streams

During Lamb's (1983) study, RWT dye was injected instantaneously at approximately the center of the stream. The amount of dye injected was determined prior to each study. Whenever possible, the dye was injected far enough upstream in an effort to allow vertical and lateral dispersion of the dye to take place before the dye cloud reached the first sampling site. If this was not possible because of time or physical constraints, the injection was made as far upstream as practical, and the error in traveltime introduced by incomplete mixing at the first sampling site was determined to be small and was disregarded.

At each sampling site, water samples were collected at predetermined intervals before and during the arrival of the dye cloud until the dye concentration was less than 10 percent of the peak concentration passing the site. Each of the samples collected at the sites were analyzed using a fluorometer. The discharge of the stream at each sampling site was measured by conducting current-meter measurements using the techniques outlined by Rantz and others (1982).

Present Study

For the present (2003) study, RWT also was used as the tracer to measure the traveltime of the stream. The amount of RWT dye injected into the stream at each of the study sites was predetermined using the methods outlined in Kilpatrick and Wilson, (1989) using the following equation:

$$Vol = 3.4 \times 10^{-4}\left(\frac{Q_m L}{V}\right)^{0.94} C_p \qquad (1)$$

where

Vol is volume of stock RWT 20-percent solution, in liters;
Q_m is the maximum expected stream discharge at the downstream site, in cubic feet per second;
L is the distance to the downstream site, in miles;
V is the estimated average stream velocity, in feet per second; and
C_p is the desired peak concentration at the downstream sampling site, in micrograms per liter.

The optimum distance for dye injection upstream from the first sample site location was calculated using the following formula (Kilpatrick and Wilson, 1989):

$$L_o = K\frac{VB^2}{E_z} \qquad (2)$$

where

L_o is length of channel required for optimum mixing, in feet;
K is a variable whose value depends on the location of injection and the
number of injections (dimensionless);
V is estimated average stream velocity, in feet per second;
B is average stream width, in feet; and
E_z is lateral mixing coefficient, in feet squared per second.

The dye was injected across the entire width of the stream by injecting it from a container while walking or boating across the stream (figs. 4, 5, and 6). The dye was injected far enough upstream from the beginning of the stream reach of interest to allow vertical and lateral dispersion of the dye to take place before the dye cloud reached the first sampling site (fig. 7).

Dye concentrations for each stream were measured at several different locations (sites) along the downstream reach. The sampling sites were located at appropriate intervals downstream, based on sampling site access and the availability of a streamflow gaging station. At each sampling site, the fluorescence (dye concentration) of the water was measured using a Self-Contained Underwater Fluorescence Apparatus (SCUFA) submersible fluorometer (Turner Designs, Inc., 2002) (fig. 8). The SCUFA measures the fluorescence of the water once per second and is capable of measuring RWT concentrations as low as 0.04 µg/L (Turner Designs, Inc., 2002). These readings were logged using a laptop computer and stored for later analysis of the data.

Figure 4. Injecting dye while wading across a stream (photograph by U.S. Geological Survey).

Figure 5. Injecting dye while boating across a stream (photograph by U.S. Geological Survey).

Figure 6. Injecting dye into a stream from a bridge (photograph by U.S. Geological Survey).

Figure 7. Lateral mixing of Rhodamine WT dye (photograph by U.S. Geological Survey).

Figure 8. Self-Contained Underwater Fluorescence Apparatus (SCUFA).

Statistical Methods

A statistical approach was taken to evaluate the national traveltime prediction equation and to develop a traveltime prediction equation for Arkansas streams. The national prediction equation was evaluated using the traveltime data collected during Lamb's (1983) traveltime study in Arkansas and during the present study. These data then were used to develop a regression equation to accurately predict specific traveltimes for Arkansas streams.

Evaluation of the National Traveltime Prediction Equation Using the Arkansas Data Set

A total of 939 data points were used to develop the USGS national traveltime prediction equation (Jobson, 1996). The national prediction equation developed by Jobson (1996) to estimate the velocity of the dye peak is:

$$V_p = 0.094 + 0.0143 \times (D'_a)^{0.919} \times (Q'_a)^{-0.469} \times S^{0.159} \times \frac{Q}{D_a} \quad (3)$$

where,

V_p is peak velocity, in meters per second;
D'_a is dimensionless drainage area coefficient;
Q'_a is dimensionless relative discharge;
S is slope, in meter per meter;
Q is discharge, in cubic meters per second; and
D_a is drainage area, in square meters.

The dimensionless drainage area is defined as:

$$D'_a = \frac{D_a^{1.25} \times \sqrt{g}}{Q_a} \quad (4)$$

where,

g is acceleration of gravity, in meters per second squared, and
Q_a is mean annual discharge, in cubic meters per second.

The dimensionless relative discharge is defined as:

$$Q'_a = \frac{Q}{Q_a} \quad (5)$$

The streams studied for the present (2003) study were required to have a USGS streamflow gaging station with at least 10 consecutive years of flow data recorded because mean annual discharge is required for use of the USGS national traveltime prediction equation. A drainage basin correction factor was used to calculate the mean annual discharge for a stream at a sampling site that did not have a streamflow gaging station. The drainage basin correction factor is a ratio that compares the drainage basin area of the sampling site that did not have a streamflow gaging station to the drainage area at a streamflow gaging station. This correction factor was multiplied by the mean annual discharge at the streamflow gaging station to obtain a mean annual discharge value for the sampling site that did not have a streamflow gaging station.

Drainage area and slope parameters needed in the predictive equations were calculated using 30-meter digital elevation model (DEM) and digital raster graph (DRG) data files. The software package Watershed Modeling System (WMS) (Brigham Young University, 1999) was used to calculate the drainage basin area at each sampling site location and the slope of the main channel of the stream. WMS is an integrated hydrologic modeling program that extracts key model input parameters from computerized maps. The slope was computed by subtracting the streambed elevation at the last sampling point on the stream reach from the streambed elevation at the point of the dye injection on the stream using the elevations obtained from the 30-meter DEM data. The change in elevation was divided by the length of the stream from the start of the dye trace to the last point sampled at the end of the dye trace obtained from DRG data files.

The relative percent difference between the velocity calculated using the national traveltime equations (Jobson, 1996) and the velocity calculated using the traveltime data from the Arkansas data set was calculated for each of the 33 sampling sites on the 18 streams. The relative percent difference was calculated in an effort to compare the differences between the stream velocity by the national equation and the actual stream velocity measured during the dye trace. To calculate the relative percent difference, the difference between the predicted velocity and the actual velocity was divided by the predicted velocity and multiplied by 100 (to obtain a percent value).

Development of the Arkansas Traveltime Prediction Equation

A multiple linear regression equation was developed to predict traveltime for streams in Arkansas using discharge and basin characteristics. The size of the data set limited the number of explanatory variables that could be used in the regression analysis. Variables in the Arkansas data set were checked against each other for correlation using the Spearman's rho test (Iman and Conover, 1983). To avoid autocorrelation, variables that were significantly correlated ($p < 0.05$) were not used together in the development of the regression equations.

A stepwise regression was used in selecting the most appropriate coefficients for the regression equation. A logarithmic transformation (log base 10) was used for the explanatory variables to minimize the standard error of estimate. The multiple linear regression equation used to predict traveltime in Arkansas streams is expressed in the following form:

$$\text{Log } Y = \beta_o + \beta_1 \times \log X_1 + \beta_2 \times \log X_2 \quad (6)$$

where,

Y is the estimated peak velocity, in feet per second (response variable);
$\beta_o, \beta_1, \beta_2$ are regression coefficients, and
X_1, X_2 are basin characteristics (stream slope, in foot per foot and drainage area, in square miles).

The standard error of estimates and the coefficient of determination (R^2) were computed for each regression. The standard error is a measure of the error about the regression. A smaller standard error indicates a more precise prediction. The R^2 is the proportion of the variation in the response variable explained by the explanatory variables (Draper and Smith, 1986). R^2 values range from 0 to 1 with values closer to 1 indicating a better fit of the data.

When equation 6 is retransformed, it becomes:

$$Y = \beta_o' \times X_1^{\beta 1} \times X_2^{\beta 2} \quad (7)$$

where,

β_o' is 10^{β}.

The retransformation of a log-transformed regression model systematically underestimates the mean response but provides a consistent estimator of median response (Miller, 1984). Therefore, a bias-correction factor (BCF) needs to be included in the retransformed regression equation if an unbiased estimate of the mean is to be obtained. A BCF was computed for the equation by using a smearing estimate that is a nonparametric method based on the average residuals in original units (Duan, 1983). After applying the BCF to equation 7, the form becomes:

$$Y = \beta_o' \times X_1^{\beta 1} \times X_2^{\beta 2} \times BCF \quad (8)$$

where,

β_o' is 10^{β}.

Evaluation of the National Traveltime Prediction Equation Using the Arkansas Data Set

The Arkansas data set provided in this report was used to evaluate the national traveltime prediction equation for use in Arkansas (Jobson, 1996). The national traveltime prediction equation yielded results that over-predicted the velocity of the streams for 29 of the 33 sample sites (table 2, fig. 9). The standard error for the national traveltime prediction equation was 105 percent and the R^2 value was 0.78 (fig. 9).

Development of the Arkansas Traveltime Prediction Equation

Three stream characteristics were used as explanatory variables in the development of the Arkansas traveltime prediction equation. These included the discharge (Q) of the section at the point of interest (downstream end of reach), drainage basin area (D_a) of the stream at the point of interest, and the stream reach slope (S) from the point of the dye injection to the point of interest. The range, mean, and median were determined for each of these variables for the 33 sites (table 3).

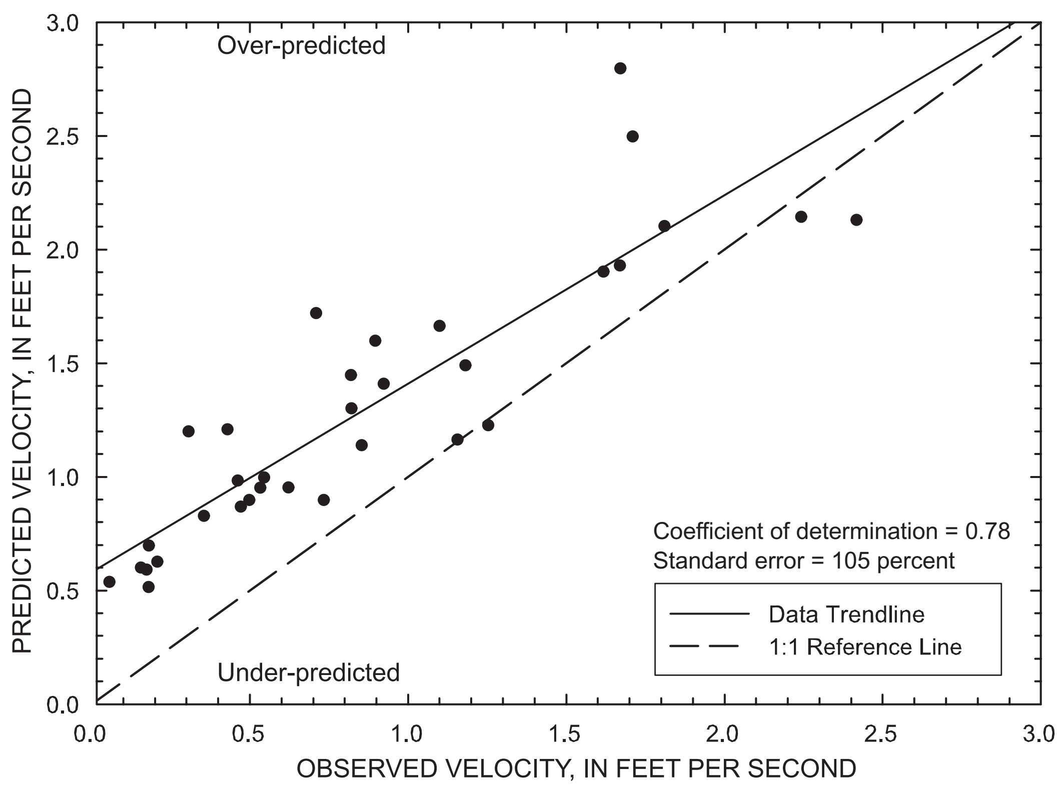


Figure 9. Relation between velocity predicted using the national traveltime prediction equation and observed velocity for Arkansas data set.

Table 2. Arkansas data used to evaluate the national traveltime prediction equation.

[Q, the discharge of the stream at the time the sample was taken; DA, the drainage area at each sample location; slope, the slope of the stream; V predicted, the predicted velocity using the national equation; V observed, the actual observed velocity of the stream during the present (2003) study and Lamb's (1983) study. Negative values for relative percent difference indicate over-prediction by the national traveltime prediction equation]

Sample site number	Total length of travel (miles)	Drainage area (square miles)	Discharge (cubic feet per second)	Mean annual discharge (cubic feet per second)	Time for leading edge to arrive (hours)	Time for peak concentration to arrive (hours)	Q/DA (cubic feet per second per square mile)	Slope (foot/foot)	V predicted (feet per second)	V observed (feet per second)	Relative percent difference (percent)
1	2.9	206	292	216	2.7	3.6	1.41	0.00087	1.49	1.18	-26.0
2	3.9	406	96	365	6.5	8.0	0.24	0.00106	0.90	0.73	-22.4
3	12.5	842	2,380	1,060	9.5	10.7	2.83	0.00093	2.50	1.71	-45.8
4	12.5	842	238	1,060	24.0	29.5	0.28	0.00093	0.95	0.62	-53.4
5	9.0	68	72	53	10.8	14.3	1.06	0.0032	1.41	0.92	-52.7
6	15.9	4,889	6,560	5,491	9.0	10.4	1.34	0.00021	2.14	2.24	4.4
7	15.9	4,889	1,780	5,491	16.6	18.6	0.36	0.00021	1.23	1.25	2.2
8	8.9	1,135	1,830	1,144	4.8	5.4	1.61	0.00066	2.13	2.42	11.9
9	4.4	204	69	194	8.8	12.1	0.34	0.00179	0.95	0.53	-78.6
10	5.2	130	55	124	12.6	16.5	0.42	0.00219	0.98	0.46	-112.8
11	8.4	204	83	194	17.8	22.6	0.41	0.00148	1.00	0.55	-83.0
12	4.1	35	50	34	17.4	19.6	1.42	0.00146	1.20	0.31	-291.1
13	6.9	509	92	482	19.1	28.5	0.18	0.000991	0.83	0.36	-133.3
14	4.0	254	10.6	241	26.3	32.6	0.04	0.00107	0.51	0.18	-185.9
15	2.6	79	6	75	46.8	67.8	0.08	0.00153	0.54	0.06	-856.0
16	8.2	511	240	484	5.4	10.4	0.47	0.000936	1.16	1.16	0.0
17	5.0	263	23.4	249	33.1	47.2	0.09	0.000742	0.60	0.16	-287.0
18	8.5	420	237	540	20.9	29.0	0.56	0.0022	1.21	0.43	-181.3
19	14.1	374	493	554	19.4	22.9	1.32	0.00219	1.60	0.90	-78.3

Table 2. Arkansas data used to evaluate the national traveltime prediction equation.—Continued

[Q, the discharge of the stream at the time the sample was taken; DA, the drainage area at each sample location; slope, the slope of the stream; V predicted, the predicted velocity using the national equation; V observed, the actual observed velocity of the stream during the present (2003) study and Lamb's (1983) study. Negative values for relative percent difference indicate over-prediction by the national traveltime prediction equation]

Sample site number	Total length of travel (miles)	Drainage area (square miles)	Discharge (cubic feet per second)	Mean annual discharge (cubic feet per second)	Time for leading edge to arrive (hours)	Time for peak concentration to arrive (hours)	Q/DA (cubic feet per second per square mile)	Slope (foot/foot)	V predicted (feet per second)	V observed (feet per second)	Relative percent difference (percent)
20	9.0	61	376	71	6.4	7.9	6.14	0.00535	2.80	1.67	-67.3
21	9.0	282	774	420	6.2	7.9	2.74	0.00121	1.93	1.67	-13.0
22	7.4	242	680	360	5.3	6.0	2.81	0.00264	2.10	1.81	-19.5
23	16.4	282	46	420	103	133	0.16	0.00187	0.70	0.18	-285.2
24	10.9	284	549	288	12.8	14.4	1.93	0.00042	1.66	1.10	-51.2
25	6.0	46	120	62	9.8	12.4	2.61	0.00626	1.72	0.71	-142.3
26	12.8	142	252	310	18.1	22.9	1.78	0.0045	1.45	0.82	-76.5
27	9.6	414	1,170	731	6.7	8.7	2.83	0.00092	1.90	1.62	-17.6
28	9.6	414	343	731	11.0	16.5	0.83	0.00092	1.14	0.85	-33.6
29	12.0	292	136	611	31.7	37.3	0.47	0.0014	0.87	0.47	-84.0
30	15.8	201	110	420	40.1	46.5	0.55	0.00195	0.90	0.50	-80.2
31	12.0	292	37.6	611	81.2	101	0.13	0.0014	0.59	0.17	-239.3
32	23.0	251	39.5	525	132	162	0.16	0.00188	0.63	0.21	-201.0
33	0.7	12	27.5	22	0.9	1.25	2.33	0.017	1.30	0.82	-58.3

Table 3. Ranges, means, and medians of explanatory variable values used to develop the Arkansas traveltime prediction equation.

Explanatory variable	Minimum	Maximum	Mean	Median
Reach length, in miles	0.7	23.0	9.3	9.0
Drainage area, in square miles	11.8	4,889	590	282
Discharge, in cubic feet per second	6	6,560	579	136
Discharge/drainage area	0.04	6.14	1.2	0.55
Slope, in foot per foot	0.00021	0.01700	0.00219	0.001400

Using the variables discharge, drainage area, and slope in a regression analysis, the most accurate prediction equation derived for the peak velocity in feet per second was:

$$V_p = 0.0731 \times \left(\frac{Q}{D_a}\right)^{0.664} \times S^{-0.377} \times 1.074 \qquad (9)$$

where,

V_p is velocity, in feet per second,
Q is discharge at point of interest, in cubic feet per second;
D_a is drainage area at point of interest, in square miles; and
S is slope from the point of injection to the point of interest, in foot per foot.

This prediction equation does not appear to overpredict the stream velocity as did the national equation. This prediction equation, developed from a regression analysis of the dye-tracing results, was a significant improvement over the national prediction equation. The standard error for the Arkansas traveltime prediction equation was calculated to be 46 percent and the R^2 value was calculated to be 0.74. The data collected during above average and base-flow conditions does not indicate a substantial variation from the trendline (fig. 10). The predicted velocities using this equation fit better than the national equation when plotted in relation to actual velocities (fig. 10) for all of the data analyzed for this study.

Traveltime of Peak Concentration

The theoretical traveltime (T_p) for streams in Arkansas can be derived from results from equation 9. This can be found by multiplying the velocity, calculated from equation 9, by the distance (in feet) between the spill site and the point of interest (downstream end of reach). This will be the theoretical time that it will take for the arrival of the peak concentration to the point of interest.

The theoretical traveltime assumes a conservative constituent that is dissolved in water. Theoretical traveltimes are not meant to represent traveltimes of non-conservative contaminants that are not dissolved in water. The accuracy of the traveltime estimated using equation 9 can be affected by differences in stream characteristics and discharge along the reach being evaluated.

Traveltime of Leading Edge

In addition to knowing when the peak concentration will arrive at a site, it is of great interest to know when the first concentration of the dye will arrive. The traveltime of the leading edge of the contaminant peak indicates when a local problem might first exist and defines the overall shape of the concentration response function.

A good correlation between traveltime of the leading edge and traveltime of the peak concentration based on dye-tracing results was found with an R^2 value of 0.99 (fig. 11). These data indicate that the traveltime of the leading edge can be estimated from:

$$T_l = 0.79 \times T_p \qquad (10)$$

where,

T_l is traveltime of leading edge, in hours, and
T_p is traveltime of peak concentration, in hours.

Example Application

An example application is presented assuming a slug injection of a potential contaminant in a stream. This example assumes that few hydrologic data are available. In this example, a tanker truck driving on Arkansas State Highway 10 runs off of the road and instantaneously spills a contaminant into the Maumelle River near Perryville, Arkansas. An estimate is needed for the most probable time that it will take for the contaminant to reach Lake Maumelle.

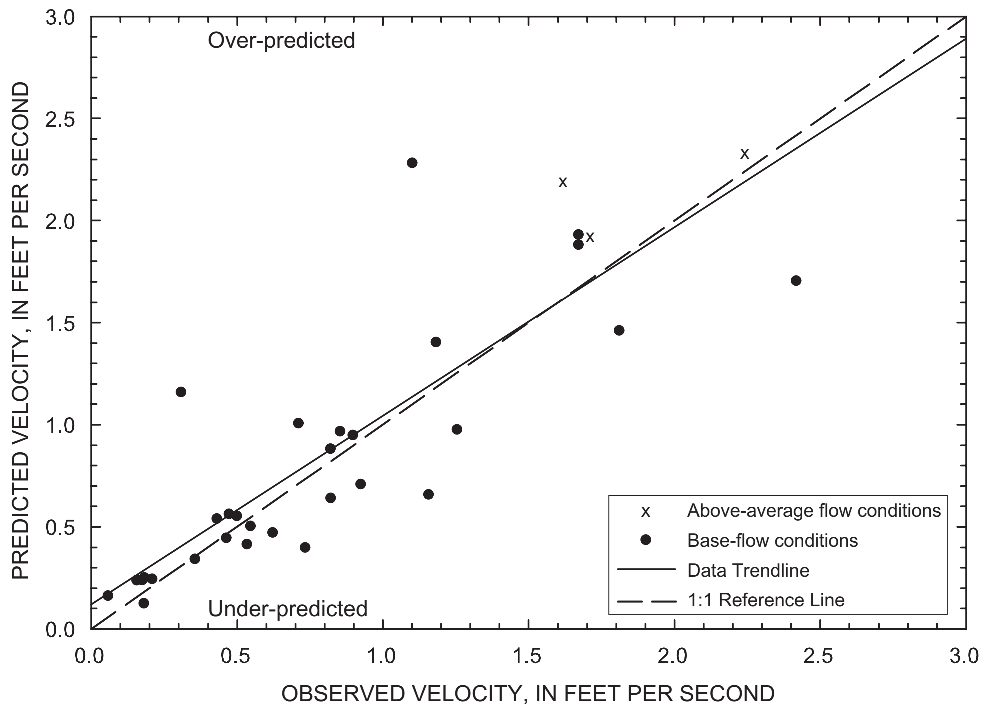


Figure 10. Relation between velocity predicted using the Arkansas traveltime prediction equation and observed velocity for Arkansas data set.

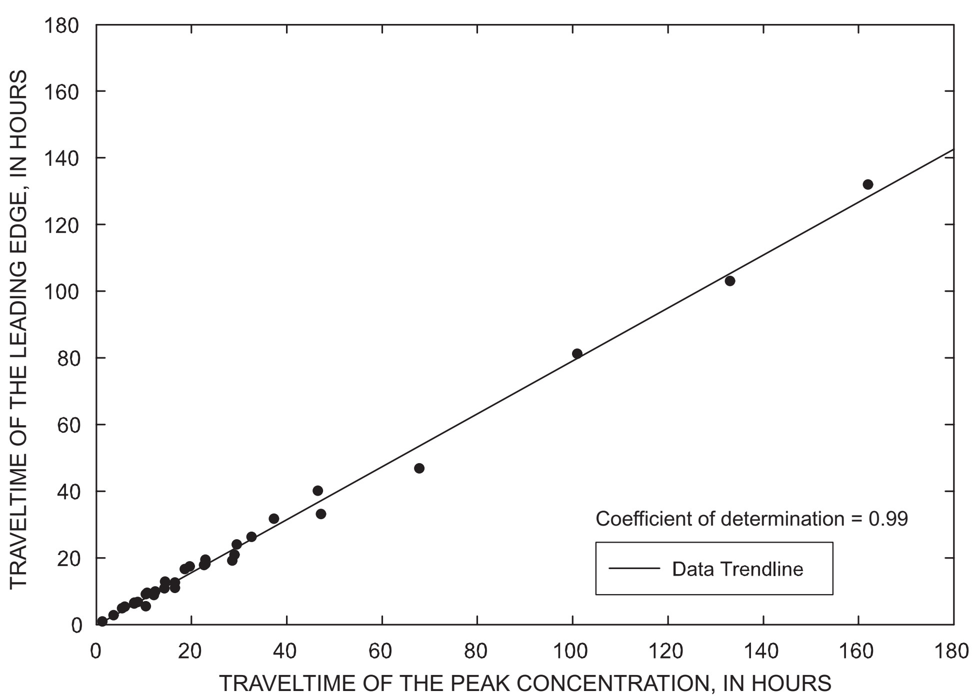


Figure 11. Relation between traveltimes of leading edge and peak of dye cloud for the Arkansas data set.

The first step is to obtain (or estimate) the discharge that is flowing at the point of interest at the time of the spill. In this example, the water plant manager for Central Arkansas Water estimates the discharge flowing in the Maumelle River to be about 100 ft^3/s.

The second, third, and fourth steps are to: (2) compute the drainage area at the point of interest (at the confluence with Lake Maumelle), (3) calculate the slope of the stream (between the point of the spill and the point of interest), and (4) calculate the length of the stream reach (between the point of the spill and the point of interest). Steps 2, 3, and 4 can be computed manually using topographic maps or on an automated basis using geographic information systems (GIS) software. For this example problem, assume the following:

Discharge (Q) is 100 ft^3/s,

Drainage area (DA) is 89.4 mi^2,

Slope (S) is 0.00390 ft/ft, and

Length (L) is 79,700 ft.

Applying equation 9:

$$V_p = 0.0731 \times \left(\frac{100}{89.4}\right)^{0.664} \times 0.00390^{-0.377} \times 1.074 = 0.684 \text{ ft/s}$$

The most probable traveltime of the peak to the point of interest is:

$$T_p = 0.684 \text{ ft/s} \times 79{,}700 \text{ ft x } \frac{1hr}{3{,}600s} = 15.1 \text{ hrs}$$

The most probable traveltime of the leading edge of the contaminant plume to the point of interest is:

$$T_l = 0.79 \times 15.1 \text{ hrs} = 11.9 \text{ hrs.}$$

Summary

The 1996 Amendments to the Safe Drinking-Water Act require that each state prepare a source-water assessment for all public water supplies. States are required to determine the sources of drinking water, the origin of contaminants monitored or the identification of the potential contaminants to be monitored, and the intrinsic susceptibility of the water supplies to these contaminants. Fluorescent dyes can be used to measure a stream's velocity and gain a better understanding of the potential rate of movement of contaminants.

During 1971 and 1981 and 2001 and 2003, traveltime measurements were made on 18 streams throughout northern and western Arkansas using fluorescent dye. Most of the measurements were made during steady-state base-flow conditions with the exception of three measurements that were made during near steady-state medium-flow conditions (for this study, medium-flow is approximately 100-150 percent of the mean monthly streamflow during the month the dye trace was conducted). These data were compared to the USGS national traveltime prediction equation and used to develop a specific traveltime prediction equation for Arkansas streams.

In general, the national traveltime prediction equation yielded results that over-predicted the velocity of the streams for 29 of the 33 sample events measured. The standard error for the national traveltime prediction equation was calculated to be 105 percent. The coefficient of determination was calculated to be 0.78.

The Arkansas prediction equation developed from a regression analysis of dye-tracing results was a significant improvement over the national prediction equation. This regression analysis yielded a standard error of 46 percent and a coefficient of determination of 0.74. The predicted velocities using this equation fit better when plotted against measured velocities.

Using the variables in a regression analysis, the most accurate Arkansas prediction derived for the peak velocity in feet per second was:

$$V_p = 0.0731 \times \left(\frac{Q}{D_a}\right)^{0.664} \times S^{-0.377} \times 1.074$$

where,

Q is discharge at point of interest, in cubic feet per second;

D_a is drainage area at point of interest, in square miles; and

S is slope from point of injection of point of interest, in foot per foot.

In addition to knowing when the peak concentration will arrive at a site, it is of great interest to know when the leading edge of a contaminant plume will arrive. The traveltime of the leading edge of the contaminant plume indicates when a potential problem might first develop and also defines the overall shape of the concentration response function.

A good correlation between traveltime of the leading edge and traveltime of the peak concentration was found, with an R^2 value of 0.99. These data indicate that the traveltime of the leading edge can be estimated from:

$$T_l = 0.79 \times T_p$$

where,

T_l is traveltime of leading edge, in hours, and

T_p is traveltime of peak concentration, in hours.

References

Arkansas Department of Health, 2002, Frequently asked questions: accessed on May 10, 2004, at URL http://www.healthyarkansas.com/eng/swp/swp.htm

Boning, C.W., 1974, Generalization of stream travel rates and dispersion characteristics from time of travel measurements: U.S. Geological Survey Journal of Research, v.2, no 4, p. 495-499.

Brigham Young University - Environmental Modeling Research Laboratory, 1999, WMS Watershed modeling system - Reference manual - Version 6.0: 250 p.

Draper, N.R., Smith, H., 1986, Applied Regression Analysis, Second Edition, p. 200 - 215.

Duan, Naihua, 1983, Smearing estimate: a nonparametric retransformation method: Journal of the American Statistical Association, v. 78, no 83, p. 605 - 610.

Gurdak, J.J., Spahr, N.E., and Szmajter, R.J., 2002, Traveltime characteristics of Gore Creek and Black Gore Creek, upper Colorado River Basin, Colorado: U.S. Geological Survey Water-Resources Investigations Report 02-4037, 14 p.

Hubbard, E.F., Kilpatrick, F.A., Martens, L.A., and Wilson, J.F., Jr., 1982, Measurement of time of travel and dispersion in streams by dye tracing: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A9, 44 p.

Iman, R.L., and Conover, W.J., 1983, A Modern Approach to Statistics, p. 126.

Jobson, Harvey E., 1996, Prediction of traveltime and longitudinal dispersion in rivers and streams, U.S. Geological Survey Water-Resources Investigations Report 96-4013, 14 p.

Kilpatrick, F.A., 1993, Simulation of soluble waste transport and buildup in surface waters using tracers: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, Chap. A20, 37 p.

Kilpatrick, F.A., and Wilson, J.F., 1989, Measurement of time of travel in streams by dye tracing, U.S. Geological Survey: Techniques of Water-Resources Investigations, book 3, chap. A9, 27 p.

Lamb, T.E., 1983, Time of travel of selected Arkansas streams, U.S. Geological Survey Water-Sources Investigations Report 82-4048, 59 p.

Miller, D.M., 1984, Reducing transformation bias in curve fitting: The American Statistician, v. 38, no. 2, p. 124 - 126.

Nordin, C.F., and Sabol, G.V., 1974, Empirical data on longitudinal dispersion in rivers: U.S. Geological Survey Water-Resources Investigations Report 20-74, 332 p.

Rantz, S.E., and others, 1982, Measurement and computation of streamflow - Volume 1, Measurement of stage and discharge: U.S. Geological Survey Water-Supply Paper 2175, chap. 5, p. 79-183.

Turner Designs, Inc. 2002, SCUFA fluorometer fact sheet: accessed on August 15, 2003, at URL http://www.turnerdesigns.com/t2/instruments/scufa.html

Wilson, J.F., Jr., 1968, Fluorometric procedures for dye tracing: U.S. Geological Survey, Techniques of Water-Resources Investigations, book 3, chap A12, 31 p.

Wilson, J.F., Jr., Cobb, E.D., and Kilpatrick, F.A., 1986, Fluorometric procedures for dye tracing: U.S. Geological Survey, Techniques of Water-Resources Investigations, book 3, chap A12, 34 p.

Funkhouser, J.E., and Barks, C.S.—DEVELOPMENT OF A TRAVELTIME PREDICTION EQUATION FOR STREAMS IN ARKANSAS—U.S. Geological Survey Scientific Investigations Report 2004-5064

125 years of science for America 1879–2004

Printed on recycled paper