FACT SHEET
Agriculture and Natural Resources

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Determining Discharge in a Stream

Andy Ward, Jessica L. D'Ambrosio, and Jonathan Witter
The Ohio State University Department of Food, Agricultural, and Biological Engineering
and the Ohio NEMO Program

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Introduction

Estimates of discharge in a channel are needed for many purposes and a wide range of scales. For example, the size of gutters and downspouts on a house requires knowledge of runoff from roofs. Similar knowledge would be needed to size rain barrels, bioretention areas, bioswales, and storm water systems. Discharge from these systems might enter constructed, modified, or natural channel systems and impact the equilibrium condition. Evaluating equilibrium in these systems would require knowledge of the channel-forming discharge. Throughout this network of different systems that collect, store, and convey water, knowledge might be needed on peak flow rate, quantity of flow, and frequency of these flows.

In many places flooding as a result of runoff is a concern. The term *runoff* is used to describe water that runs over the surface of the land. Knowledge is needed of the probability of extreme flows, such as the 50- or 100-year return period flows, impacting locations along the system. In this case, quantities of interest are the peak flow, the volume of flow, and the flow distribution with time (hydrograph). A hydrograph for Big Walnut Creek, a tributary of the Scioto River in central Ohio, is shown in Figure 1.

At the start of the hydrograph in Figure 1, the creek contained a low amount of flow, called baseflow, that consisted of snow melt, runoff from earlier events, a contribution from groundwater, and urban and industrial discharges into the creek (Point A). At about 25 hours, a winter storm event began that was a mixture of rainfall, freezing rain, and snow. The storm event produced more than 1 inch of precipitation. As a result, discharge in the channel began to increase (Point B). At about 65 hours, the hydrograph reached a peak that was a little larger than the channel-forming discharge, and it caused some flooding (Point C; and Figure 2). The slow falling (receding) limb of the hydrograph was caused by snowmelt, releases from an upstream dam, and some small precipitation events (Point D).

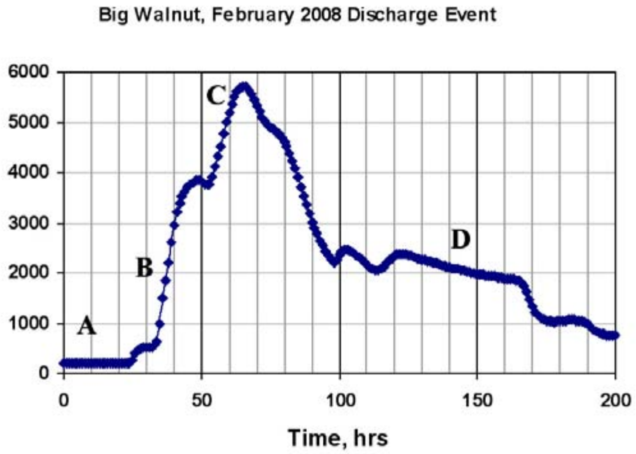

Figure 1. Discharge hydrograph at USGS Gage 03229500 Big Walnut Creek at Rees, Ohio, showing 4 different phases: A) beginning of storm event, B) rising limb, C) peak discharge, and D) falling limb.

Figure 2. Flooding resulting from the discharge event shown in Figure 1 on the Big Walnut at Rees (left) and a small tributary to Big Walnut Creek (right).

The four general approaches to determining discharge in a channel are as follows:

1. Calculate discharge based on the hydraulics of the channel.
2. Determine the discharge based on measuring the velocity of flow in a channel.
3. Estimate discharge based on calculating runoff from a storm event.
4. Determine discharge based on a gage that measures changes in flow stage and a previously determined relationship between stage and discharge.

Each of these approaches has important uses as well as limitations and uncertainties. This fact sheet describes these issues with a focus on how to reduce uncertainties in discharge estimates. Other methods, such as those that determine discharge associated with groundwater or snowmelt long after a storm event, will not be presented.

Determining Discharge in a Channel

Method 1: Calculating Discharge Based on Channel Hydraulics

Discharge is calculated by knowing the cross-sectional area of the channel and the average velocity of the flowing water (see Figure 3). This is also called the *continuity equation*:

$$q = va$$

where, q is discharge (ft^3/sec), a is cross-sectional area of the stream (ft^2) and v is average velocity of flowing water (ft/sec). Determining average velocity is not simple, as the flow can have many forms. Often it is turbulent in some places and very tranquil in others. Sometimes the flow might actually move in an upstream direction while at other times or other locations the flow might flow over natural or constructed structures such as beaver dams and weirs.

If flow is fairly uniform and not very turbulent, average velocity can be estimated by *Manning's equation*:

$$v = \frac{1.5}{n} R^{2/3} S^{1/2}$$

Where *v* is average velocity (ft/s), *S* is slope of the channel bed (ft/ft), *R* is hydraulic radius of the channel (ft), and *n* is the Manning's roughness coefficient. Manning's *n* is an indicator of how much resistance to flow a channel bed has, and obtaining an accurate estimate of its value is difficult. The hydraulic radius of the channel, *R,* is the cross-sectional area of the flow divided by the wetted perimeter of the channel cross-section.

A limitation of this method is that it does not provide information on the return period of the discharge. The main sources of uncertainty are unaccounted for variability in flow at different places in the cross-section, and Manning's *n* cannot be determined easily from field measurements. Normally, Manning's *n* is estimated based on published values that are associated with general descriptions of the flow conditions. Estimation errors of 50% are probable.

Method 2: Measuring Discharge

*The following description was obtained from a USGS presentation on Data Collection at U.S. Geological Survey Stream Gages (**http://md.water.usgs.gov/publications/presentations/md-de-dc_rt98/sld001.htm**)*

The most practical method of measuring stream discharge is through the velocity-area method. Discharge is determined as the product of the cross-sectional area of the water and velocity. Measuring average velocity of an entire cross-section is impractical, so the United States Geological Survey (USGS) uses what's called the mid-section velocity-area method. Using this method, the width of the stream is divided into a number of increments, each usually

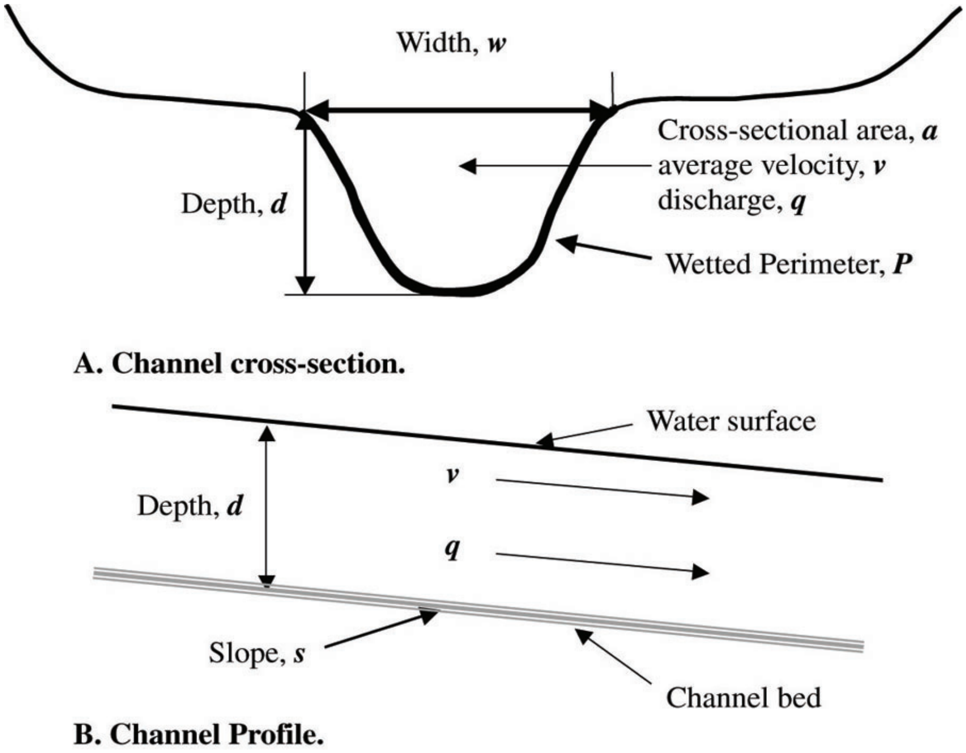

Figure 3. Channel cross-section (A) and profile (B) of a typical stream showing parameters used in calculating discharge.

containing no more than 5% of the total discharge. For each incremental width, stream depth and average velocity are measured with a current meter. The product of velocity, depth, and width of the section is the discharge through that increment of the cross-section. The total of the incremental discharges equals the discharge of the stream.

Like Method 1, a limitation of this method is that it does not provide information on the return period of the discharge. Also, the discharge that occurs on the day that measurements are made is arbitrary and if made by wading, will need to be much less than the channel-forming discharge for safety reasons. The approach is useful, however, in making estimates of Manning's roughness coefficient, and is used to develop relationships (called *rating curves*) between discharge and stage at USGS stream gages.

Method 3: Estimating Discharge Using Runoff Methods

Watershed-scale factors affecting runoff are drainage area size, topography, shape, and orientation; geology; interflow; and perhaps most importantly, soils and land use. Depth from the ground surface to an impeding layer (i.e., heavy clay) and the interaction between surface and groundwater flow regimes will, in some locations, have a major influence on flows in channels and the response to precipitation of these connected systems. Runoff models can be grouped into landscape models and models based on measured discharge data. Numerous models have been developed primarily because of the wide range of complex conditions that require estimates of runoff and the rather poor performance of the models across the entire range of these conditions. Reference should be made to hydrology texts such as *Environmental Hydrology, 2nd Edition*[1] to obtain details on common models used today. For illustration purposes, later in this document we will use the Rational Method[2], the Natural Resource Conservation Service (NRCS) Graphical Peak Discharge Method[3], and the USGS rural and urban peak discharge methods[4,5], all of which are based on a statistical analysis of measured discharge data. Each of these methods is simple to use but often provides poor estimates of discharge.

In the United States, the Rational Method is one of the most widely used empirical methods for estimating peak discharge in watersheds that are less than a few hundred acres:

$$q = CiA$$

where *q* is peak flow (cfs), *C* is an empirical coefficient, *i* is average rainfall intensity (in/hr) during the time of concentration, and *A* is drainage area (acres). *Time of concentration* is the time it takes flow to move from the most remote point on a watershed to the outlet of the watershed. This longest flow path is called the *hydraulic length*. Limitations to this method are that it does not account for all the variables that influence runoff, and there are considerable inaccuracies in determining the time of concentration and the *C* factor. Without calibration, errors in estimating peak flow might easily be greater than 100 percent.

The most commonly used method in the United States for estimating runoff volume is the NRCS curve number procedure[6]:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

where *Q* is accumulated runoff or rainfall excess in inches, *P* is rainfall depth in inches, and *S* is a parameter given by:

$$S = \frac{1000}{CN} - 10$$

where *CN* is known as the curve number. The curve number is a function of soil properties, antecedent soil moisture conditions, and land use. Lookup tables are used to determine the curve numbers. The major limitation to this method is that it is difficult to obtain accurate estimates of curve numbers that adequately depict runoff conditions for the drainage area of interest.

The Graphical Peak Discharge method was developed for application in small rural and urban watersheds. It was developed from hydrograph analyses using the TR-20 *Computer Program for Project Formulation—Hydrology*[7] and has seen widespread application. The peak discharge equation is:

$$q = q_u AQF$$

where q is peak discharge (cfs), q_u is unit peak discharge (cfs per square mile per inch of runoff, csm/in), A is drainage area (mi2), Q is runoff depth (inches) based on 24 hours, and F is an adjustment factor for ponds and swamps. This method depends on the curve number method to obtain Q and the necessary information to determine q_u (Figure 4).

For Ohio and most central regions of the United States, the value of q_u can be determined from Figure 4. The value of Q that is used in this method is not intuitive and, like the Rational Method, obtaining an accurate estimate of the time of concentration is difficult.

The USGS rural peak discharge regression equations are available for all 50 States, Puerto Rico, and American Samoa. Urban peak discharge regression equations have been developed for the nation and the following states: Alabama, Georgia, Montana, North Carolina, Ohio, Oregon, Tennessee, Texas, and Wisconsin. The rural and urban regression equations are based on measured stream discharges, are simple to use, and are accepted by the Federal Emergency Management Agency (FEMA) and many state and federal agencies. Due to the short length of record of the stream gage data used to develop many of the equations, there are 15%–100% estimation errors in peak discharges using the USGS equations. Another limitation to this method is that most of the urban equations are suitable only for use on small watersheds (less than a few square miles). The application of the rural equations varies from watersheds that are less than a few square miles to more than a thousand square miles. It is recommended that the reader check with the USGS for the most current equations available for their region and for the applicable size of watershed.

Method 4: Determining Discharge from Stream Gage Measurements

The USGS collects stream data from gages, including real-time data, at more than 1.5 million sites in the United States (**http://waterdata.usgs.gov/oh/nwis/**), often having many decades of discharge information. Figure 5 illustrates the distribution of real-time sites within the United States, which provides useful information on discharge events as they occur and on stage and discharge within the previous 31 days. The hydrograph in Figure 1 was obtained from this database.

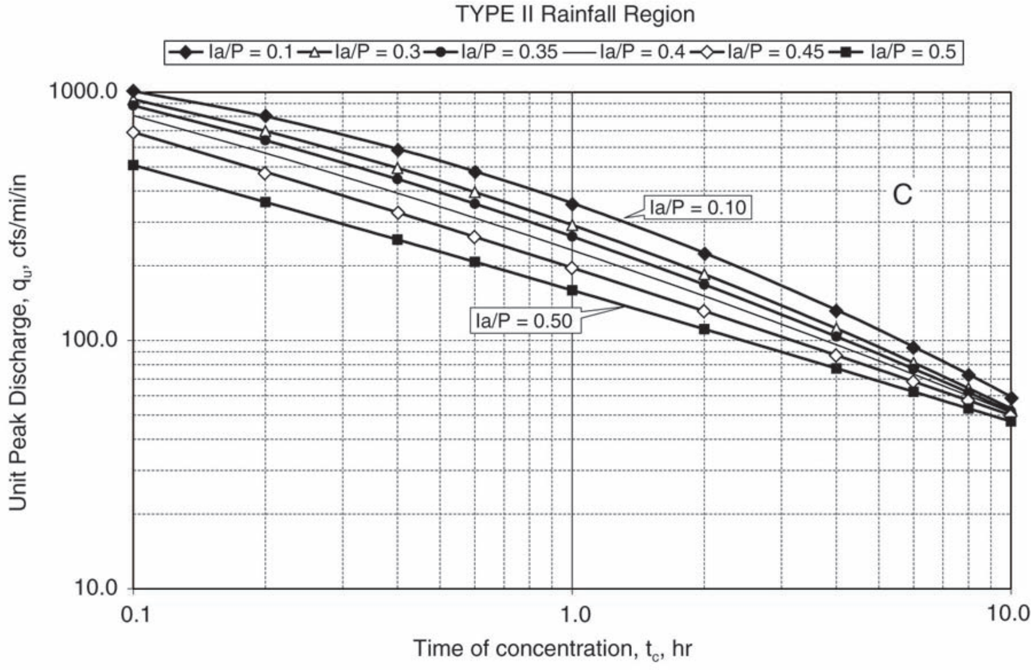

Figure 4. Relationship between Unit Peak Discharge, q_u, and Time of Concentration for Ohio. The term *Ia* is equal to *0.2S* in the fourth equation in this fact sheet.

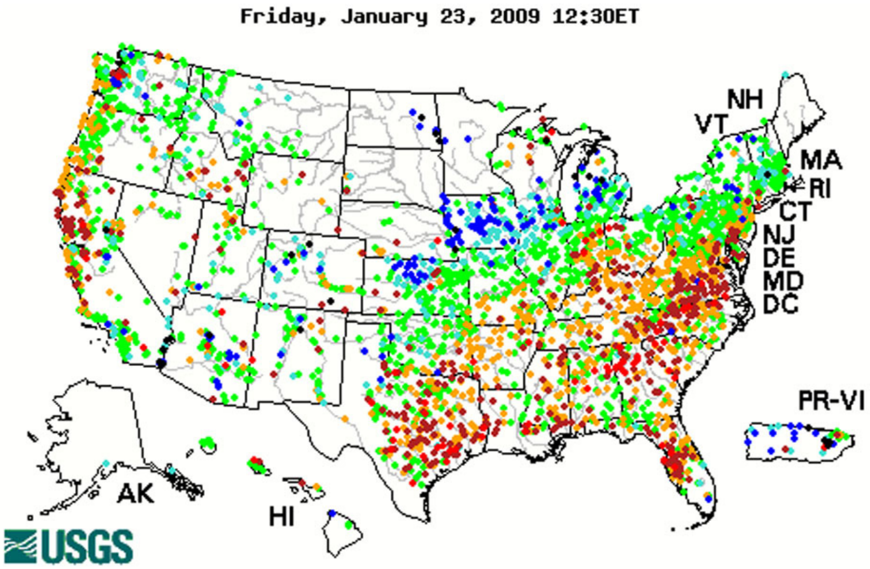

Figure 5. Real-time stream pages in the United States. The colors provide an indication of the probability of the measured flow occurring on this day of the year.

In addition to real-time data, other data collected at gages include stage, discharge, and some water quality. One useful database available for each gage is information on the annual peak instantaneous discharge for each year since the establishment of the gage. These data commonly are used to develop a relationship between discharge and return period (also called recurrence interval, RI). To develop the relationship, an annual series of peak discharges is ranked from highest to lowest and then statistical analysis, such as the Weibull method[1], is performed to obtain the recurrence interval as follows:

$$R = \left(\frac{n + 1}{m}\right)$$

where *R* is the recurrence interval (years), *n* is the number of years of record and *m* is the rank of each discharge. Data are entered into a spreadsheet and then plotted on a semi-log (logarithmic x-axis) or log-log scale. The data usually will yield a linear relationship for the less frequent values (RI > 2 years), and will produce an "elbow" tailing down towards zero for the more frequent events (RI < 2 years; Figure 6). In practical applications, a regression (trend) line is fitted through all or part of the data or an interpolation approach is used to relate the bank-forming discharge to the return period. The smallest discharge plotted will have a return period that approaches one year.

Use of an annual series has practical advantages because, in the United States, this type of data is readily available and the number of values that need to be manipulated will be small. However, concern and confusion arises when we relate theory to the practical application of the approach. By definition an X-year RI event or larger will occur on average once every X years. For many streams, an evaluation of daily discharge values will show that frequent events (RI = 2 years or less) actually occur much more frequently than the RI suggests—perhaps several times annually for a 1-year event. This approach is best suited for extreme events and it is unclear how appropriate it is for frequent events. The period of record needed will vary based on the range of flows that occurred during the period of record. Records that exceed 30 years usually provide good confidence and commonly produce Pearson Product Moment relationships that exceed 0.9. Once a relationship has been determined, the return period can be determined for other events such as the 10-year, 50-year, 100-year, and channel-forming discharge.

The primary limitation of this method is that gages usually are not located in the vicinity of many

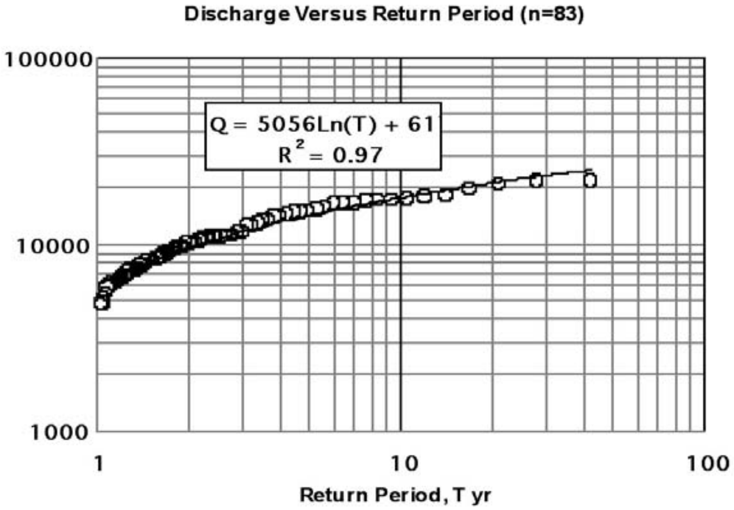

Figure 6. Discharge versus return period relationship at the USGS gage on Big Walnut Creek at Rees, Ohio.

projects requiring discharge versus return period information, and most long-term and active gages obtain information for much larger drainage areas than the majority of stream projects; however, those discharge-return period relationships are very useful in calibrating runoff models such as those used in Method 3 discussed earlier.

Calibration of Discharge Methods for Ungaged Watersheds

Two calibration methods will be illustrated by using USGS discharge data for the 544 mi^2 watershed that drains to the Big Walnut Creek gage at Rees, Ohio, to improve discharge estimates for the approximately 1 mi^2 tributary shown in Figure 1. Both methods are based on the assumption that land use, soil, and topographic conditions for the two watersheds are similar and calibration factors at the gage can be applied to the small tributary. This was an actual analysis performed on the small tributary to aid in evaluating its geomorphology so that it could be relocated to reduce flooding impacts on houses in a new residential area.

The first step is to use the historic annual peak discharge data series measured at the gage to develop a relationship such as that shown in Figure 4. Then, one or more hydrologic models are used to develop similar predicted relationships. In this case, both the USGS Urban and Rural Peak Discharge Methods were used. The USGS Urban Method is not intended for use in watersheds larger than a few square miles and often will greatly over-predict discharge for larger drainage areas; however, for small watersheds that are undergoing urban development, it is more useful than the Rural Method because it accounts for the influence of urban development on discharge.

A summary of the measured and predicted discharge values for return periods ranging from 2 to 50 years are shown in Table 1. As information relating to channel forming discharges was of interest in this particular analysis, the values in Row 1 were obtained by taking the ratio of the values in Row 2 to the measured 2-year return period discharge of 9,682 cfs. For example, the 50-year measured discharge of 25,957 cfs is 2.68 times 2-year return period discharge of 9,682 cfs.

The values in Row 4 are the ratios of the measured and predicted discharges obtained using the USGS Urban Method. For example, 0.73 is the ratio of measured 2-year return period discharge of 9,682 and the predicted (calculated) 2-year return period discharge of 13,292 cfs. Similarly, the values in Row 8 are the ratios of the measured discharges and the predicted discharges obtained using the USGS Rural Method.

Calibration 1 multiplied the 2-year predicted value by the calibration ratio of 0.73 for the 2–year return period (Rows 5 and 9). These values were then

Table 1. Discharge (cfs) versus return period (years) data for the USGS gage on Big Walnut Creek at Rees, Ohio.

		Return Period (years)			
Method of Discharge Prediction	**Row**	**2**	**10**	**25**	**50**
Measured Ratio	1	**1.00**	**1.84**	**2.32**	**2.68**
Measured	2	9,682	17,820	22,453	25,957
USGS Urban Un-calibrated	3	13,292	55,848	85,948	114,555
Row 2/Row 3 Calibration Ratio	4	**0.73**	**0.32**	**0.26**	**0.23**
USGS Urban Calibration 1	5	9,682	17,820	22,453	25,957
USGS Urban Calibration 2	6	4723	19,842	30,537	40,701
USGS Rural	7	11,819	24,809	32,021	37,463
Row 6/Row 7 Calibration Ratio	8	**0.82**	**0.72**	**0.70**	**0.69**
USGS Rural Calibration 1	9	9,682	17,820	22,453	25,957
USGS Rural Calibration 2	10	8,581	18,010	23,247	27,197

multiplied by the measured ratios (Row 1) for each return period. Therefore, at the gage, the measured and calibrated predicted values were identical regardless of the method used. One of the other calibration ratios in Row 4 could have been used, but the 2-year event was chosen because we were most interested in the channel-forming discharge.

Calibration 2 multiplied each of the un-calibrated predicted values by a single calibration ratio. In this example, the average of the ratios in Row 4 was used (a value of 0.35) for the USGS Urban Method, and the average of the ratios in Row 8 was used (a value of 0.73) for the USGS Rural Method. An alternative approach is to use the largest ratio in Rows 4 and 8 for the USGS Urban Method and the USGS Rural Method, respectively.

Calibration results were then applied to the ungaged small tributary (results are summarized in Table 2). For illustration purposes, all results in this table are related to the USGS Urban Method using **Calibration 1**. For example, the un-calibrated 2-year discharge for the USGS Urban Method is 1.3 times the calibrated value. In addition to the two USGS Methods, un-calibrated results are presented for Rational Method and the Graphical Peak Discharge Method. Like the USGS methods, a calibration could have been done with these methods if they had also been used to make estimates at the gage. However, results from the Rational Method are not valid since the method was not developed for use on watersheds larger than just a few square miles.

Intuitively, it might seem that a better approach than **Calibration 2** might be to use each of the calibration ratios in Rows 4 and 8 in Table 1. However, it can be seen in Table 2 that if this approach is used, as represented by the USGS Urban Poor and USGS Rural Poor values, some of the calibrated results will not be logical. For example, the 50-year discharge for the USGS Urban Poor approach was obtained by multiplying the un-calibrated result by 0.23. This gives a 50-year relative discharge that is the same as the 25-year relative discharge.

It can be seen that even with calibration there is variability in discharge estimates obtained by different methods. If the results are extended to the more frequent events associated with channel-forming discharges, the variability increases and, on occasion, a very small or negative discharge might be predicted. In summary, the **Calibration 1** approach is recommended because it provides the most consistent results.

Table 2. Relative discharge (cfs/cfs) versus return period data for an approximately 1-mi^2 tributary of Big Walnut Creek in Ohio.

	Return Period (years)			
Method	**2**	**10**	**25**	**50**
USGS Urban Un-calibrated	1.3	3.6	4.9	5.8
Calibrated 1	1.0	1.8	2.3	2.7
Calibrated 2	0.5	1.3	1.7	2.1
USGS Rural Un-calibrated	0.8	1.9	2.5	3.0
Calibrated 1	0.7	1.2	1.5	1.8
Calibrated 2	0.6	1.4	1.8	2.2
Rational Method	1.3	1.5	1.7	1.8
Graphical Peak Discharge	1.0	2.4	3.2	3.9
USGS Urban Poor	1.0	1.1	1.3	1.3
USGS Rural Poor	0.7	1.4	1.8	2.1

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Keith L. Smith, Ph.D., Associate Vice President for Agricultural Administration and Director, Ohio State University Extension

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