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University of Maryland, Baltimore County,
The Institute of Ecosystem Studies,
and the Baltimore Ecosystem Study

# Hydraulic Geometry Characteristics of Continuous-Record Streamflow-Gaging Stations on Four Urban Watersheds Along the Main Stem of Gwynns Falls, Baltimore County and Baltimore City, Maryland

Scientific Investigations Report 2006–5190

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

**Cover.** Photograph showing typical measurement section at station 01589197, Gwynns Falls near Delight, Maryland (view looking downstream from centerline of channel at gage). (Photograph by Robert H. Pentz, U.S. Geological Survey)

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**U.S. Department of the Interior**
DIRK KEMPTHORNE, Secretary

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# Contents



# Figures

## Tables

# Conversion Factors and Vertical Datum

| 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 ($m^2$) |
| acre | 0.004047 | square kilometer ($km^2$) |
| square mile ($mi^2$) | 259.0 | hectare (ha) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| | Flow rate | |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second ($m^3/s$) |
| | Mass | |
| pound, avoirdupois (lb) | 0.4536 | kilogram (kg) |
| ton, short (2,000 lb) | 907.2 | kilogram (kg) |

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

**Vertical datum**: In this report, vertical coordinate information is referenced to the thalweg elevation of the measurement cross section at each streamflow-gaging station. Vertical coordinate elevations for streamflow records at these stations are referenced to the National Geodetic Vertical Datum of 1929.

**Water year**: In this report, "water year" refers to the 12-month period beginning October 1 and ending September 30. The water year is determined according to the calendar year in which it ends and includes 9 of the 12 months. The year beginning October 1, 2004 and ending September 30, 2005 is called "water year 2005." All references to years of operation for streamflow-gaging stations in this report are in water years.

# Hydraulic Geometry Characteristics of Continuous-Record Streamflow-Gaging Stations on Four Urban Watersheds Along the Main Stem of Gwynns Falls, Baltimore County and Baltimore City, Maryland

By Edward J. Doheny and Gary T. Fisher

## Abstract

Four continuous-record streamflow-gaging stations are currently being operated by the U.S. Geological Survey on the main stem of Gwynns Falls in western Baltimore County and Baltimore City, Maryland. The four streamflow-gaging stations drain urban or suburban watersheds with significantly different drainage areas. In addition to providing continuous-record discharge data at these four locations, operation of these stations also provides a long-term record of channel geometry variables such as cross-sectional area, channel width, mean channel depth, and mean velocity that are obtained from physical measurement of the discharge at a variety of flow conditions.

Hydraulic geometry analyses were performed using discharge-measurement data from four continuous-record streamflow-gaging stations on the main stem of Gwynns Falls. Simple linear regression was used to develop relations that (1) quantify changes in cross-sectional area, channel width, mean channel depth, and mean velocity with changes in discharge at each station, and (2) quantify changes in these variables in the Gwynns Falls watershed with changes in drainage area and annual mean discharge.

Results of the hydraulic geometry analyses indicated that mean velocity is more responsive to changes in discharge than channel width and mean channel depth for all four streamflow-gaging stations on the main stem of Gwynns Falls. For the two largest and most developed watersheds, on Gwynns Falls at Villa Nova, and Gwynns Falls at Washington Boulevard at Baltimore, the slope of the regression lines, or hydraulic exponents, indicated that mean velocity was more responsive to changes in discharge than any of the other hydraulic variables that were analyzed. This was true even when considering changes in cross-sectional area with discharge, which incorporates the combined effects of channel width and mean channel depth.

A comparison of hydraulic exponents for Gwynns Falls to average values from previous work indicated that the velocity exponents for all four stations on the Gwynns Falls are larger than the average value of 0.34. For stations 01589300 and 01589352, the exponents for mean velocity are about twice as large as the average value.

Analyses of cross-sectional area, channel width, mean channel depth, and mean velocity in conjunction with changes in drainage area and annual mean discharge indicated that channel width is much more responsive to changes in drainage area and annual mean discharge than are mean channel depth or mean velocity. Cross-sectional area, which combines the effects of channel width and mean channel depth, was also found to be highly responsive to changes in drainage area and annual mean discharge.

## Introduction

Urban development and suburban sprawl can significantly alter the hydrology of watersheds over time. Increased runoff from impervious surfaces can result in changes to the form and process of stream channels in order to accommodate the increased streamflow. Such changes can include channel-bed degradation, increased bank erosion and failure, channel widening, and increased sediment supply (Hammer, 1972).

Previous research has indicated that river cross sections are shaped and dimensioned over time to accept a range of streamflows (Leopold, 1994). Previous research also indicates that there is some consistency from one river to another and from one cross section to another in the way that hydraulic variables change as discharge increases (Leopold, 1994). Hydraulic geometry is a quantitative method of describing changes in hydraulic variables such as cross-sectional area, channel width, mean channel depth, and mean velocity with changes in discharge. If multiple streamflow-gaging stations are in operation on a particular stream or river, hydraulic geometry can be analyzed at different locations in relation to changes in drainage area or differences in watershed characteristics.

Four continuous-record streamflow-gaging stations are currently being operated by the U.S. Geological Survey (USGS) on the main stem of Gwynns Falls in western Baltimore County and Baltimore City, Maryland. These stations are operated as part of the Baltimore Ecosystem Study (BES), which is among the National Science Foundation's Long-Term Ecological Research (LTER) network of study locations. BES has been monitoring hydrologic conditions in the Gwynns Falls watershed since 1998 and is tasked with investigating long-term hydrologic changes in the Baltimore metropolitan area. Each of the stations drains significantly different drainage areas, with varying degrees of urban development. In addition to providing continuous-record discharge data at these four locations, these stations also provide a long-term record of channel geometry variables such as cross-sectional area, channel width, mean channel depth, and mean velocity that are obtained from physical measurement of the discharge at a variety of flow conditions.

Much of the previous research on hydraulic geometry has dealt with non-urban streams and watersheds (McCandless and Everett, 2002). The nested gage coverage within the Gwynns Falls watershed provides an opportunity to evaluate changes in channel geometry along a land-use gradient, where the watershed land use gradually changes from predominantly suburban in Baltimore County to heavily urban in Baltimore City. The flashiness of streams in developed watersheds also indicates that changes in channel geometry variables in these watersheds can occur much more quickly than in non-urban watersheds. A hydraulic geometry analysis was performed using data from discharge measurements at the four continuous-record streamflow-gaging stations on the main stem of Gwynns Falls in order to (1) quantify changes in geometry variables with changes in discharge at each station, and (2) quantify changes in geometry variables in the Gwynns Falls watershed with changes in drainage area and annual mean discharge.

## Purpose and Scope

This report presents an analysis of hydraulic geometry for four continuous-record streamflow-gaging stations along the main stem of Gwynns Falls in western Baltimore County and Baltimore City, Maryland. Hydraulic geometry was evaluated using selected data from discharge measurements that were made between July 1972 and October 2004 as part of basic station operations. Simple linear regression was used to develop logarithmic relations between discharge and cross-sectional area, channel width, mean channel depth, and mean velocity for each station. Changes in these geometry variables were also evaluated for the Gwynns Falls watershed in relation to changes in drainage area and changes in annual mean discharge for the period of record.

## Description of Study Area

Gwynns Falls drains a 66.5-$mi^2$ (square mile) subbasin of the larger Patapsco River watershed in Baltimore County and Baltimore City, Maryland. (Doheny, 1999). The study area includes the main stem of Gwynns Falls between USGS streamflow-gaging station 01589180, Gwynns Falls at Glyndon, Maryland and station 01589352, Gwynns Falls at Washington Boulevard at Baltimore, Maryland (figs. 1a and 1b). Descriptive information for the four continuous-record streamflow-gaging stations on the main stem of Gwynns Falls is presented in table 1.

Land use in the Gwynns Falls watershed is predominantly urban with areas of forest, agriculture, and inland water. From 1970 through 1990, the percent of urban land use in the Gwynns Falls watershed increased from approximately 64.6 percent to 74.3 percent, while the total percentage of forest cover decreased from approximately 24.8 percent to 18.9 percent and agriculture decreased from approximately 10.5 percent to 6.7 percent (Baltimore Ecosystem Study, 2006). By 1994, the watershed included approximately 75.8 percent urban land use, 18.1 percent forest cover, and 5.1 percent agricultural land. Approximately 42.2 percent of the watershed was overlain by impervious surfaces in 1994 (Parks and People Foundation, 1999).

Land-use data for 1997 were compiled for the sub-watersheds that drain the four active, continuous-record streamflow-gaging stations on the main stem of Gwynns Falls. The distribution of land-use types and impervious-surface percentages in the Gwynns Falls watershed by streamflow-gaging station based on 1997 land-use data is summarized in table 2 (Maryland Office of Planning, 1999).

The four streamflow-gaging stations on the main stem of Gwynns Falls are all heavily urban with a combination of residential and commercial/industrial land use (table 2). The largest percentage of urban residential land use occurs at station 01589197, which resulted from increased urban development over time in and around the town of Owings Mills. The total percentages of impervious surfaces are largest in the headwaters (station 01589180) and at the lower end of the watershed in Baltimore City (station 01589352), but are relatively large at all four stations.

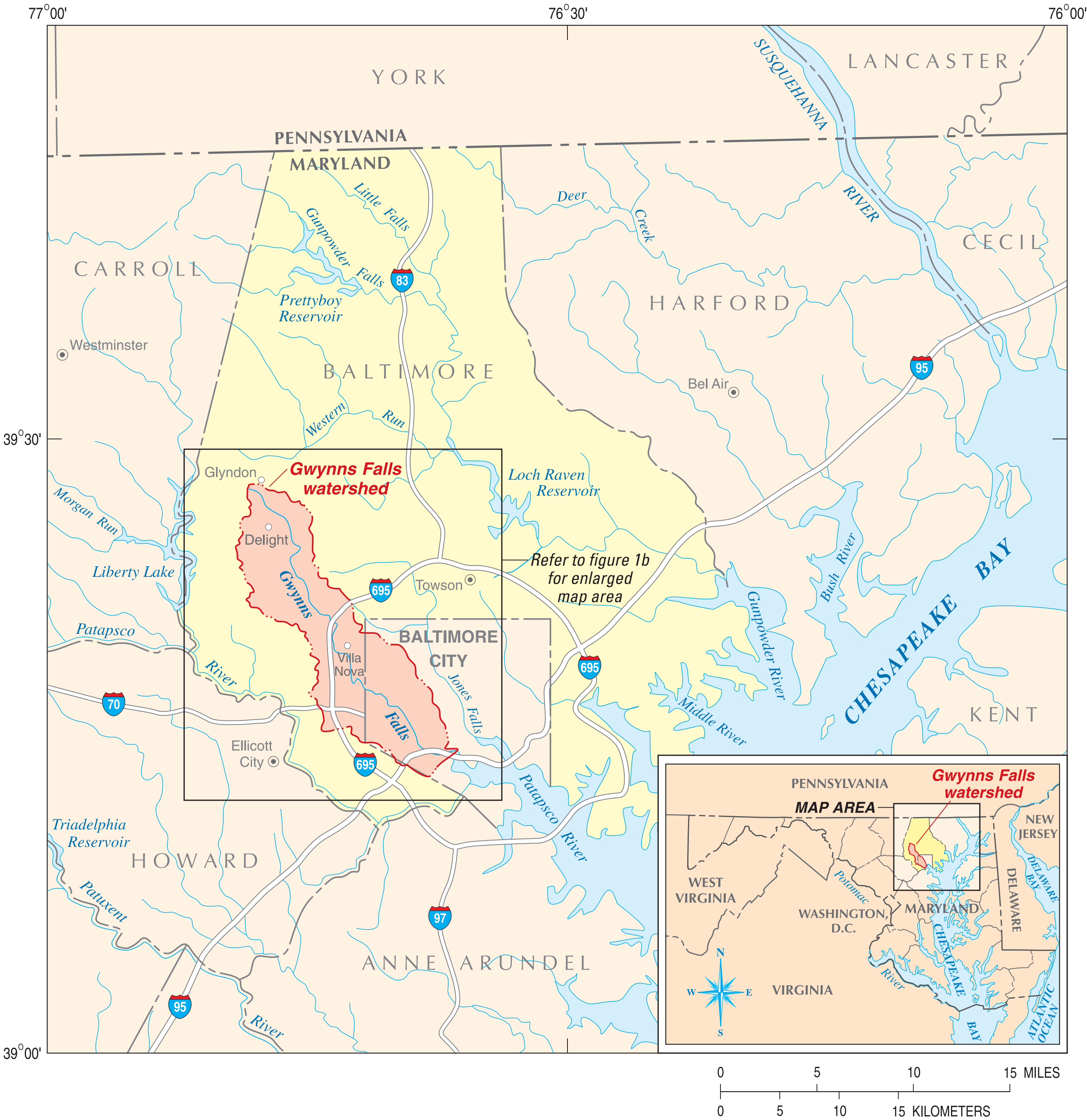


**Figure 1a.** Location of Gwynns Falls watershed, Baltimore County and City, Maryland.


**Figure 1b.** Location of active continuous-record streamflow-gaging stations on the main stem of Gwynns Falls, Baltimore County and City, Maryland.

**Table 1.** Descriptive information for active, continuous-record streamflow-gaging stations on the main stem of Gwynns Falls, Baltimore County and City, Maryland.

[°, degrees; ‘, minutes; “, seconds; $mi^2$, square miles]

| Station number | Station name | Location of station | Control feature | Latitude (° ‘ “) | Longitude (° ‘ “) | Drainage area ($mi^2$) | Period of record (water years) |
|---|---|---|---|---|---|---|---|
| 01589180 | Gwynns Falls at Glyndon, Md. | On left bank, 375 feet downstream of bridge on Chatsworth Avenue, Baltimore County, Md. | V-notch weir | 39 28 18.1 | 76 49 00.8 | 0.32 | 1999–present |
| 01589197 | Gwynns Falls near Delight, Md. | At downstream side of bridge on Gwynnbrook Avenue, Baltimore County, Md. | Rock riffle | 39 26 34.6 | 76 47 00.3 | 4.23 | 1999–present |
| 01589300 | Gwynns Falls at Villa Nova, Md. | On right bank, 300 feet downstream of bridge on Essex Road, Baltimore County, Md. | Rock riffle | 39 20 45.2 | 76 43 59.5 | 32.5 | 1957–1988; 1997–present |
| 01589352 | Gwynns Falls at Washington Boulevard at Baltimore, Md. | On left bank, 350 feet upstream of bridge on Washington Boulevard, Baltimore City, Md. | Rock riffle | 39 16 17.4 | 76 38 54.8 | 65.9 | 1999–present |

**Table 2.** Distribution of land-use types and impervious surfaces in the Gwynns Falls watershed by streamflow-gaging station, 1997.

[%, percent]

| Station number | Station name | Urban (residential) (%) | Urban[1] (other) (%) | Forest (%) | Agriculture (%) | Other[2] (%) | Impervious surfaces (%) |
|---|---|---|---|---|---|---|---|
| 01589180 | Gwynns Falls at Glyndon, Md. | 43.0 | 46.0 | 9.0 | 2.0 | 0.0 | 43.5 |
| 01589197 | Gwynns Falls near Delight, Md. | 66.0 | 13.0 | 12.0 | 8.0 | 1.0 | 35.7 |
| 01589300 | Gwynns Falls at Villa Nova, Md. | 47.0 | 18.0 | 24.0 | 7.0 | 4.0 | 32.0 |
| 01589352 | Gwynns Falls at Washington Boulevard at Baltimore, Md. | 50.0 | 24.0 | 18.0 | 4.0 | 4.0 | 41.4 |

[1] Commercial, institutional, industrial, open urban land.

[2] Water, brush, extractive, or bare ground.

# Hydraulic Geometry Analysis for Active, Continuous-Record Streamflow-Gaging Stations on the Main Stem of Gwynns Falls

Hydraulic geometry analysis of stream channels was first described by Leopold and Maddock (1953) as a means of quantifying changes in hydraulic variables, such as channel width, mean channel depth, and mean velocity, as discharge changes. In general terms, cross-sectional area, channel depth, and mean velocity tend to increase significantly with changes in discharge. Channel width generally increases at a much smaller rate than the other hydraulic variables, until the discharge spills out of the banks and onto the flood plain. Hydraulic variables, such as cross-sectional area, channel width, mean channel depth, and mean velocity can be quantitatively related to discharge as a power function by use of simple linear regression. Datasets for determining these relations come from discharge-measurement data that are collected as part of the operation of streamflow-gaging stations (Leopold, 1994).

Equations that describe hydraulic geometry generally take the following form:

$$A = aQ^b;\ W = cQ^d;\ D = fQ^h;\ V = jQ^k\ ,$$

where

| | |
|---|---|
| $A$ | is cross-sectional area in ft$^2$ (square feet); |
| $W$ | is channel width, in ft (feet); |
| $D$ | is mean channel depth, in ft; |
| $V$ | is mean velocity, in ft/s (feet per second); |
| $Q$ | is discharge, ft$^3$/s (cubic feet per second); |
| $a$, $c$, $f$, and $j$ | are coefficients; and |
| $b$, $d$, $h$, and $k$ | are exponents. |

As cross-sectional area is the product of channel width times mean channel depth, the sum of the exponents, $d + h$, should be equal to the exponent $b$, for a given stream and given dataset. In addition, because channel width times mean channel depth times mean velocity is equal to the discharge, the sum of the exponents, $d + h + k$, should be equal to 1. Exponents in hydraulic geometry analysis are also referred to as hydraulic exponents. The product of the coefficients $(c) \times (f) \times (j)$ should also be equal to 1.

Hydraulic geometry relations of cross-sectional area, channel width, mean channel depth, and mean velocity to discharge at each of the four active continuous-record streamflow-gaging stations on the main stem of Gwynns Falls were developed by use of the S-Plus 6 statistical package (Insightful Corporation, 2001). The criteria used for generating the relations at each of the stations and the resulting relations for each channel variable are described in the following sections.

## Relations for Station 01589180, Gwynns Falls at Glyndon, Maryland

Hydraulic geometry relations were developed for station 01589180, Gwynns Falls at Glyndon, Maryland, using discharge-measurement data that were collected from October 1998 through October 2004. The typical cross section used for measuring discharge is composed of a mixture of gravel, cobbles, and sand, and is located within a reach from 70 ft upstream to 50 ft downstream from the station (figs. 2 and 3). Fifty-six discharge measurements were used in the analysis with streamflow ranging from 0.01 ft$^3$/s to 16.9 ft$^3$/s. Four measurements that were made during severe drought conditions were not used in the analysis because the measurement cross section had to be significantly altered and improved for measuring extremely low flows. Relations of cross-sectional area, channel width, mean channel depth, and mean velocity to discharge are shown in table 3. The power functions are plotted in figure 4.

Mean velocity is more responsive to changes in discharge than channel width or mean channel depth for this station, as the hydraulic exponent for the mean velocity relation is the largest among these three variables (table 3). When the effects of channel width and mean channel depth are combined within the relation for cross-sectional area, this variable is much more responsive to changes in discharge than mean velocity for this station. The cross-sectional area relation has the largest **coefficient of determination**[1] ($R^2$), indicating that discharge explains a large amount of the variability in cross-sectional area at this station (table 3). $R^2$ values for the other hydraulic variables also indicate a relatively good fit to the data when related to discharge. The **residual standard error** (RSE) ranged from 21.4 to 32.8 percent for the four hydraulic variables, with channel width having the smallest RSE, and mean velocity having the largest RSE (Helsel and Hirsch, 1992). These RSE values are much larger than those for the other stations used in this analysis and could be attributed to the variability in the measurement section used to measure streamflow over time.

[1] Words that are **bold** are found in the "Glossary" section of the report.

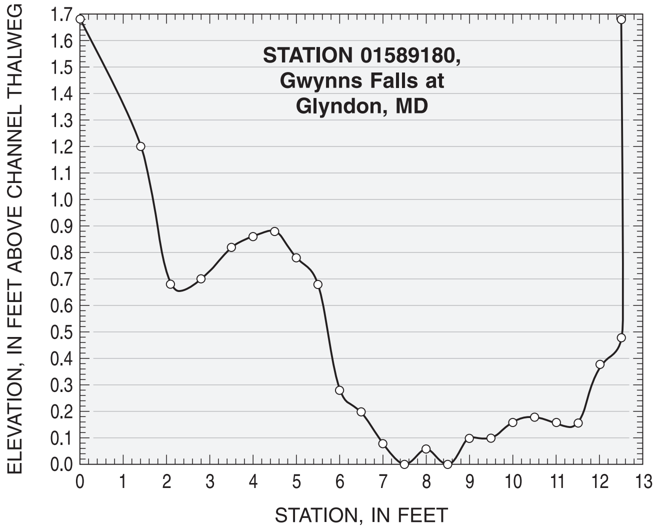


**Figure 2.** Typical measurement cross section at station 01589180, Gwynns Falls at Glyndon, Maryland (view looking downstream).

**Figure 3.** Typical measurement section at station 01589180, Gwynns Falls at Glyndon, Maryland (view looking upstream from centerline of foot bridge). (Photograph by Edward J. Doheny, U.S. Geological Survey)

**Table 3.** Relations of cross-sectional area, channel width, mean channel depth, and mean velocity to discharge at station 01589180, Gwynns Falls at Glyndon, Maryland.

[Q, discharge]

| Regression equation | $R^2$, coefficient of determination | Residual standard error (in percent) |
|---|---|---|
| Cross-sectional area = $1.445Q^{0.6081}$ | 0.94 | 31.1 |
| Channel width = $3.158Q^{0.3333}$ | 0.91 | 21.4 |
| Mean channel depth = $0.458Q^{0.2734}$ | 0.87 | 21.7 |
| Mean velocity = $0.688Q^{0.3870}$ | 0.85 | 32.8 |

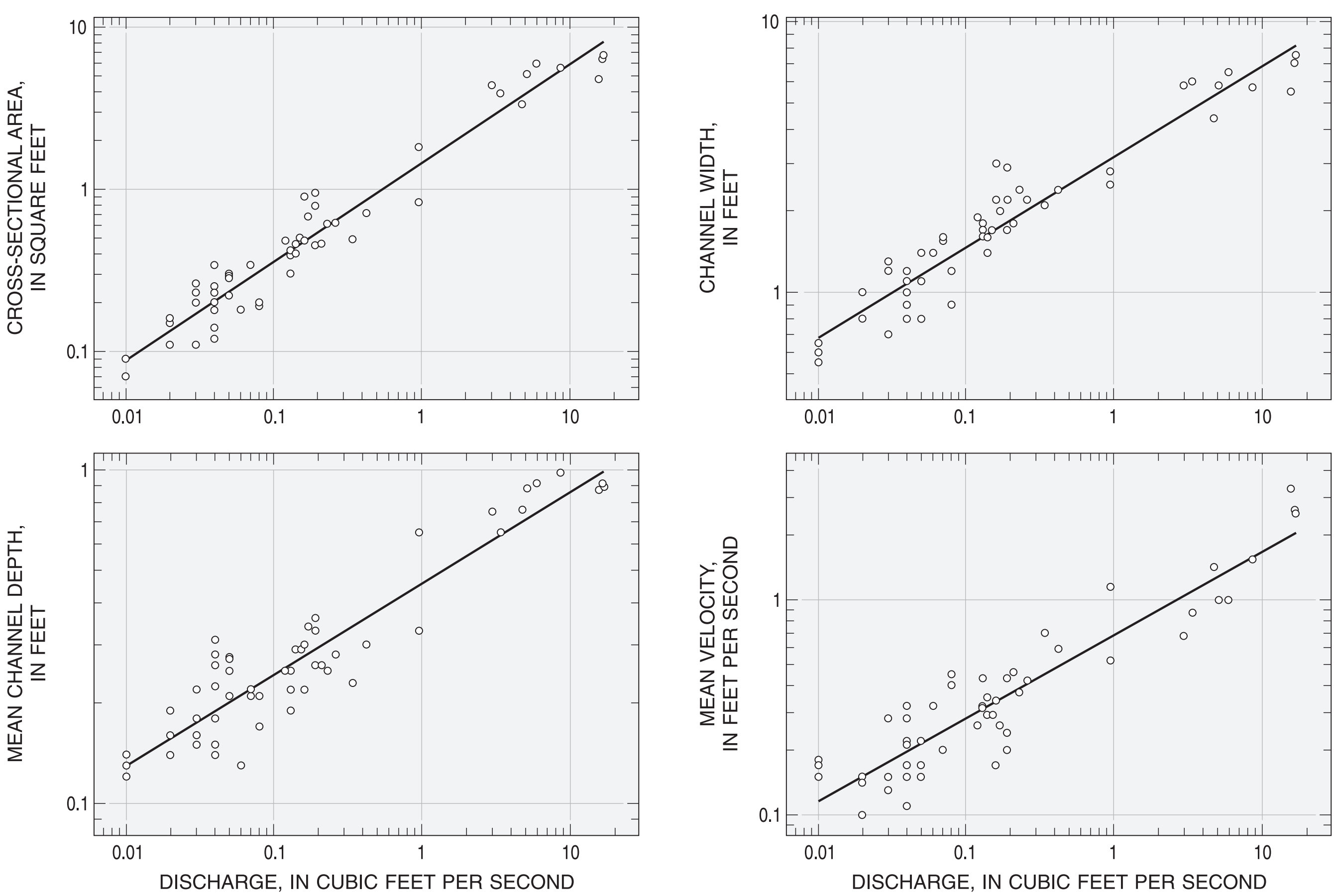


**Figure 4.** Relations of cross-sectional area, channel width, mean channel depth, and mean velocity to discharge for station 01589180, Gwynns Falls at Glyndon, Maryland.

## Relations for Station 01589197, Gwynns Falls near Delight, Maryland

Hydraulic geometry relations were developed for station 01589197, Gwynns Falls near Delight, Maryland, using discharge-measurement data that were collected from October 1998 through November 2004. The typical cross section used for measuring discharge is composed of a mixture of gravel, cobbles, and sand, and is located approximately 10 ft downstream from the station (figs. 5 and 6). Sixty-one discharge measurements were used with streamflow ranging from 0.30 $ft^3/s$ to 377 $ft^3/s$. Relations of cross-sectional area, channel width, mean channel depth, and mean velocity to discharge are shown in table 4. The power functions are plotted in figure 7.

Mean velocity is slightly more responsive to changes in discharge than mean channel depth for this station, and much more responsive to changes in discharge than channel width, as the hydraulic exponent for the mean velocity relation is the largest among these three variables (table 4). When the effects of channel width and mean channel depth are combined within the relation for cross-sectional area, it is much more responsive to changes in discharge than mean velocity for this station. Both the cross-sectional area relation and the mean channel depth relation have the largest values of $R^2$, indicating that discharge accounts for a large amount of the variability in both cross-sectional area and mean channel depth at this station (table 4). The $R^2$ value of 0.86 for mean velocity also indicates a relatively good fit to the data when related to discharge. The $R^2$ value of 0.68 for channel width indicates that discharge accounts for a smaller amount of the variability in channel width for this station than for the other hydraulic variables. Some distinct outliers for the channel width regression can be seen in figure 7, however, all discharge measurements at this station were made at the same location, plus or minus 10 ft, and no justification could be found for excluding them from the regressions. The RSE ranged from 10.9 to 16.7 percent for the four hydraulic variables, with mean channel depth having the smallest RSE, and mean velocity having the largest RSE.

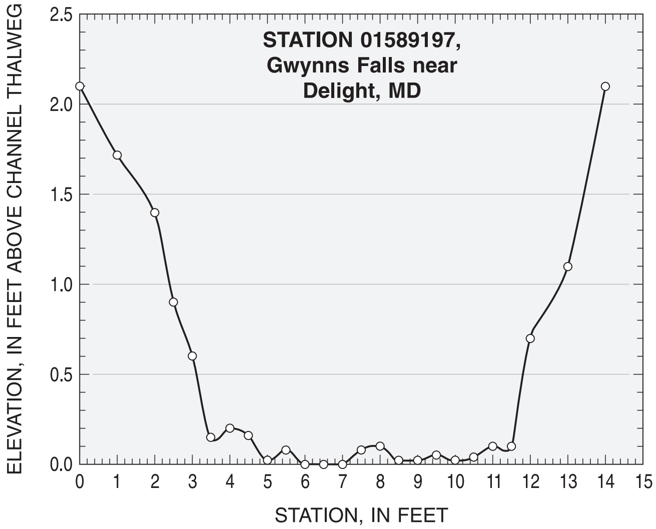


**Figure 5.** Typical measurement cross section at station 01589197, Gwynns Falls near Delight, Maryland (view looking downstream).

**Figure 6.** Typical measurement section at station 01589197, Gwynns Falls near Delight, Maryland (view looking downstream from centerline of channel at gage). (Photograph by Robert H. Pentz, U.S. Geological Survey)

**Table 4.** Relations of cross-sectional area, channel width, mean channel depth, and mean velocity to discharge at station 01589197, Gwynns Falls near Delight, Maryland.

[Q, discharge]

| Regression equation | $R^2$, coefficient of determination | Residual standard error (in percent) |
|---|---|---|
| Cross-sectional area = $2.43Q^{0.5941}$ | 0.93 | 16.4 |
| Channel width = $7.75Q^{0.2071}$ | 0.68 | 14.3 |
| Mean channel depth = $0.32Q^{0.3861}$ | 0.93 | 10.9 |
| Mean velocity = $0.41Q^{0.4064}$ | 0.86 | 16.7 |

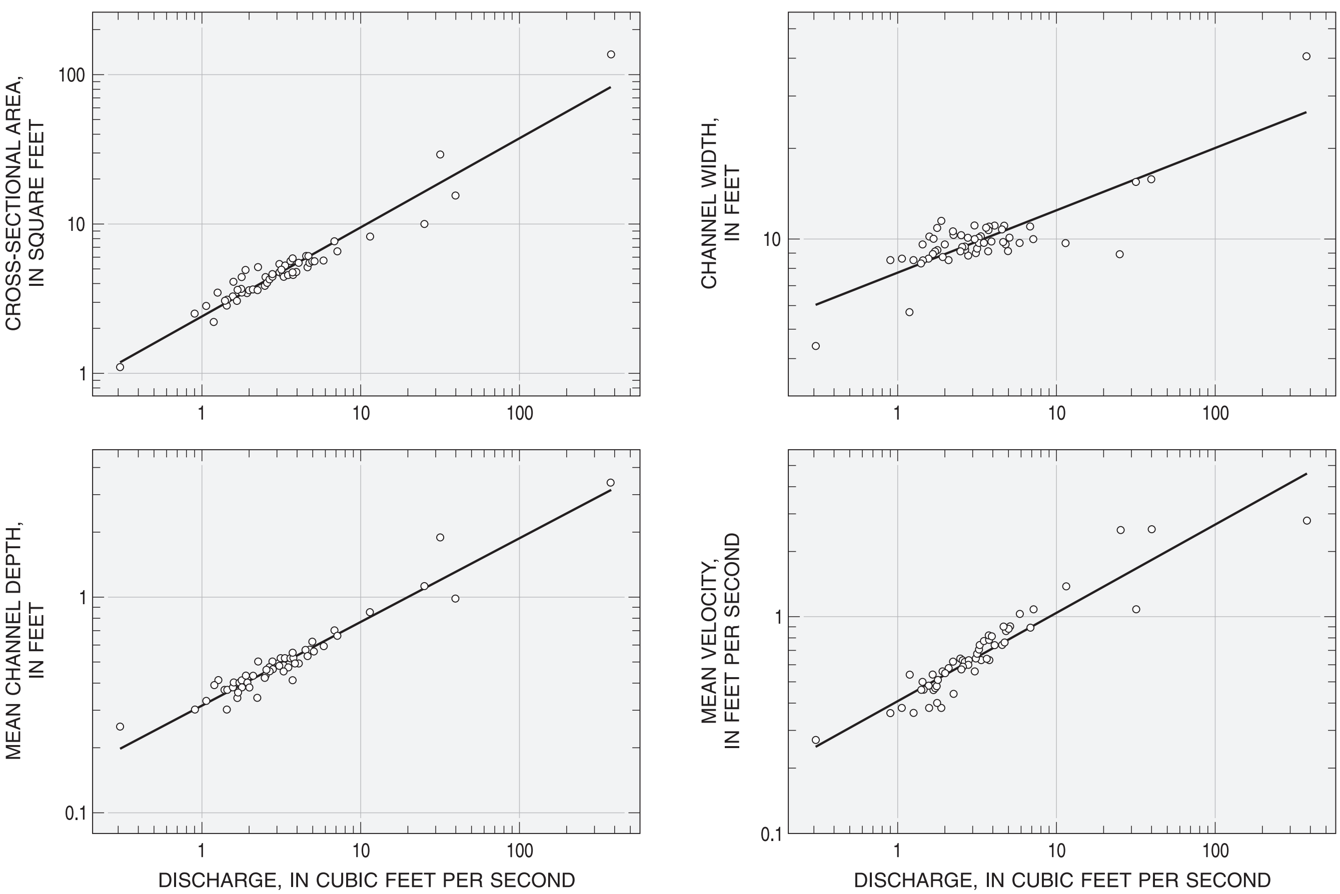


**Figure 7.** Relations of cross-sectional area, channel width, mean channel depth, and mean velocity to discharge for station 01589197, Gwynns Falls near Delight, Maryland.

## Relations for Station 01589300, Gwynns Falls at Villa Nova, Maryland

Hydraulic geometry relations were developed for station 01589300, Gwynns Falls at Villa Nova, Maryland using discharge-measurement data that were collected from July 1972 through October 2004. The typical cross section used for measuring discharge is composed of a mixture of gravel and sand, and is located approximately 20 to 30 ft downstream from the station (figs. 8 and 9). Although data were available for this station dating back to 1957, major flooding that occurred in June 1972 was considered as a logical break point for (1) quantifying current channel geometry conditions, and (2) comparison of data with the newer stations on Gwynns Falls. Seventy-eight discharge measurements were used with streamflow ranging from 6.3 $ft^3/s$ to 237 $ft^3/s$. Three discharge measurements that were made during severe drought conditions were not used in the analysis because the cross section used for the measurements had to be significantly altered and improved for measuring extreme low flows. The analysis was also limited to discharge measurements of less than 300 $ft^3/s$, since the higher flow measurements appeared to represent a different population of data for cross-sectional area, channel width, and mean velocity. The graphical break point between the two data populations was at approximately 300 $ft^3/s$. Relations of cross-sectional area, channel width, mean channel depth, and mean velocity to discharge are shown in table 5. The power functions are plotted in figure 10.

Mean velocity is much more responsive to changes in discharge than channel width and mean channel depth for this station, as the hydraulic exponent for the mean velocity relation is the largest among these three variables (table 5). When the effects of channel width and mean channel depth are combined within the relation for cross-sectional area, mean velocity is still much more responsive to changes in discharge for this station. Mean velocity has the largest value of $R^2$, indicating that discharge explains a large amount of the variability in mean velocity at this station (table 5). The $R^2$ values of 0.88 for cross-sectional area and 0.83 for mean channel depth also indicate a relatively good fit to the data when related to discharge. The $R^2$ value of 0.36 for channel width indicates that discharge explains a much smaller amount of the variability in channel width for this station than for the other hydraulic variables. The RSE for the channel width regression is less than half that of the other regressions, however. This indicates that the stream channel is confining the flow and restricting the channel width to a very small range within the banks at this location. The RSE ranged from 4.1 to 9.7 percent for the four hydraulic variables, with channel width having the smallest RSE, and mean channel depth having the largest RSE.

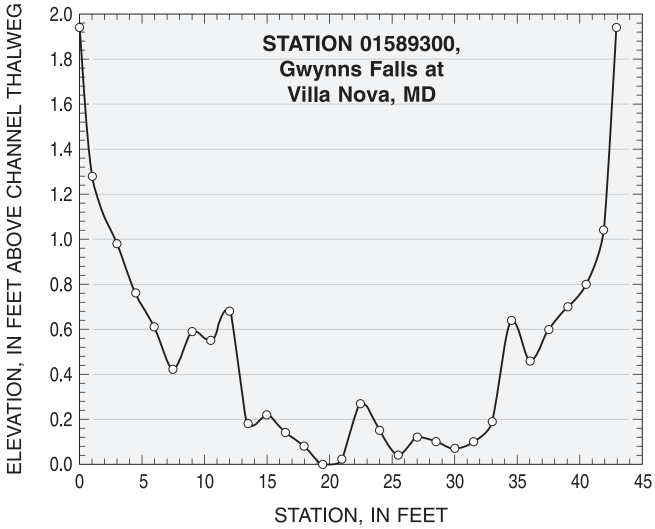


**Figure 8.** Typical measurement cross section at station 01589300, Gwynns Falls at Villa Nova, Maryland (view looking downstream).

**Figure 9.** Typical measurement section at station 01589300, Gwynns Falls at Villa Nova, Maryland (view looking downstream from right edge of water, just upstream of gage). (Photograph by Joseph M. Fisher, formerly of U.S. Geological Survey)

**Table 5.** Relations of cross-sectional area, channel width, mean channel depth, and mean velocity to discharge at station 01589300, Gwynns Falls at Villa Nova, Maryland.

[Q, discharge]

| Regression equation | $R^2$, coefficient of determination | Residual standard error (in percent) |
|---|---|---|
| Cross-sectional area = $15.81Q^{0.3063}$ | 0.88 | 9.0 |
| Channel width = $36.34Q^{0.0393}$ | 0.36 | 4.1 |
| Mean channel depth = $0.436Q^{0.2661}$ | 0.83 | 9.7 |
| Mean velocity = $0.064Q^{0.6923}$ | 0.97 | 9.2 |

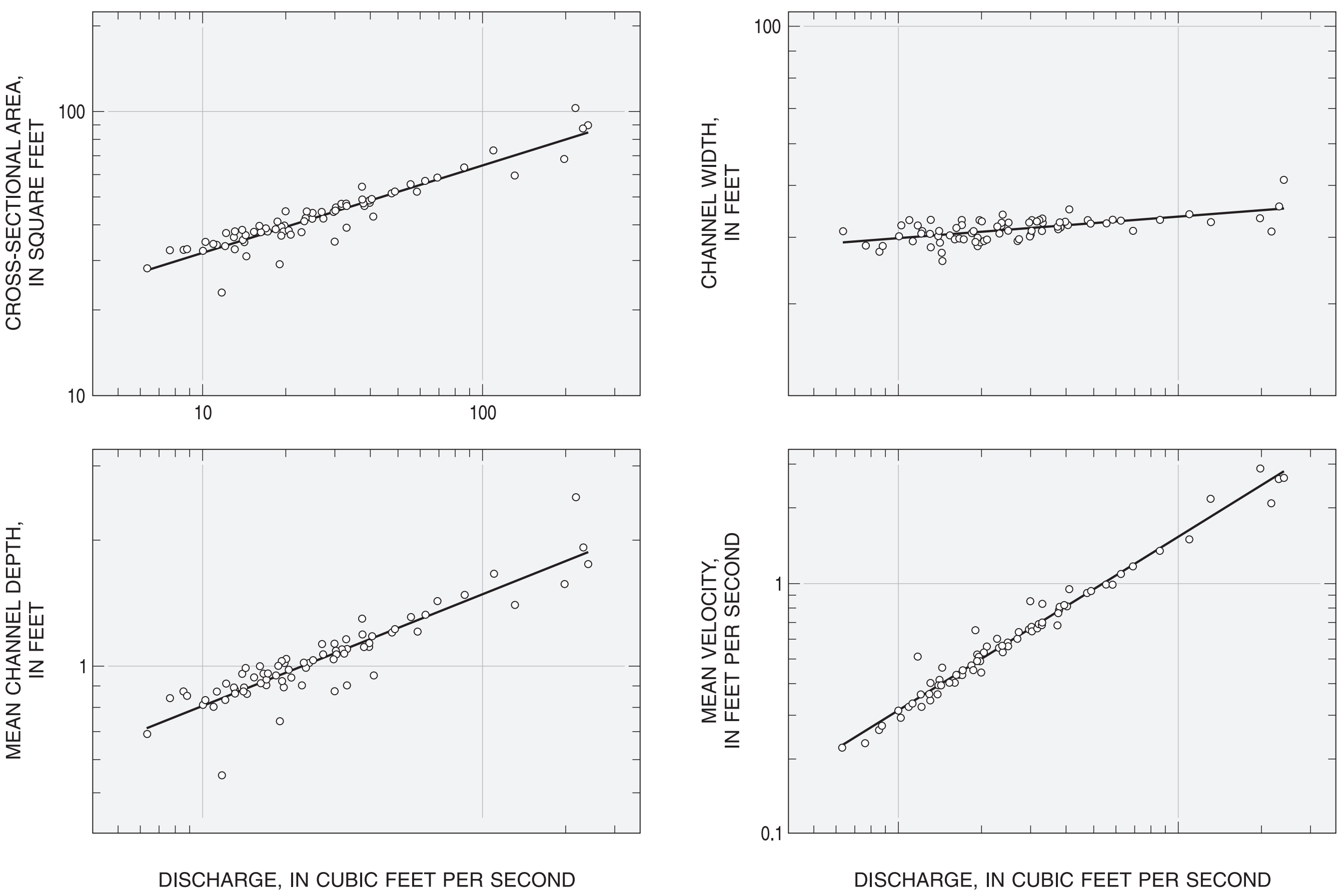


**Figure 10.** Relations of cross-sectional area, channel width, mean channel depth, and mean velocity to discharge for station 01589300, Gwynns Falls at Villa Nova, Maryland.

## Relations for Station 01589352, Gwynns Falls at Washington Boulevard at Baltimore, Maryland

Hydraulic geometry relations were developed for station 01589352, Gwynns Falls at Washington Boulevard at Baltimore, Maryland using discharge-measurement data that were collected from October 1998 through October 2004. The typical cross section used for measuring discharge is composed of a mixture of gravel, cobbles, and sand, and is located approximately 500 ft upstream from the station (figs. 11 and 12). Sixty-two discharge measurements were used with streamflow ranging from 10.5 $ft^3/s$ to 1,420 $ft^3/s$. Two measurements that were made during extreme high-flow conditions were not used in the analysis because they represent streamflow conditions that include significant flood-plain flow. Relations of cross-sectional area, channel width, mean channel depth, and mean velocity to discharge are shown in table 6. The power functions are plotted in figure 13.

Mean velocity is much more responsive to changes in discharge than channel width and mean channel depth for this station, as the hydraulic exponent for the mean velocity relation is the largest among these three variables (table 6). Channel width is least responsive to changes in discharge for this station, indicating that channel width can be expected to change at a much smaller rate than mean channel depth or mean velocity with changes in discharge. When the effects of channel width and mean channel depth are combined within the relation for cross-sectional area, mean velocity is still much more responsive to changes in discharge for this station. Mean velocity has the largest value of $R^2$, indicating that discharge explains a large amount of the variability in mean velocity at this station (table 6). The $R^2$ values of 0.86 for cross-sectional area and 0.78 for mean channel depth also indicate a relatively good fit to the data when related to discharge. The $R^2$ value of 0.22 for channel width indicates that discharge explains a much smaller amount of the variability in channel width for this station than for the other hydraulic variables. There are four distinct outliers for the channel width regression (fig. 13). Further investigation showed that these four measurements were made at slightly different locations within the gage reach, however, the differences in measurement location do not produce distinct outliers for the cross-sectional area, mean channel depth, and mean velocity regressions (fig. 13). Removal of the outliers from the width regression also produced results that did not make physical sense. As a result, the data for these four measurements were left in the dataset for purposes of this investigation. The RSE ranged from 11.3 to 14.8 percent for the four hydraulic variables, with channel width having the smallest RSE, and mean channel depth having the largest RSE.

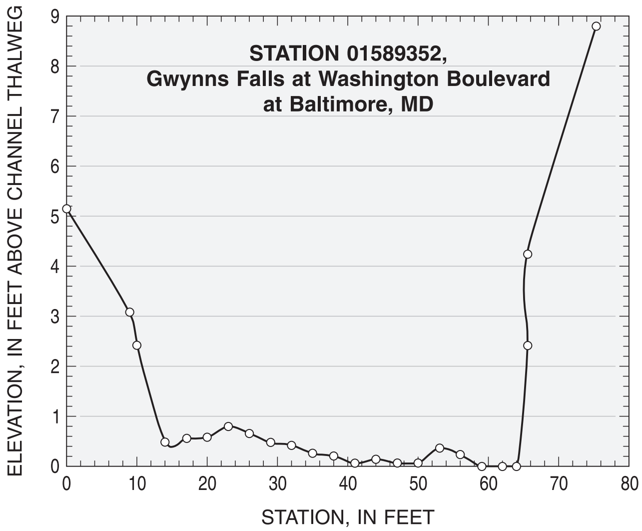


**Figure 11.** Typical measurement cross section at station 01589352, Gwynns Falls at Washington Boulevard at Baltimore, Maryland (view looking downstream).

**Figure 12.** Typical measurement section at station 01589352, Gwynns Falls at Washington Boulevard at Baltimore, Maryland (view looking upstream from centerline of channel approximately 400 feet upstream of gage). (Photograph by Edward J. Doheny, U.S. Geological Survey)

**Table 6.** Relations of cross-sectional area, channel width, mean channel depth, and mean velocity to discharge at station 01589352, Gwynns Falls at Washington Boulevard at Baltimore, Maryland.

[Q, discharge]

| Regression equation | $R^2$, coefficient of determination | Residual standard error (in percent) |
|---|---|---|
| Cross-sectional area = $11.70Q^{0.4139}$ | 0.86 | 13.6 |
| Channel width = $39.20Q^{0.0742}$ | 0.22 | 11.3 |
| Mean channel depth = $0.298Q^{0.3404}$ | 0.78 | 14.8 |
| Mean velocity = $0.086Q^{0.5852}$ | 0.93 | 13.6 |

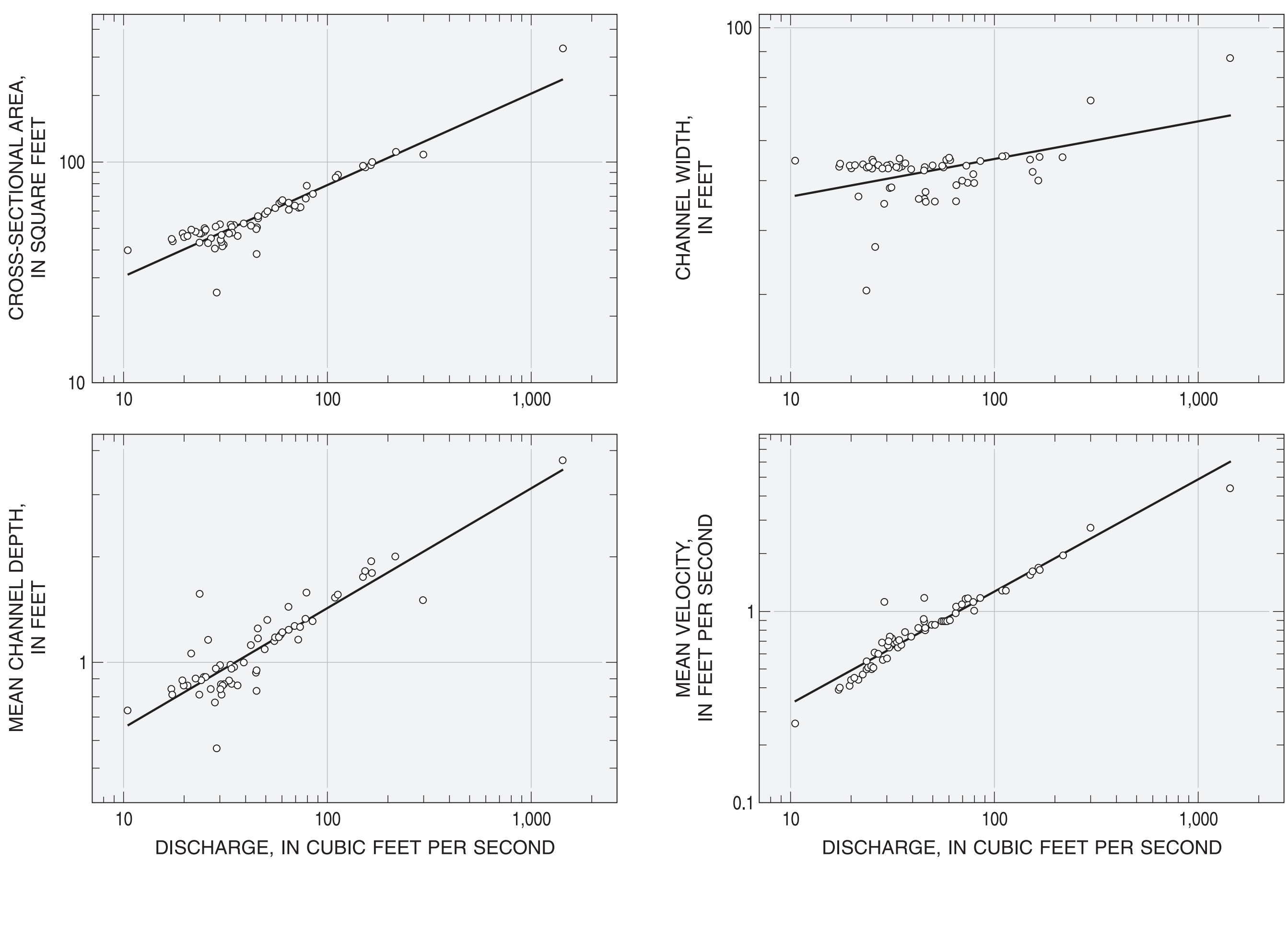


**Figure 13.** Relations of cross-sectional area, channel width, mean channel depth, and mean velocity to discharge for station 01589352, Gwynns Falls at Washington Boulevard at Baltimore, Maryland.

## Comparison of Hydraulic Exponents from Hydraulic Geometry Relations

Leopold (1994) presented averages for the most common values of the hydraulic exponents for width, mean depth, and velocity that are typically generated from analysis of hydraulic geometry. These average values are 0.26 for channel width, 0.40 for mean channel depth, and 0.34 for mean velocity. Summing the channel width and channel depth exponents for these values gives an average exponent for cross-sectional area of 0.66. The hydraulic exponents developed from the hydraulic geometry relations for the four continuous-record streamflow-gaging stations on the main stem of Gwynns Falls are summarized in table 7. These exponents are rounded to the nearest hundredth for comparison with the exponents presented in Leopold (1994).

When the exponents in table 7 are compared to the average values presented by Leopold (1994), the velocity exponents for all four stations on the Gwynns Falls are larger than the average value of 0.34. For stations 01589300 and 01589352, the exponents for mean velocity are about twice as large as the average value presented by Leopold (1994). The exponents for channel width at these stations are 0.04 and 0.07, respectively, whereas the average value for channel width presented by Leopold (1994) is 0.26. The channel width exponent for station 01589197 is also less than the average value, and greater than the average for station 01589180. The mean channel depth exponents for all four stations on the Gwynns Falls are less than the average value of 0.40. These results indicate that in an urban watershed such as Gwynns Falls, increases in discharge are influenced more by increases in stream velocity than by increases in channel depth or channel width. In the heavily urban areas of Baltimore City, the stream velocity has an even greater effect on discharge, whereas channel width has a noticeably lesser effect on discharge. Large stream velocities with relatively small changes in channel width are often typical of entrenched channels in urban watersheds.

# Variation of Hydraulic Geometry Variables Through the Gwynns Falls Watershed

The hydraulic geometry relations that were developed for the four continuous-record streamflow-gaging stations on the main stem of Gwynns Falls were used to quantify changes in hydraulic geometry variables with changes in drainage area and in **annual mean discharge** for the period of record. The period of record, drainage areas, and annual mean discharges for each of the four continuous-record streamflow-gaging stations on the main stem of Gwynns Falls are shown in table 8 (James and others, 2004).

**Table 7.** Summary of hydraulic exponents developed from hydraulic geometry relations for the four continuous-record streamflow-gaging stations on the main stem of Gwynns Falls.

| Station number | Station name | Exponent for cross-sectional area | Exponent for channel width | Exponent for mean channel depth | Exponent for mean velocity |
|---|---|---|---|---|---|
| 01589180 | Gwynns Falls at Glyndon, Md. | 0.61 | 0.33 | 0.27 | 0.39 |
| 01589197 | Gwynns Falls near Delight, Md. | 0.59 | 0.21 | 0.39 | 0.41 |
| 01589300 | Gwynns Falls at Villa Nova, Md. | 0.31 | 0.04 | 0.27 | 0.69 |
| 01589352 | Gwynns Falls at Washington Boulevard at Baltimore, Md. | 0.41 | 0.07 | 0.34 | 0.59 |

**Table 8.** Period of record, drainage area, and annual mean discharge for the four continuous-record streamflow-gaging stations on the main stem of Gwynns Falls.

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

| Station number | Station name | Period of record (water years) | Drainage area (mi$^2$) | Annual mean discharge (ft$^3$/s) |
|---|---|---|---|---|
| 01589180 | Gwynns Falls at Glyndon, Md. | 1999–2003 | 0.32 | 0.34 |
| 01589197 | Gwynns Falls near Delight, Md. | 1999–2003 | 4.23 | 4.58 |
| 01589300 | Gwynns Falls at Villa Nova, Md. | 1957–1988, 1997–2003 | 32.5 | 39.8 |
| 01589352 | Gwynns Falls at Washington Boulevard at Baltimore, Md. | 1999–2003 | 65.9 | 85.7 |

## Variation with Drainage Area

The hydraulic geometry relations that were developed for each of the four continuous-record streamflow-gaging stations were used to calculate the cross-sectional area, channel width, mean channel depth, and mean velocity at the annual mean discharge for the period of record. The results are shown in table 9.

The calculated cross-sectional areas, channel widths, mean channel depths, and mean velocities were then related to drainage area by use of simple linear regression. The results are shown in table 10. The regressions are plotted in figure 14.

The relations shown in table 10 indicate that channel width is much more responsive to changes in drainage area than are mean channel depth or mean velocity, as the slope of the regression line for channel width is much greater than the slope for mean channel depth or mean velocity. The slope of the regression line for cross-sectional area against drainage area, which combines the effects of channel width and mean channel depth, is also very responsive to changes in drainage area. The $R^2$ values of 0.906 to 0.998 indicate that changes in drainage area can account for a large amount of the variability of all hydraulic variables among the four active stations on the main stem of Gwynns Falls. The RSE values ranged from 9.0 to 16.2 percent, with channel width having the smallest RSE and cross-sectional area having the largest RSE.

**Table 9.** Calculated hydraulic geometry variables at the annual mean discharge for streamflow-gaging stations on the main stem of Gwynns Falls.

[$ft^3/s$, cubic feet per second; $ft^2$, square feet; ft, feet; ft/s, feet per second]

| Station number | Annual mean discharge ($ft^3/s$) | Cross-sectional area ($ft^2$) | Channel width (ft) | Mean channel depth (ft) | Mean velocity (ft/s) |
|---|---|---|---|---|---|
| 01589180 | 0.34 | 0.75 | 2.2 | 0.34 | 0.45 |
| 01589197 | 4.58 | 5.99 | 10.6 | 0.57 | 0.76 |
| 01589300 | 39.8 | 48.9 | 42.0 | 1.16 | 0.81 |
| 01589352 | 85.7 | 73.8 | 54.5 | 1.35 | 1.16 |

**Table 10.** Relations of channel geometry variables to drainage area at annual mean discharge for continuous-record streamflow-gaging stations on the main stem of Gwynns Falls.

[DA, drainage area]

| Regression equation | $R^2$, coefficient of determination | Residual standard error (in percent) |
|---|---|---|
| Cross-sectional area = $1.94(DA)^{0.8832}$ | 0.996 | 16.2 |
| Channel width = $4.45(DA)^{0.6163}$ | 0.998 | 9.0 |
| Mean channel depth = $0.44(DA)^{0.2664}$ | 0.984 | 9.9 |
| Mean velocity = $0.55(DA)^{0.1554}$ | 0.906 | 14.8 |

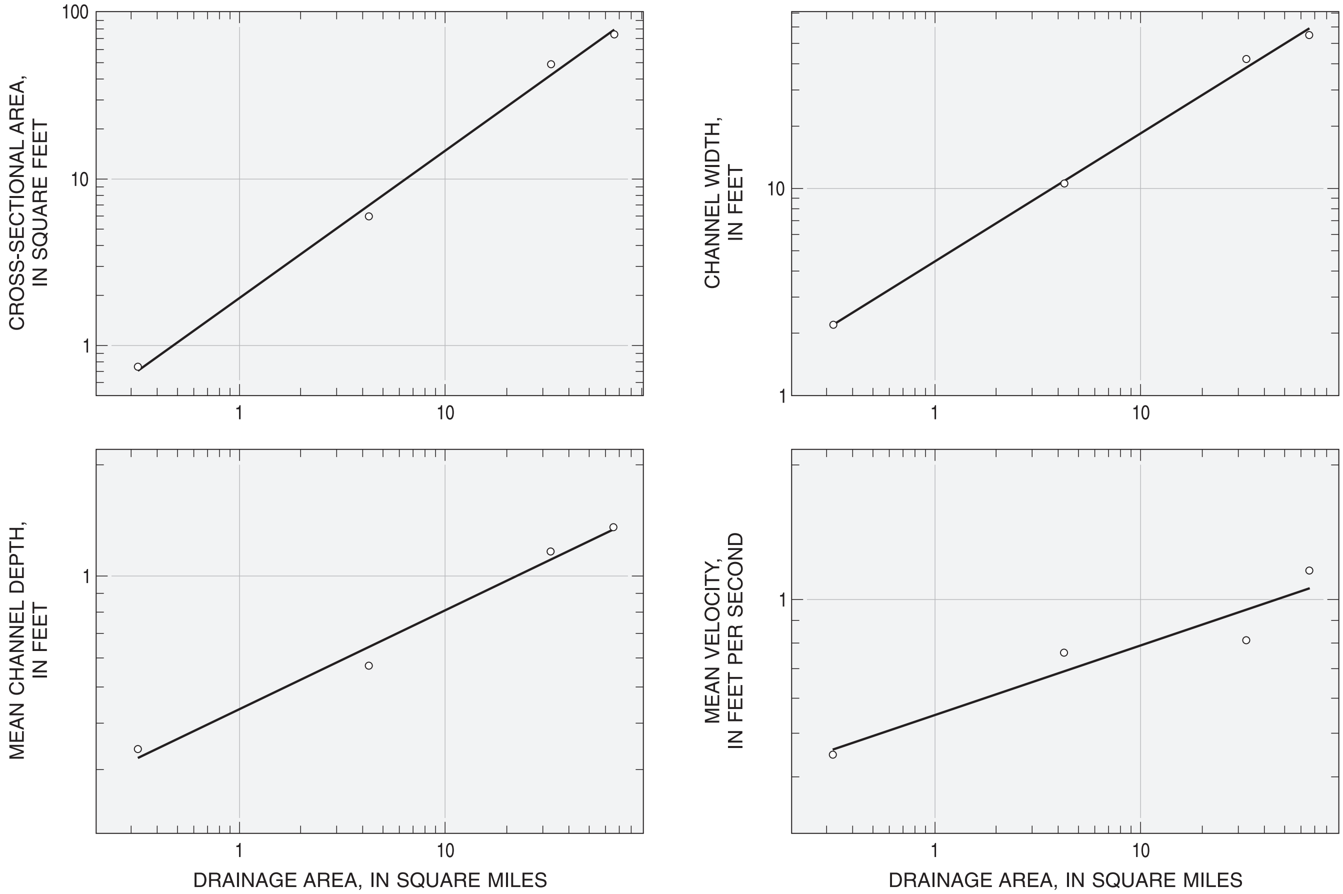


**Figure 14.** Relations of channel geometry variables to drainage area at annual mean discharge for continuous-record streamflow-gaging stations on the main stem of Gwynns Falls, Baltimore County and Baltimore City, Maryland.

## Variation with Annual Mean Discharge

The calculated hydraulic geometry variables from table 9 were also related to annual mean discharge using simple linear regression. The results are shown in table 11. The power functions are plotted in figure 15.

The relations shown in table 11 indicate that channel width is much more responsive to changes in the annual mean discharge on a watershed scale than are mean channel depth or mean velocity, as the slope of the regression line for channel width is significantly greater than the slopes for mean channel depth and mean velocity. The slope of the regression line for cross-sectional area against annual mean discharge, which combines the effects of channel width and mean channel depth, is also very responsive to changes in annual mean discharge. The $R^2$ values of 0.904 to 0.997 indicate that changes in annual mean discharge can account for a large amount of the variability of all hydraulic variables among the four active stations on the main stem of Gwynns Falls. The RSE values ranged from 8.8 to 14.8 percent, with mean depth having the smallest RSE and mean velocity having the largest RSE.

**Table 11.** Relations of channel geometry variables to annual mean discharge for continuous-record streamflow-gaging stations on the main stem of Gwynns Falls.

[Q, discharge]

| Regression equation | $R^2$, coefficient of determination | Residual standard error (in percent) |
|---|---|---|
| Cross-sectional area = $1.82Q^{0.8514}$ | 0.997 | 14.8 |
| Channel width = $4.26Q^{0.5937}$ | 0.997 | 9.9 |
| Mean channel depth = $0.43Q^{0.2571}$ | 0.987 | 8.8 |
| Mean velocity = $0.55Q^{0.1496}$ | 0.904 | 14.8 |

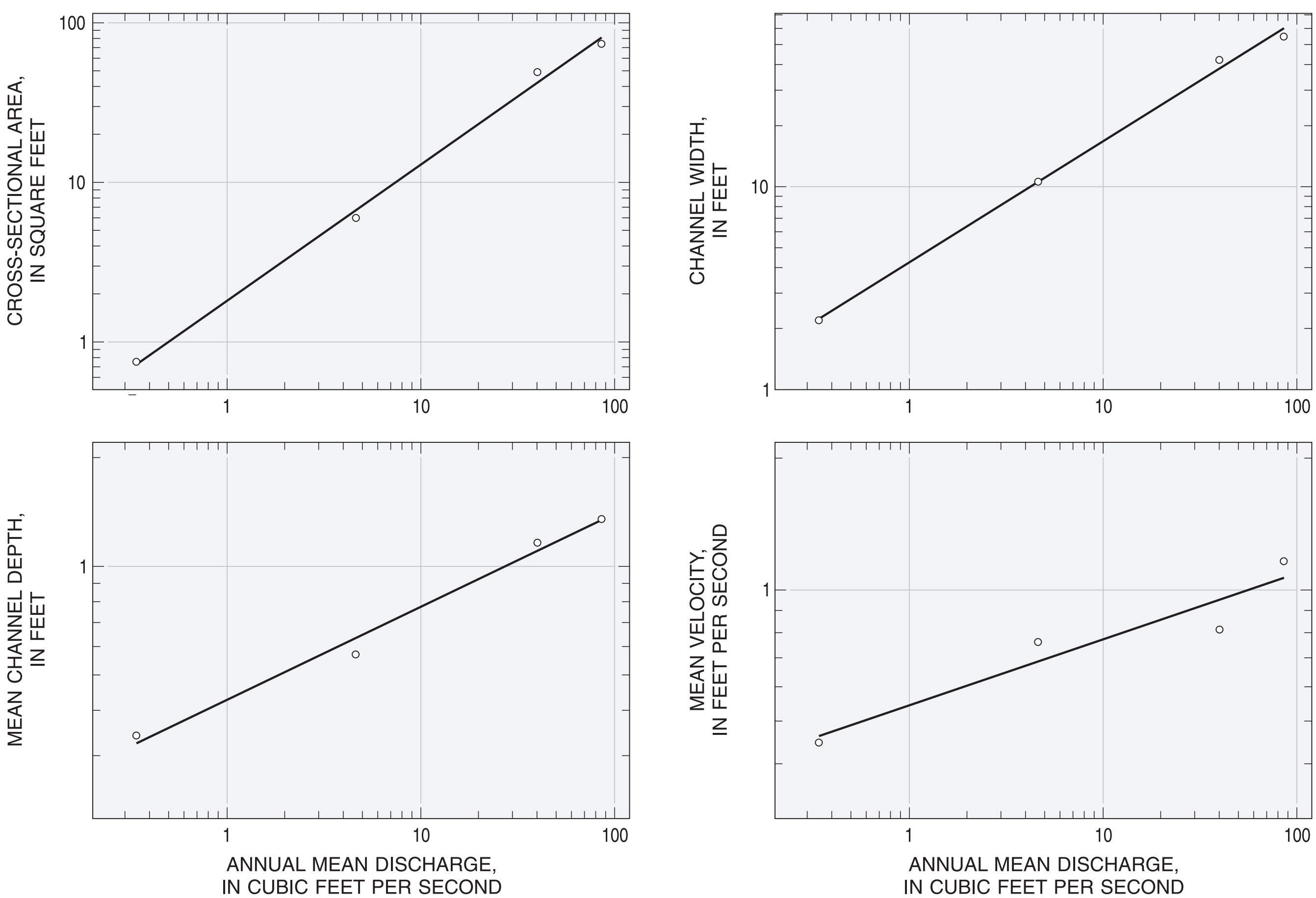


**Figure 15.** Relations of channel geometry variables to annual mean discharge for continuous-record streamflow-gaging stations on the main stem of Gwynns Falls, Baltimore County and Baltimore City, Maryland.

## Limitations of Analyses and Implications for Further Study

The regression equations developed for this report are intended as tools for generally describing changes in channel geometry variables with increasing stream discharge and drainage area. The equations are intended for use only within the range of streamflow conditions for which they were developed. Due to the typical data scatter associated with hydraulic geometry analysis, the equations are not intended for direct use in designing stream-restoration projects.

Locations of cross sections for measuring discharge differed slightly in some cases due to changes in measuring conditions between station visits. Changes in cross-section location can contribute to scatter in the hydraulic geometry regressions, but is commonly necessary to accurately measure the discharge over a range of depths and flow conditions.

The cross-section plots presented in this report were developed from incremental widths and depths that were documented during measurements of discharge rather than by conventional leveling techniques. In some cases, plots represent only the range of depths defined by the measurements and not a full valley cross section.

The regression equations developed in this report were intended to establish a baseline condition for comparison of channel geometry variables along the main stem of Gwynns Falls. Additional discharge measurements and analysis at all four stations over longer periods of time could allow for additional comparisons of data between stations and a better assessment of potential impacts of urban development on channel geometry variables, as well as other streamflow characteristics.

The RSE associated with the hydraulic geometry relations could possibly be improved as the stations are operated for longer periods of time, and additional discharge-measurement data become available. Longer data records could also allow for investigation of geometry variable changes over time at individual stations. Inclusion of data from stations on tributaries to the main stem of Gwynns Falls could also provide more data points to improve the watershed analyses by drainage area and annual mean discharge.

## Summary and Conclusions

Four continuous-record streamflow-gaging stations are currently being operated by the U.S. Geological Survey on the main stem of Gwynns Falls in the western section of Baltimore County and Baltimore City, Maryland. These stations are operated in cooperation with the Baltimore Ecosystem Study, which is part of the Long-Term Ecological Research network of study locations. The Baltimore Ecosystem Study has been monitoring hydrologic conditions in the Gwynns Falls watershed since 1998 and is tasked with investigating long-term hydrologic changes in the Baltimore metropolitan area. Each of the four streamflow-gaging stations drains urban or suburban watersheds with significantly different drainage areas. In addition to providing continuous-record discharge data at these four locations, operation of these stations also provides a long-term record of channel geometry variables such as cross-sectional area, channel width, mean channel depth, and mean velocity that are obtained from physical measurement of the discharge at a variety of flow conditions.

The hydraulic geometry at the four continuous-record streamflow-gaging stations on the main stem of Gwynns Falls was analyzed on the basis of discharge-measurement data from the stations. Cross-sectional area, channel width, mean channel depth, and mean velocity were related to discharge for each station by use of simple linear regression. Relations were established that (1) quantify changes in geometry variables with changes in discharge at each station, and (2) quantify changes in geometry variables in the Gwynns Falls watershed with changes in drainage area and annual mean discharge.

Mean velocity was found to be more responsive to changes in discharge than either channel width or mean depth for all four stations on the main stem of Gwynns Falls. Cross-sectional area, which combines the effects of channel width and mean channel depth, was found to be more responsive to changes in discharge than mean velocity in the upper section of the Gwynns Falls watershed at the stations Gwynns Falls at Glyndon and Gwynns Falls near Delight. The relations for the stations at Gwynns Falls at Villa Nova and Gwynns Falls at Washington Boulevard at Baltimore, which are more heavily urbanized and developed watersheds, show greater responsiveness in velocity with changes in discharge than for cross-sectional area, channel width, or mean channel depth with changes in discharge. In comparing the hydraulic exponents that were developed from the hydraulic geometry analyses to average values, the velocity exponents for all four stations on the Gwynns Falls are larger than the average value of 0.34. The velocity exponents for Gwynns Falls at Villa Nova and Gwynns Falls at Washington Boulevard at Baltimore, which are in locations that drain more heavily developed areas of the watershed, are about twice as large as the average value.

Analyses of the hydraulic variables by drainage area and by annual mean discharge indicate that channel width is more responsive to changes in drainage area and annual mean discharge than are mean channel depth or mean velocity. Cross-sectional area was also found to be very responsive to changes in drainage area and annual mean discharge.

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# Glossary

### A

**annual mean discharge** The arithmetic mean of the individual daily mean discharges for a particular year, or for a designated period of time. The annual mean discharge values used in this report are those for the period of station record up to and including water year 2003 (October 1, 2002 to September 30, 2003).

### C

**coefficient of determination ($R^2$)** The fraction of the variation in the dependent variable that is explained by the explanatory variable(s). $R^2$ ranges between 0 and 1. The closer $R^2$ is to 1, the better the explanation of variation in the dependent variable with changes in the explanatory variable(s).

### R

**residual standard error (RSE)** The square root of the mean square error, which is the sum of the squared differences between the observed and predicted values divided by the number of observations minus 2. Residual standard error is also commonly known as the standard error of estimate.

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