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Prediction of Velocities for a Range of Streamflow Conditions in Pennsylvania

by Lloyd A. Reed and Marla H. Stuckey

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TABLE

CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
	Length	
mile (mi)	1.609	kilometer
	Area	
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer
	Flow	
foot per second (ft/s)	0.3048	meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

Other abbreviations:

m/s meter per second

PREDICTION OF VELOCITIES FOR A RANGE OF STREAMFLOW CONDITIONS IN PENNSYLVANIA

by Lloyd A. Reed and Marla H. Stuckey

ABSTRACT

A regression equation that is used nationwide to predict traveltime in streams during periods of low and moderate flow was developed by H.E. Jobson in 1996. Because none of the data used in the development of the equation were from streams in Pennsylvania, velocities for low and moderate flows predicted by the equation were compared to velocities measured during time-of-travel studies on the Susquehanna, Delaware, and Lehigh Rivers. Although these comparisons showed good agreement, a similar comparison using velocities for higher flows indicated an overestimate by this regression equation. Because of the need for a method of computing traveltimes for periods of high flows, a new regression equation was developed using data from three sources: (1) time-of-travel studies conducted at low and moderate flow, (2) slope-area measurements of flood flows, and (3) velocities of the 100-year floodway as reported in various flood-insurance studies.

The new regression equation can be used for predicting velocities associated with flows up to the 100-year flood for Pennsylvania streams. It has standard errors of estimate of 0.18 feet per second, 0.37 feet per second; and 0.31 feet per second, for time-of-travel studies in the Susquehanna, Delaware, and Lehigh Rivers, respectively. The standard error of estimate is 1.71 feet per second for velocities determined from the slope-area measurements and 1.22 feet per second for velocities determined from the flood-insurance studies.

INTRODUCTION

Under Federal guidelines, Pennsylvania is required to complete surface-water assessments for all public-water systems for potential spill contamination. The U.S. Geological Survey (USGS) in cooperation with the Pennsylvania Department of Environmental Protection (PaDEP) delineated the boundaries for the 5- and 25-hour traveltimes of public surface-water-supply intakes on Pennsylvania streams. The traveltimes of 5 and 25 hours were predetermined by the State to be zones of critical concern and high concern, respectively. These delineated boundaries are based on stream velocities during periods of high flow and will aid state and municipal officials in the event of contamination of a water supply upstream from the intake.[1] As part of this surface-water assessment, a method of determining mean stream velocity over a range of streamflow conditions was required.

Regression equations were developed by Jobson (1996) to predict traveltime and dispersion in streams and rivers in the United States. Jobson's time-of travel of peak concentration equation was based on data from about 90 different streams and more than 980 subreaches nationwide during periods of low to moderate flow. Data from Pennsylvania streams were not used in the development of these equations.

[1] The 5- and 25-hour traveltime delineations were developed using an unpublished version of the equation presented in this report prior to the inclusion of the Lehigh River time-of-travel study.

Purpose and Scope

This report presents an evaluation of the applicability of the Jobson velocity equation (Jobson, 1996) for predicting velocities of streams during a range of low to high flow conditions commonly experienced in Pennsylvania. Data were used from three time-of-travel studies (Kauffman and others, 1976; White and Kratzer, 1994; Kauffman, 1982), 57 slope-area measurements of high flow made by the USGS from about 1965 through 1999, and over 50 flood-insurance studies published between 1978 and 1999. A new regression equation is presented for predicting velocities of the flow in Pennsylvania streams during a range of low to high flow conditions.

Previous Investigations

A time-of-travel study was conducted on the Susquehanna River during periods of low flow during 1965-67 by Kauffman and others (1976) (fig. 1). Time-of-travel studies also were conducted on the upper Delaware River during periods of low and median flow in 1991 (White and Kratzer, 1994) and on the Lehigh River during periods of low and median flow during 1970-77 (Kauffman, 1982) (fig. 1). Velocity data from slope-area measurements in stream reaches near stream-gaging stations have been collected after periods of high water by USGS from about 1965-99. Velocity data were provided in flood-insurance studies (Federal Emergency Management Agency, 1978-99) conducted for stream reaches near stream-gaging stations in Pennsylvania. Jobson (1996, 1997) developed equations to predict traveltime of low and moderate flows in streams in the United States. None of the above data sources were used in the development of Jobson's equations.

Prediction of Stream Velocities with the Jobson Equation

Regression equations were developed by Jobson (1996) to predict traveltime and dispersion of a soluble, conservative constituent in streams and rivers nationwide for low to moderate flow. Data from approximately 90 different rivers and streams were used to develop the equations and a total of 986 data points were used. The equations were based on drainage area, the reach slope, the mean annual discharge, and the discharge at the time of the measurement (Jobson, 1996). The velocities used in the development of the equation for velocity of peak concentration ranged from 0.01 m/s (0.03 ft/s) to 1.51 m/s (4.95 ft/s) with more than 90 percent of the velocities less than 2.0 ft/s (Jobson, 1996).

The equation recommended by Jobson (1996) for predicting traveltime of the peak concentration of a conservative constituent, modified for English units, is

$$V(p)=0.0656\;\;0.051\,(Da')^{0.821}\times(Qa')^{-0.465}\times Q/Da, \qquad (1)$$

where

$V(p)$ is mean stream velocity of peak concentration of a slug of a dissolved constituent, in feet per second.

The factor 0.0656 has units of feet per second; and

$$Da' = (Da^{1.25}\times g^{0.5})/Qa, \qquad (2)$$

where

Da is drainage area, in square feet;
g is acceleration of gravity, in feet per second squared; and
Qa is mean annual streamflow, in cubic feet per second; and

$$Qa' = Q/Qa, \qquad (3)$$

where

Q is streamflow at the time of interest, in cubic feet per second; and
Qa is mean annual streamflow, in cubic feet per second.

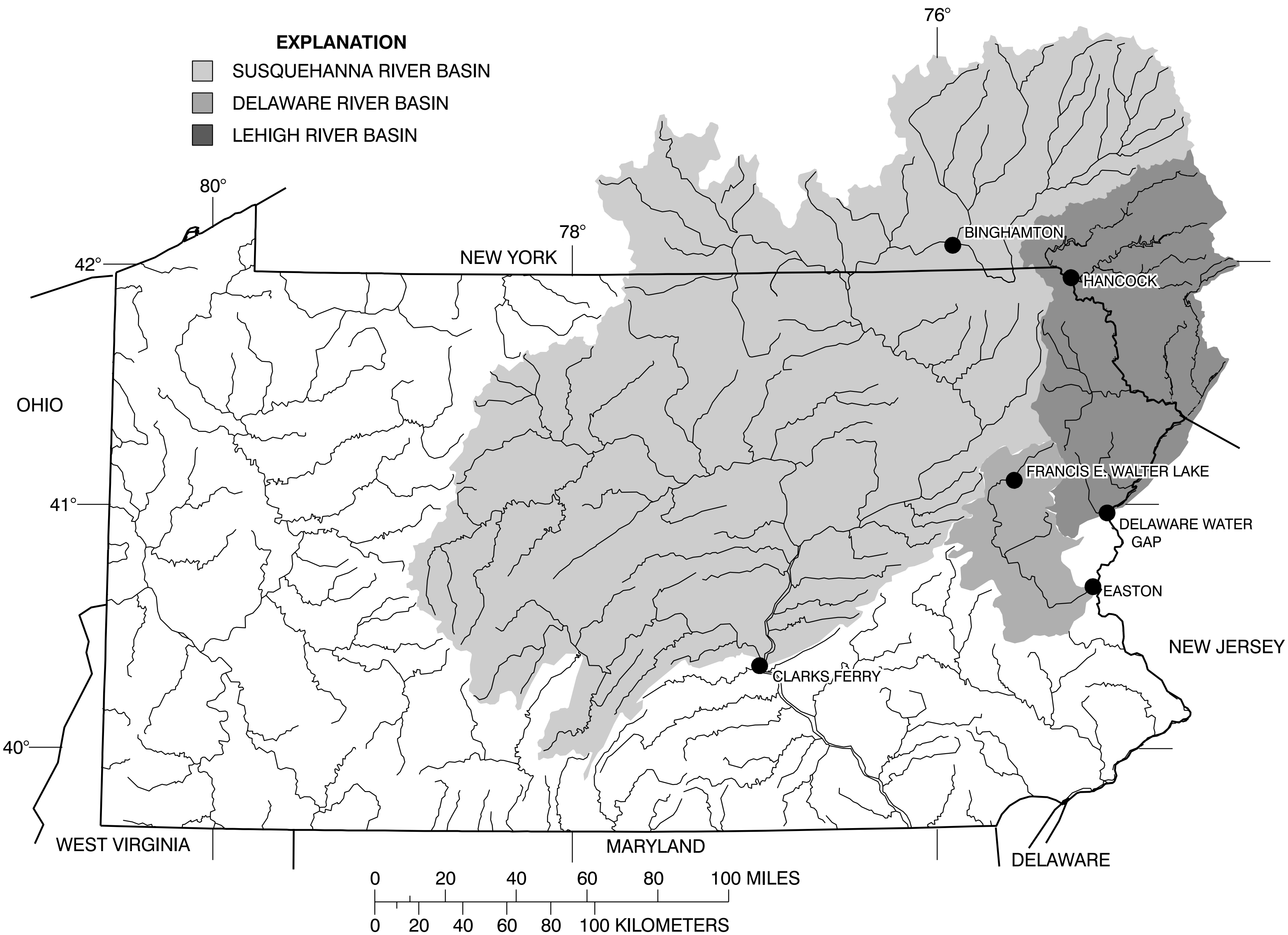

Figure 1. Location of time-of-travel studies conducted in parts of the Susquehanna, Delaware, and Lehigh River Basins, Pennsylvania.

As an example, the velocity of the maximum concentration of a dye cloud for a time-of-travel study on the Susquehanna River between Shickshinny and Danville was 1.16 ft/s. The drainage area of the river at Shickshinny is about 10,600 mi^2 (2.955×10^{11} ft^2), and the mean annual streamflow for the period of record at Shickshinny, on the basis of data from the stream-gaging station at Danville, is about 14,360 ft^3/s. At the time of the study, the streamflow was 3,610 ft^3/s.

Substituting into equation (1);

$$V(p) = 0.0656\ ft/s\ \ (0.051)\ \{[(2.955\times10^{11}\ ft^2)^{1.25}] \times ((32.2\ ft/s^2)^{0.5})/(14{,}360\ ft^3/s)\}^{0.821}$$

$$\times \{[(3{,}610\ ft^3/s)/(14{,}360\ ft^3/s)]^{-0.465}\} \times ((3{,}610\ ft^3/s)/(2.955\times10^{11}\ ft^2)$$

$$V(p) = 0.0656\ ft/s\ \ (0.051)\ (9.4978\times10^8)(1.90036)(1.2216\times10^{-8}\ ft/s)$$

$$V(p) = 0.0656\ ft/s\ \ 1.124\ ft/s$$

$$V(p) = 1.19\ ft/s$$

Note the velocity calculated by use of Jobson's equation, 1.19 ft/s, is within 3 percent of the measured velocity of 1.16 ft/s.

COMPARISON OF STREAM VELOCITIES COMPUTED USING THE JOBSON EQUATION WITH VELOCITIES DETERMINED FROM OTHER SOURCES

To evaluate the applicability of Jobson's equation for predicting velocities for a range of low to high flows in streams in Pennsylvania, velocities computed by use of the Jobson equation were compared to velocities determined during time-of-travel studies, and to velocities determined from indirect methods used in slope-area measurements, and to velocities determined in flood-insurance studies.

Time-of-Travel Studies

Time-of-travel studies are conducted by adding a traceable constituent to a river and determining the time required for the tracer to arrive at and pass selected downstream points in a study reach. This information is crucial in the event of a contaminant spill. The velocities determined from time-of-travel studies are dependent on the discharge and the hydraulic characteristics of a river. Collecting time-of-travel data at two (or more) different discharges can define a relation through the study reach that integrates the combination of discharge and hydraulics. For example, velocity usually increases and traveltime decreases as the discharge increases. If a selected reach of a river has a deep pool, the velocity may be slower and the traveltime may be longer than those determined from a reach with uniform depths. Time-of-travel studies in Pennsylvania have been limited to the Susquehanna, Delaware, and Lehigh Rivers. These studies are discussed below and the study areas are shown on figure 1.

Susquehanna River

Time-of-travel studies were conducted on the Susquehanna River at low or moderately low flow at six times during 1965-67 (Kauffman and others, 1976). Flows during the studies ranged from 67- to 98-percent exceedence probability, which is the percentage of time flows are equalled or exceeded based on the gaged period of record. The river between Binghamton, N.Y., and Clarks Ferry, Pa. (fig. 1), was divided into 17 reaches. Velocities obtained for the reaches by the time-of-travel studies are compared to velocities predicted by the Jobson equation for corresponding flows in figure 2. Velocities from the time-of-travel studies ranged from 0.22 ft/s to 1.86 ft/s. Although the Jobson equation tended to overestimate at low velocities, the velocities predicted by the Jobson equation generally are in good agreement with those measured during

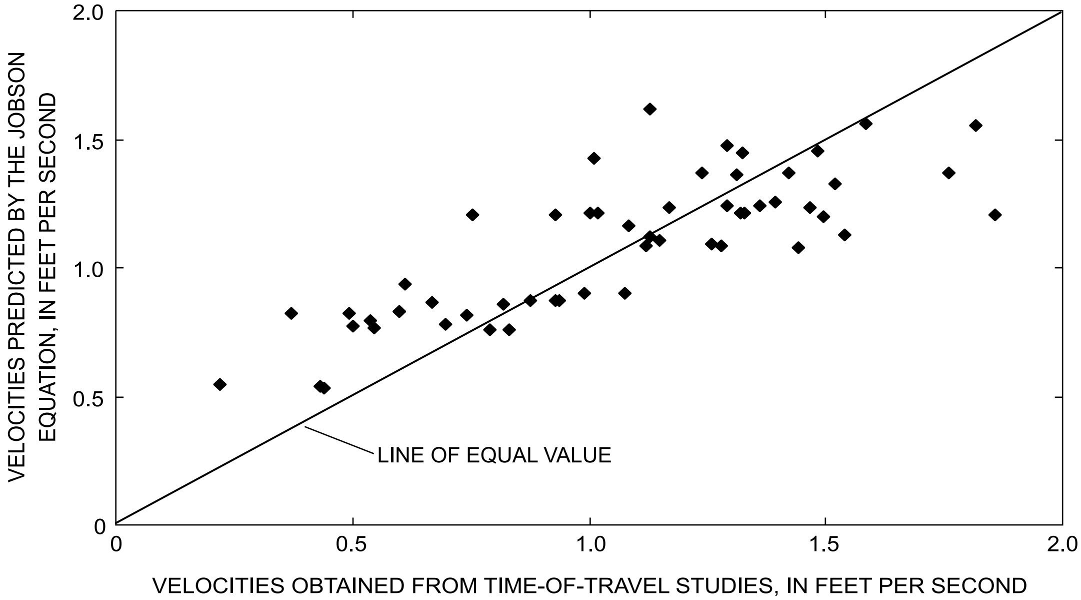

Figure 2. Comparison of velocities from time-of travel studies (Kauffman and others, 1976) and those predicted by the Jobson equation (Jobson, 1996) for reaches of the Susquehanna River from Binghamton, N.Y., to Clarks Ferry, Pa.

the time-of-travel studies (fig. 2). The mean and standard deviation of the measured velocities were 1.05 and 0.40 ft/s, respectively, and the mean and standard deviation of the velocities predicted by the Jobson equation were 1.08 and 0.27 ft/s, respectively. The standard error of the differences in velocities predicted by the Jobson equation and the time-of-travel studies on the Susquehanna River was 0.24 ft/s.

Delaware River

Time-of-travel studies were conducted on the Delaware River from Hancock, N.Y., to Delaware Water Gap, Pa. (fig. 1), in May and August of 1991 (White and Kratzer, 1994). The May study was conducted when river flows ranged from 25- to 30-percent exceedence probability, and the August study was conducted when river flows ranged from 85- to 95-percent exceedence probability. The flows from the May study were higher than flows measured during the Susquehanna River studies. The river was divided into 15 reaches. Velocities determined during the time-of-travel studies for 14 of the reaches are compared to velocities predicted by the Jobson equation (fig. 3). The Jobson equation was not used to predict velocities for the reach near Narrowsburg known as the Narrowsburg pool and eddy because depths in the Narrowsburg pool exceed 110 ft and traveltime in the pool, which is about 0.5 mi long, is not representative of the rest of the river. Velocities measured during the May study ranged from 1.76 to about 2.71 ft/s, and velocities measured during the August study ranged from 0.64 to about 1.18 ft/s. The mean and standard deviation of the measured velocities were 1.59 and 0.71 ft/s, respectively, and the mean and standard deviation of the velocities predicted by the Jobson equation were 1.47 and 0.62 ft/s, respectively. The standard error of the differences in velocities predicted by the Jobson equation from the time-of-travel studies on the Delaware River was 0.31 ft/s.

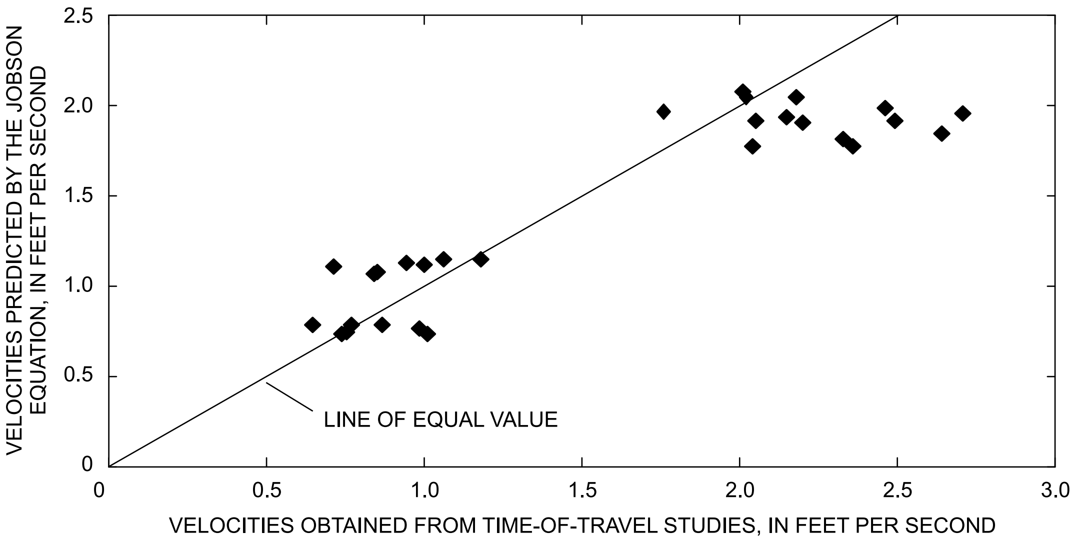

Figure 3. Comparison of velocities from time-of-travel studies and those predicted by the Jobson equation (Jobson, 1996) for reaches of the Delaware River from Hancock, N.Y., to Delaware Water Gap, Pa.

Lehigh River

Time-of-travel studies were conducted on the Lehigh River from the outlet of Francis E. Walter Lake to Easton (fig. 1) four times during 1970 to 1977 (Kauffman, 1982). The streamflows on the Lehigh River were at 42-percent exceedence probability during the 1970 study, 80 percent during the 1973 study, 67 percent during the 1974 study, and 92 percent during the 1977 study. Velocities determined from the time-of-travel studies on the Lehigh River are compared in figure 4 to velocities predicted by Jobson's equation. Velocities from the time-of-travel studies ranged from 0.37 ft/s to 1.88 ft/s. The mean and standard deviation of the measured velocities were 0.89 and 0.48 ft/s, respectively, and the mean and standard deviation of velocities predicted by the Jobson's equation are 0.93 and 0.37 ft/s, respectively. The standard error of the difference in velocities predicted by Jobson's equation to the measured velocities on the Lehigh River was 0.30 ft/s.

Slope-Area Measurements

Slope-area measurements made in the vicinity of stream-gaging stations in the Delaware and Susquehanna River Basins were reviewed and the mean velocity, streamflow, drainage area, and number of cross-sections were tabulated. A comparison between velocities computed from the slope-area measurements and velocities computed by use of the Jobson equation for the 57 slope-area measurements is shown in figure 5. Many of the slope-area measurements had mean velocities that exceeded the maximum velocity used in the development of the Jobson equation but were included in the comparison to evaluate Jobson's equation at higher flows. Velocities from the slope-area measurements ranged from 2.43 to 14.4 ft/s. Velocities predicted by the Jobson equation averaged about 40 percent higher than those determined by the slope-area measurements. The mean and standard deviation of the velocities determined by the slope-area measurements were 6.67 and 2.26 ft/s, respectively. The mean and standard deviation of the velocities computed by use of the Jobson equation were 9.70 and 4.05 ft/s, respectively. The standard error of the velocities computed by use of the Jobson equation relative to mean velocities from the slope-area measurements was 4.10 ft/s.

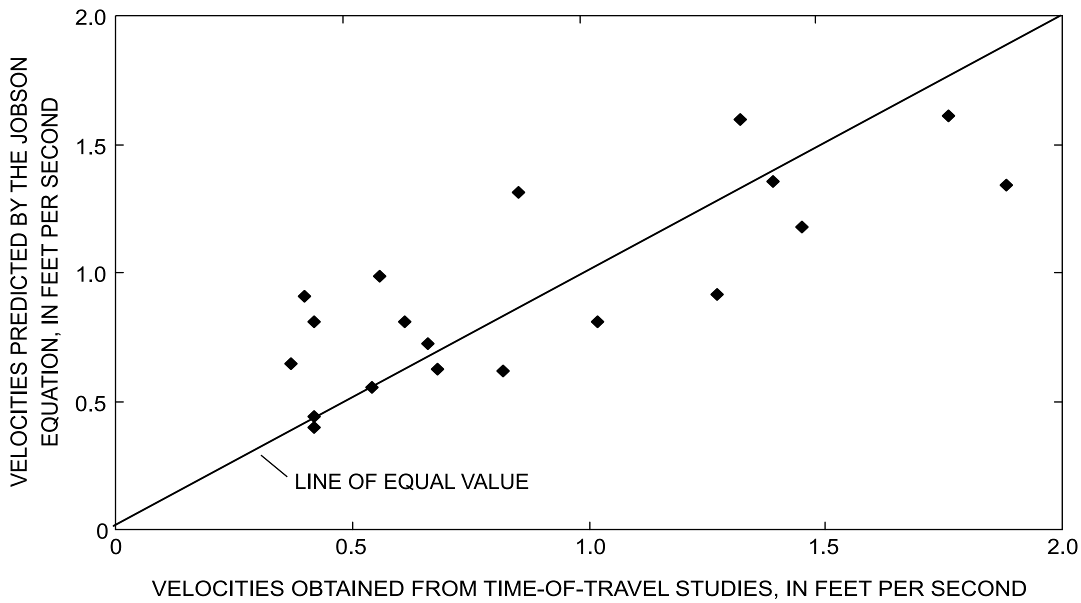

Figure 4. Comparison of velocities from time-of-travel studies and those predicted by the Jobson equation (Jobson, 1996) for reaches of the Lehigh River from Francis E. Walter Lake to Easton, Pa.

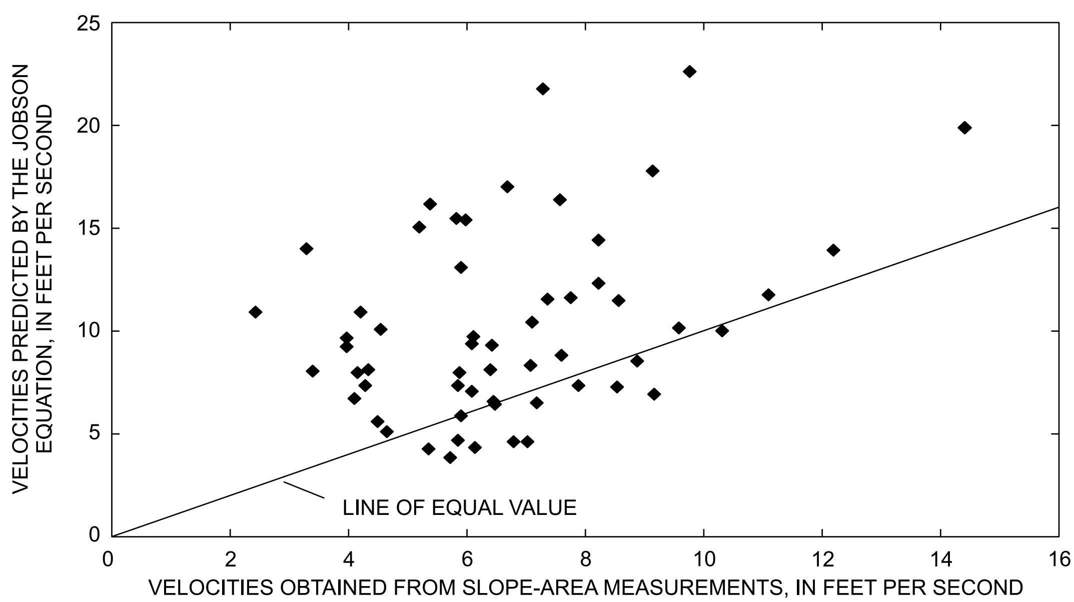

Figure 5. Comparison of velocities from slope-area measurements and those predicted by the Jobson equation (Jobson, 1996) for sites in the vicinity of stream-gaging stations in Pennsylvania.

Current-meter measurements, contracted-opening measurements, and flow-over-dam measurements were not used in the evaluation. Velocities obtained from current-meter measurements of streamflow were not used because many of these measurements have been made by wading at or near riffles where the flow is confined and velocities are higher than the mean velocity in a reach of the stream or river. Current-meter measurements of streamflow can also be made by suspending a meter from a bridge. Because many bridges were built at a natural narrow point or the bridge itself provides some constriction to flow, velocities from these measurements also are higher than the mean velocity of a nearby reach of the stream or river and therefore were not used. Because velocities obtained from contracted-opening and flow-over-dam measurements do not represent mean velocities in long stream reaches, they were not used.

Flood-Insurance Studies

The floodway data tables published in many flood-insurance studies (Federal Emergency Management Agency, 1978-99) list stream velocities at each of the cross sections used in the computation of floodways for a 100-year flood. Mean velocities published in the floodway data tables represent the mean velocity for that part of the channel and flood plain that is conveying most of the flood water. Cross sections with over-bank areas of relatively low velocity water that can be blocked by fill material and not produce significant increases in stage during the 100-year flood generally are not used in the calculation of the mean velocities reported in the floodway data tables. Velocities from flood-insurance studies ranged from 0.84 to 12.4 ft/s. The velocities computed by use of the Jobson equation averaged about 40 to 50 percent greater than those published in the floodway data tables for reaches above and below stream-gaging stations (fig. 6). The data shown on figure 6 include every stream in Pennsylvania with a stream-gaging station for which one or more floodway data tables were available. A total of 191 stream reaches were evaluated. The mean and standard deviation of the velocities from the floodway data tables were 6.59 and 2.17 ft/s, respectively, very close to the mean and standard deviation of the

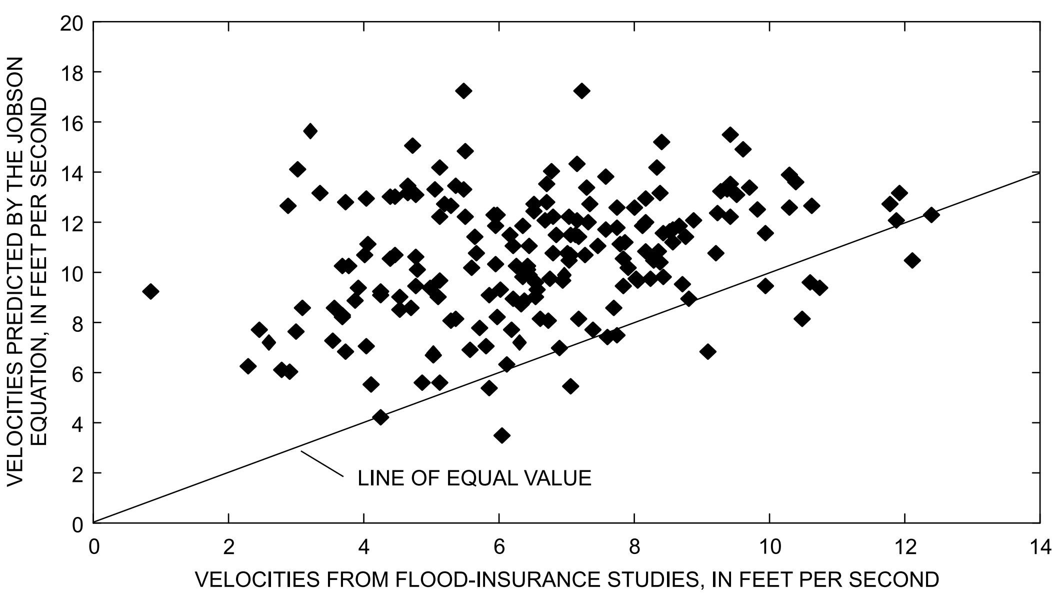

Figure 6. Comparision of velocities from flood-insurance studies (Federal Emergency Management Agency, 1978-99) and those predicted by the Jobson equation (Jobson, 1996) for stream reaches near stream-gaging stations in Pennsylvania.

velocities from the data set from slope-area measurements. The mean and standard deviation of the velocities computed by use of the Jobson equation were 10.6 and 2.50 ft/s, respectively. The standard error of the velocities computed by use of the Jobson equation relative to velocities from the floodway data tables was 2.77 ft/s.

PREDICTION OF VELOCITIES FOR A RANGE OF STREAMFLOW CONDITIONS IN PENNSYLVANIA

The evaluation of Jobson's equations for use in high-flow conditions showed that the equations tended to overestimate velocities during high flows. This meant the equation could not be used to accurately predict velocities above the maximum velocity of 4.95 ft/s that was used in the development of the equation. Therefore, a new equation was developed to predict velocities in Pennsylvania streams using data from the time-of-travel studies on the Susquehanna, Delaware, and Lehigh Rivers, from the slope-area measurements, and from the floodway data tables in the flood-insurance studies.

Development of a New Equation for Predicting Stream Velocities

The two most important variables for predicting stream velocities in Pennsylvania are streamflow and drainage area. Many other variables could be included in an equation to predict velocity including stream slope, channel roughness, cross-sectional area at bank full stage, channel storage at low flow, and over-bank storage at high flow. For Pennsylvania streams, recurrence-interval discharges are related closely to drainage area raised to varying coefficients (Flippo, 1982).

Stuckey and Reed (2000) developed regression equations for predicting flows with recurrence intervals of 10, 25, 50, 100, and 500 years. These equations include the term drainage area raised to a coefficient that ranges from 0.678 to 0.777 depending on the recurrence interval and the region of the State. The median of these coefficients is 0.73, excluding that for the 500-year flood due to the extremity of the flood event. The 0.73 coefficient was used to develop a relation for predicting stream velocities for specific streamflow, based on discharge divided by drainage area as shown below.

$$Q/DA^{0.73}$$

A measure of the recurrence interval of each of the flows in the three data sets was determined. A scatter plot is shown in figure 7 of the streamflow of interest divided by drainage area raised to the 0.73 coefficient plotted against the measured velocities from the time-of-travel studies in the Susquehanna, Delaware, and Lehigh Rivers, the velocities computed from slope-area measurements, and the velocities reported in floodway data tables in the flood-insurance studies. The regression equation describing the relation shown in figure 7 is given below.

$$V = 0.6067\ e^{[0.8834\ (\log(Q/DA^{0.73}))]}, \tag{4}$$

where

V is velocity, in feet per second;
e is log to base e;
$\log$ is log to base 10;
Q is streamflow, in cubic feet per second; and
DA is drainage area, in square miles.

This new regression equation has standard errors of estimate of 0.18 ft/s, 0.37 ft/s, and 0.31 ft/s for reaches with time-of-travel studies on the Susquehanna, Delaware, and Lehigh Rivers, respectively. The standard error of estimate is 1.71 ft/s for the slope-area measurements, and 1.22 ft/s for data from the floodway data tables. The equation has a coefficient of determination (R^2) equal to 0.83.

Standard errors for the regression equation shown in figure 7 and statistical data for velocities from time-of-travel studies, slope-area measurements, and flood-insurance studies are summarized in table 1. A comparison between velocities predicted by the regression equation and the measured velocities from the time-of-travel studies and the computed velocities from the slope-area measurements and flood-insurance studies is shown in figure 8.

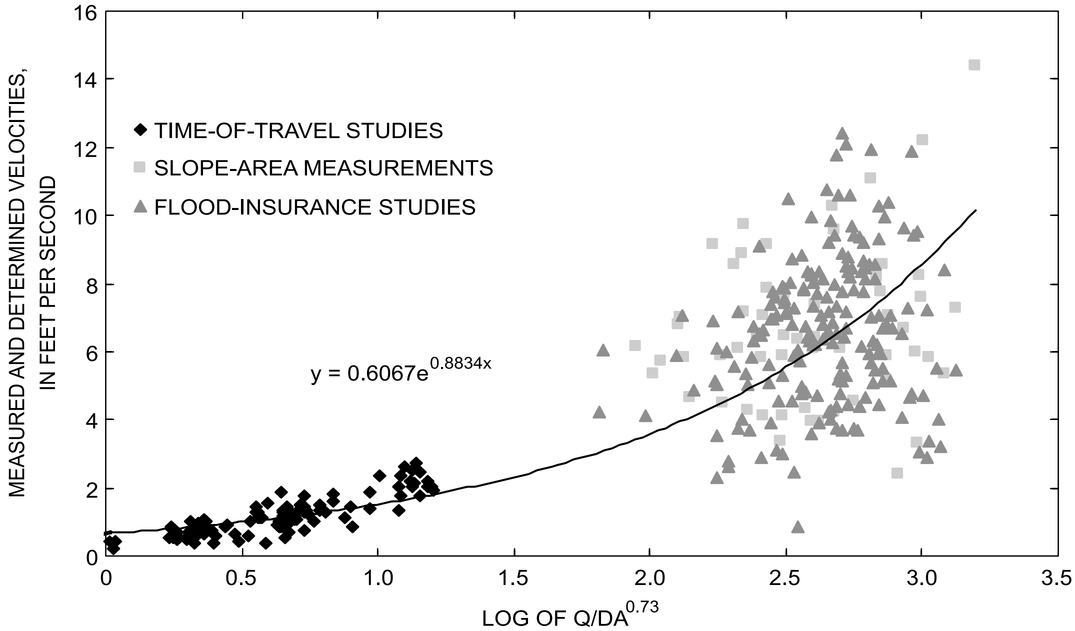

Figure 7. Relation between log $(Q/DA^{0.73})$ and stream velocities from time-of-travel studies, slope-area measurements, and flood-insurance studies in Pennsylvania.

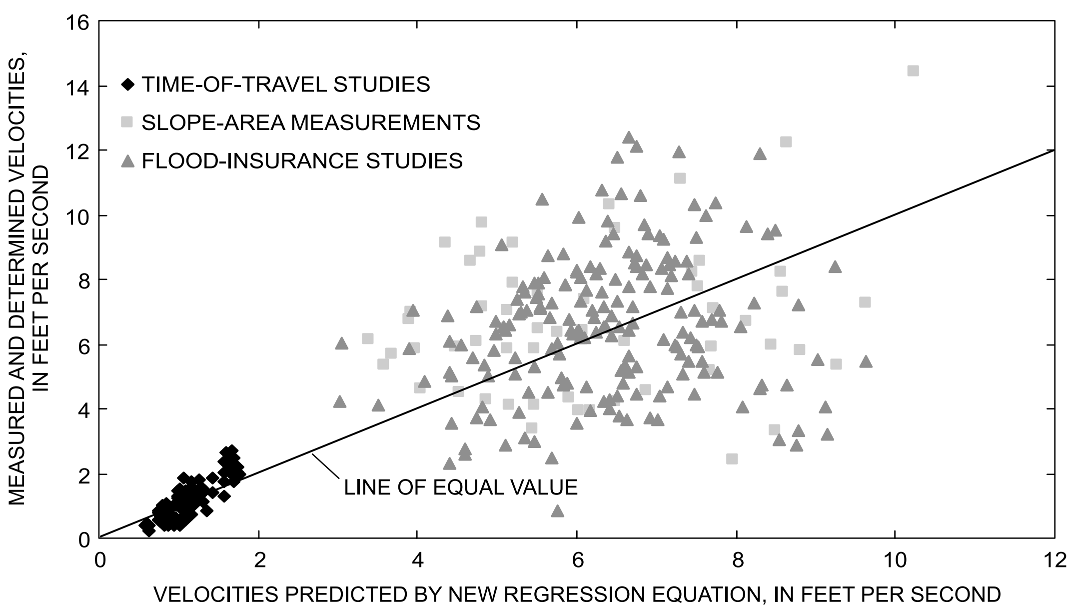

Figure 8. Comparison of stream velocities predicted by the new regression equation and those from time-of-travel studies, slope-area measurements, and flood-insurance studies in Pennsylvania.

Table 1. *Statistical data for velocities from time-of-travel studies, slope-area measurements, and flood-insurance studies in Pennsylvania*

[ft/s, feet per second; Q = discharge in cubic feet per second; DA = drainage area in square miles]

	Mean	Standard deviation (ft/s)	Standard error of difference in velocities (ft/s)	Range of the term $Q/DA^{0.73}$
Susquehanna River time-of-travel				0.97 - 7.51
Measured velocity	1.05	0.40		
Jobson equation	1.08	.27	0.24	
Regression equation	1.99	.18	.27	
Delaware River time-of-travel				2.06 - 16.0
Measured velocity	1.59	.71		
Jobson equation	1.47	.62	.31	
Regression equation	1.34	.37	.40	
Lehigh River time-of-travel				.87 - 9.29
Measured velocity	.89	.48		
Jobson equation	.93	.37	.30	
Regression equation	1.06	.31	.28	
Slope-area measurements				88.3 - 1,567
Measured velocity	6.67	2.26		
Jobson equation	9.70	4.05	4.10	
Regression equation	6.17	1.71	2.52	
Federal Emergency Management Floodway data tables				65.6 - 1,340
Measured velocity	6.59	2.17		
Jobson equation	10.6	2.50	2.77	
Regression equation	6.38	1.22	2.29	

The Jobson equation is relatively accurate for Pennsylvania streams if the factor log $(Q/DA^{0.73})$ is about 2 or less, as shown in figure 7. If the factor log $(Q/DA^{0.73})$ is over 2, velocities predicted by the Jobson equation can be notably higher than those from slope-area measurements or floodway data tables and the regression equation shown on figure 7 should be used to compute velocities.

Considerations and Limitations of Available Velocity Data for Streams in Pennsylvania

Time-of-travel data are not available for periods of high flow, and the relation between velocities from slope-area measurements and actual velocities in long stream reaches during periods of high flow is not known. The relation between traveltime obtained from data published in the floodway data tables of flood-insurance studies and actual stream velocities also is not known. Floodway velocities are not measured data; rather, they are determined based on a maximum 1-ft rise in the 100-year water-surface elevation while encroaching the 100-year flood plain boundary. These velocities may not always duplicate real streamflow conditions. Velocities computed from the slope-area measurements and those published in the floodway data tables of the flood-insurance studies have similar means (6.67 and 6.59 ft/s, respectively) and a similar standard deviation (2.26 and 2.17 ft/s, respectively). Although the two sets of velocities are similar, it should be noted that both numbers are computed from the same open-channel equations. Further analysis of equations to predict stream velocities at high flows would be needed if time-of-travel studies are conducted at high flows.

The Jobson equation works reasonably well for Pennsylvania streams if the factor log $(Q/DA^{0.73})$ is 2.0 or less; however, it tends to overpredict velocities if the factor log $(Q/DA^{0.73})$ is greater than 2.0. The new regression equation can be used throughout the range of flow conditions up to the 100-year flood event. The velocities used to develop the equation ranged from 0.22 to 14.4 ft/s. Streams used in the analysis and development of the equation had drainage areas from 2.4 to 26,000 mi^2 and discharges from 58 to 740,000 ft^3/s.

SUMMARY

The USGS, in cooperation with PaDEP, delineated the boundaries for the 5- and 25-hour traveltimes of public surface-water-supply intakes on Pennsylvania streams. To determine these traveltimes, a method of calculating mean stream velocity over a range of streamflow conditions was required. Equations to predict traveltime in streams in the United States were presented by Jobson (1996, 1997). Most of the data used to develop the equations were collected during periods of low and moderate flow and none of the data were from Pennsylvania streams. Three data sets were used to evaluate the Jobson equation for Pennsylvania streams over a range of low to high flows: time-of-travel studies on the Susquehanna, Delaware, and Lehigh Rivers, slope-area measurements of flood flows, and velocities of the 100-year floodway as reported in flood-insurance studies.

A comparison of velocities computed from the traveltime regression equation by Jobson to velocities measured during the time-of-travel studies showed good agreement for low and moderately low flow. Comparison of velocities computed with the Jobson regression equation to velocities from slope-area measurements of high flows and to velocities of the 100-year floodway from various flood-insurance studies (Flood Emergency Management Agency, 1978-99) indicated that velocities were over-estimated by the regression equation. Although the low and moderate-flow comparisons showed good agreement, an equation was needed for computing velocities during the range of low to high flows commonly experienced in Pennsylvania streams.

A new regression equation was developed to predict velocities from 0.22 to 14.4 ft/s for streams in Pennsylvania. This new regression equation was developed using data from three sources: 1) time-of-travel studies conducted at low and moderate flow, 2) slope-area measurements of flood flows, and 3) velocities of the 100-year floodway as reported in flood-insurance studies. The regression equation had standard errors from 0.18 to 0.37 for the time-of-travel studies, 1.71 for the slope-area measurements, and 1.22 for the flood-insurance studies.

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