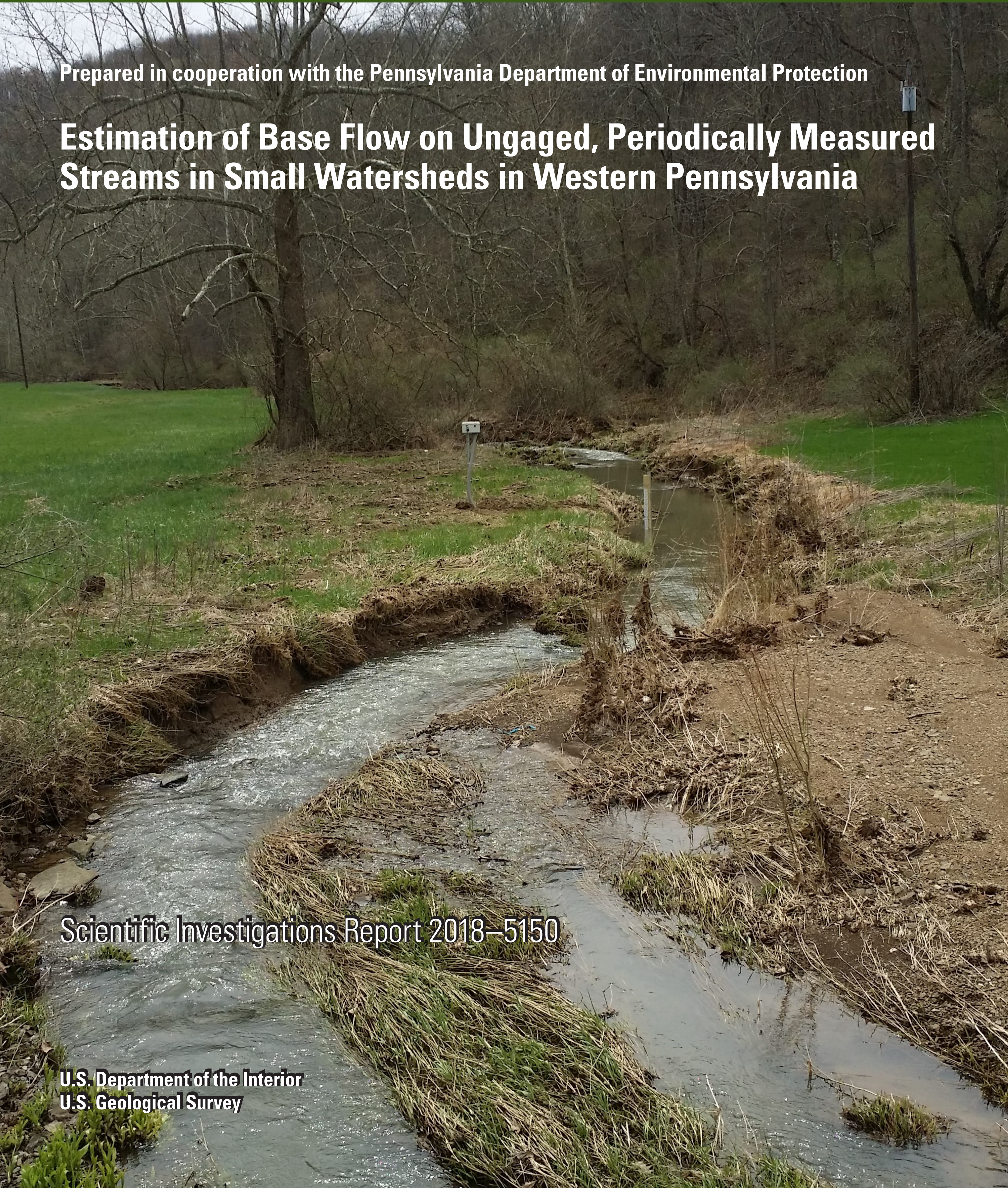
Prepared in cooperation with the Pennsylvania Department of Environmental Protection

Estimation of Base Flow on Ungaged, Periodically Measured Streams in Small Watersheds in Western Pennsylvania



Scientific Investigations Report 2018–5150

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

Cover: Photo of U.S. Geological Survey station 03114094, representative of the streams that were monitored for this project, Herod Run near New Freeport Pa., April 16, 2015, photograph by Stephanie Roussel, U.S. Geological Survey.

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U.S. Geological Survey
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U.S. Geological Survey, Reston, Virginia: 2019

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Suggested citation:
Hittle, E., and Risser, D.W., 2019, Estimation of base flow on ungaged, periodically measured streams in small watersheds in western Pennsylvania: U.S. Geological Survey Scientific Investigations Report 2018–5150, 42 p., https://doi.org/10.3133/sir20185150.

ISSN 2328-0328 (online)

Acknowledgments

The authors wish to acknowledge Michele Hamlin at the Pennsylvania Department of Environmental Protection for her help with data requests and general information throughout the project and the U.S. Geological Survey (USGS) personnel in the Pennsylvania Water Science Center, Pittsburgh office, for their hard work and dedication to this project. The authors thank William Farmer, Greg Koltun, Marla Stuckey, and Linda Zarr, of the USGS, for their careful reviews and helpful suggestions.

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Figures

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Streamflow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile ($[ft^3/s]/mi^2$)	0.01093	cubic meter per second per square kilometer ($[m^3/s]/km^2$)

Datum

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

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

Abbreviations

GZF	Gage height of Zero Streamflow
HISAZ	Highest Index Streamflow At Zero
K	Median Recession Index
MOVE.1	Maintenance of Variance Extension, Type 1
MRC	Master Recession Curve
NSE	Nash-Sutcliffe Efficiency
PADEP	Pennsylvania Department of Environmental Protection
r	Pearson’s correlation coefficient
USGS	U.S. Geological Survey

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Abstract

A 2.5-year data collection program was undertaken by the U.S. Geological Survey, in cooperation with the Pennsylvania Department of Environmental Protection (PADEP), to quantify and estimate base flow in small watersheds in western Pennsylvania where only periodic streamflow measurements had been obtained. Twelve streamgages with watershed areas of less than 10 square miles were established in western Pennsylvania for this study, with most established within Greene and Washington Counties (an area where a type of underground coal mining known as longwall mining occurs). Data from five previously established streamgages with watershed areas ranging from 48.9 to 281 square miles were also used in the analyses for this study. The index-gage method was used to relate streamflow at one streamgage referred to as the "index streamgage" to streamflow at another site of interest (usually an ungaged site, but for this study another streamgage) using a regression technique.

Streamflow regressions were developed for all newly established streamgages by using the Maintenance of Variance Extension, Type 1 (MOVE.1) method. Not all streamflow data from the newly established streamgages were used for MOVE.1 regression development; only data that have little to no influence from runoff were considered. Runoff-influenced streamflow for this study was defined as streamflow on a day that precipitation occurs plus streamflow on the following 2 days. One streamflow value per day selected from a specified schedule that captures numerous non-runoff periods was used to develop a MOVE.1 regression.

Prediction limits were calculated from the regression to provide the upper and lower bounds for the regression-produced streamflow estimates. Using these data, base flow at a site can be estimated with the index-gage method. The log_{10}-tranformed prediction interval width and other regression diagnostics were used as indicators of regression quality when comparing streamgage relations to determine the best index streamgage among the streamgages established for this study. It was determined that index streamgages within about 10 miles of the site of interest provided the best estimated base flow and could, in the future, be used by mine operators and the PADEP to quantify base flow and to evaluate the effects of mining on streamflow.

Introduction

In areas where human activity can affect streamflow overall and base flow specifically, there is a need for water resource managers to assess hydrologic conditions and estimate base flow in a watershed of a stream as if it were not appreciably affected by human activities, such as mining, water regulation, municipal/industrial water supply, or other water withdrawals or inputs. It is acknowledged that there are other activities in the stream watersheds, such as farming, oil and gas production, and water supply for private wells, but these factors were not considered for this study. Base flow is the sustained flow of a stream in the absence of direct runoff (U.S. Geological Survey, 2017). If periodic streamflow measurements at an ungaged site are made to establish base-flow conditions in advance of land-use change or land disturbance and a similar watershed, that is unchanged or undisturbed, with an established streamgage that continuously monitors streamflow is present in the area, it is possible to develop a relation and estimate base flow at the periodically measured site.

Longwall mining is an example of a human activity with the potential to affect streamflow in southwestern Pennsylvania. The Kentucky Coal Education organization describes longwall mining as follows: "longwall mining is a highly productive underground coal mining technique. Longwall miners extract 'panels', which are rectangular blocks of coal. Massive shearers cut coal from a wall face, which falls onto a conveyor belt for removal. As a longwall miner advances along a panel, the roof behind the miner's path is allowed to collapse." (http://www.coaleducation.org/technology/Underground/Longwall_Mining.htm, accessed December 15, 2017). As the roof collapses, a void is created causing the void walls to compress and the overlying rock to tilt and collapse into the void. The effects of this collapse can be seen at the surface because the land directly above and some distance beyond the void collapses vertically; the collapse is called land subsidence.

(http://www.iesc.environment.gov.au/publications/subsidence-longwall-coal-mining, http://pittgeosociety.dot5hosting.com/subsidence.pdf, accessed June 15, 2018). In 2008, the size of the longwall panels in southwestern Pennsylvania ranged between 1,200 and 1,500 feet (ft) in width and were often more than 10,000 ft in length (Tonsor and others, 2014). Subsidence caused by longwall mining of coal beneath streams can cause streamflow to be temporarily or permanently disrupted. This disruption can be a change to the streamflow in the guise of streamflow reduction, a difficult scenario to quantify, or complete loss of streamflow in the stream. Although cessation of flow in small headwater streams can be a natural occurrence during seasonally dry periods in a given year, mining induced subsidence may enhance the effect by temporarily or permanently affecting the groundwater hydrogeology by creating fractures, changing hydraulic conductivity, and increasing the capacity of the subsurface to store water. Studies have been done in Greene County documenting changes in hydraulic conductivity (Karacan and Goodman, 2009) and groundwater hydrogeology (Walker, 1988; Li and others, 2015) due to longwall mining.

For mining plans that may cause subsidence of intermittent or perennial streams or valley floors immediately adjacent to streams, the Pennsylvania Department of Environmental Protection (PADEP) requires coal-mine operators to make periodic streamflow measurements. Measurements of instantaneous streamflow must be made at locations representative of the undermined area in these streams monthly for 2 years prior to mining, on a weekly basis for 6 months immediately prior to mining, and every day for 2 weeks prior to undermining the area of interest (Pennsylvania Department of Environmental Protection, 2005). Daily streamflow measurements must continue until the longwall face advances beyond the area of concern. Additionally, if a streamflow loss occurs, which is defined by PADEP as the absence of water in an intermittent or perennial stream channel, daily streamflow measurements must continue until streamflow fully recovers to a normal range of conditions, is fully restored, or it is found that the loss of streamflow in the stream is not the result of underground mining operations. A normal range of conditions for streamflow is defined as "the variation of a monitored parameter (especially flow) that exists in the absence of drought or human influences…." (Pennsylvania Department of Environmental Protection, 2005). All streamflow measurement results are provided to PADEP to characterize the normal range of streamflow in the stream and determine whether a mining induced streamflow loss has occurred. If mining induced streamflow loss has occurred, the operator must implement remediation efforts until streamflow has been restored (Pennsylvania Department of Environmental Protection, 2005). Owing to the high density of streams in southwestern Pennsylvania, the streams that potentially can be affected by longwall mining often have watershed areas less than 1 square mile (mi^2).

As described in the previous paragraph, streamflow is monitored for approximately 2.5 years before mining commences to determine the normal range of streamflow; base flow is not necessarily targeted. However, if the time frame that is monitored is particularly wet or dry, these conditions may not relate well to future conditions. Techniques used to describe ranges of flow, such as the 7-day 10-year low streamflow frequency statistic, require at least 10 years of continuous daily streamflow record (Ries and Eng, 2010) in order to capture a wide range of environmental conditions. A technique that uses another streamgage to help estimate streamflow statistics at an ungaged site is the watershed-area ratio method. This technique assumes that the streamflow at an ungaged site is the same per unit area as at a nearby site, and streamflow statistics such as those mentioned earlier in this paragraph are adjusted accordingly. Sloto and others (2017) show that the watershed-area ratio method is generally most accurate when the watershed-area ratio for an ungaged site of interest is 0.33–3 times the watershed area of the index streamgage. However, existing streamgages that can be used as index streamgages are often in watersheds with watershed areas many times larger than the site of interest.

This study, conducted by the U.S. Geological Survey (USGS) in cooperation with the PADEP, examined the index-gage method for estimating base flow at ungaged, periodically measured sites in the bituminous coal region of southwestern Pennsylvania. To augment periodic streamflow measurements, an estimate of base flow in a small watershed can be made using an index streamgage for comparison. Index streamgages should account for short-term fluctuations in precipitation that are different from long-term trends that would be captured by streamflow statistics mentioned such as the 7-day 10-year low streamflow frequency statistic. For the purposes of this report, the term "periodically measured" refers to a stream that does not have an autonomous sensor that is measuring stage at a continuous interval, such as 15 or 60 minutes (ungaged site). A small watershed is herein defined as a watershed with a watershed area of less than 10 mi^2. Estimating the base flow of a stream not appreciably affected by human activities will assist mine operators and water-resource managers in determining whether or when a stream that has been affected by longwall mining returns to its natural streamflow conditions as defined by PADEP. For this application, the measurement period of the stream before mining occurs is approximately 2.5 years.

Purpose and Scope

The purpose of this report is to describe the results of a study that examined the use of index streamgages to estimate base flow at streams in small, ungaged watersheds where periodic streamflow measurements are made. This report describes the streamgage network established for this study, methods used to determine relations between streamgages, frequency of periodic streamflow measurements at the streamgages, and base-flow characteristics that can be used to determine how well the base flow at an index streamgage relates to streamflow at an estimation site in bituminous coal region of southwestern Pennsylvania and adjacent states. Analysis of the streamflow relations is used to determine a schedule for making the streamflow measurements needed to estimate base flow not appreciably affected by human activities and to evaluate the defined streamgage relations over a large area.

Description of Study Area

The study area is located in western Pennsylvania and encompasses low-streamflow region 4, as described by Stuckey (2006; fig. 1). Low-streamflow regions within Pennsylvania share similar geologic characteristics, base-flow characteristics, and precipitation patterns. The study area lies within three physiographic sections of the Appalachian Plateaus Physiographic Province and is underlain by twelve geologic formations ranging in age from Permian to Mississippian (fig. 1). The predominant land cover/uses in the region are urban and forested.

Streamgage Network

There were seven streamgages in the study area before the study began. One of the streamgages (03049800) is within an urban area and was excluded from this study owing to potential anthropogenic effects on streamflow. Streamflow at another streamgage (03106300) in the northernmost part of the study area is completely regulated by a dam and therefore was excluded from this study. Watersheds of the remaining five streamgages range in area from 48.9 to 281 mi^2 (table 1; fig. 1). To analyze streamflow in small watersheds with areas less than 10 mi^2, it was necessary to establish additional streamgages within the study area.

Potential watersheds for the establishment of streamgages were located using the website "eMapPA" developed by PADEP (http://www.depgis.state.pa.us/emappa/, accessed May 1, 2014). This website was used to identify water-use activities in the area that could affect streamflow, including water discharges, groundwater withdrawals, and surface-water withdrawals. Additionally, maps of past, current, and permitted longwall mining available on "eMapPA" were consulted. If an activity that could appreciably affect streamflow, including permitted longwall mining, was found to occur in a watershed, that area was not considered for a new streamgage. Other considerations for streamgage establishment included ability to obtain good streamflow record and ease of access. Locations that were relatively close to roads and bridges were given preference.

Twelve streamgages were established within the study area between August 2014 and May 2015; most were established in Greene and Washington Counties (fig. 1). Basin characteristics were determined using the USGS program StreamStats (http://streamstats.usgs.gov). Watershed areas of the newly established streamgages ranged from 0.28 mi^2 to 10.0 mi^2 (table 1). The percentage of urban land cover (2011) in these watershed areas was less than 12 percent, except for one streamgage (22 percent), and percentage of area covered by forest varied greatly among the watersheds (40–94 percent). The geologic unit formations that are closest to the land surface and the percentage of those formations at the surface in each watershed are listed in table 2.

Six of the newly established streamgages were continuous-record streamgages, where streamflow was measured at all stages to support a rating that would be applicable at all flows (table 1). The other six new streamgages were established as partial-record streamgages, where streamflow was measured only at low and medium stages.

Development of a Method for the Estimation of Base Flow on Ungaged, Periodically Measured Streams

The index-gage method is used to estimate streamflow at one site (ungaged) on the basis of streamflow from another hydrologically similar streamgage site referred to as the "index streamgage." The method and regression technique used to estimate base flow on an ungaged, periodically measured stream, based on the index-gage method, is described in the next section.

Index-Gage Method

The index-gage method relates instantaneous or daily mean values of streamflow at an index streamgage to instantaneous streamflow values at a site of interest using regression modeling. For this study, the index-gage method was used to estimate streamflow at the site of interest (referred to herein as the "estimation site") for a period when observed streamflow occurred at the index streamgage and estimation site; then the observed and estimated streamflow values could be compared. Data from the index streamgage and the estimation site were analyzed in MOVE.1. Streamflow values (1 value per day or 1 value every 2 or 3 days) from the estimation site were selected to simulate periodically measured streamflow. Each set of MOVE.1 regressions was evaluated as a function of the Nash-Sutcliffe Efficiency, Pearson's correlation coefficient (r), and the log prediction interval width. The results of all index-gage method analyses are available in a companion data release (Hittle, 2019a). The data release contains an Excel workbook for every data regression developed for this study; each workbook includes the MOVE.1 regression development data, regression analysis, regression diagnostics, and streamflow evaluation (if data were available).

MOVE.1 Regression Technique

The relation between streamflow at two streamgages in this study is described by a Maintenance of Variance Extension, Type 1 (MOVE.1) regression (Hirsch, 1982; Helsel and

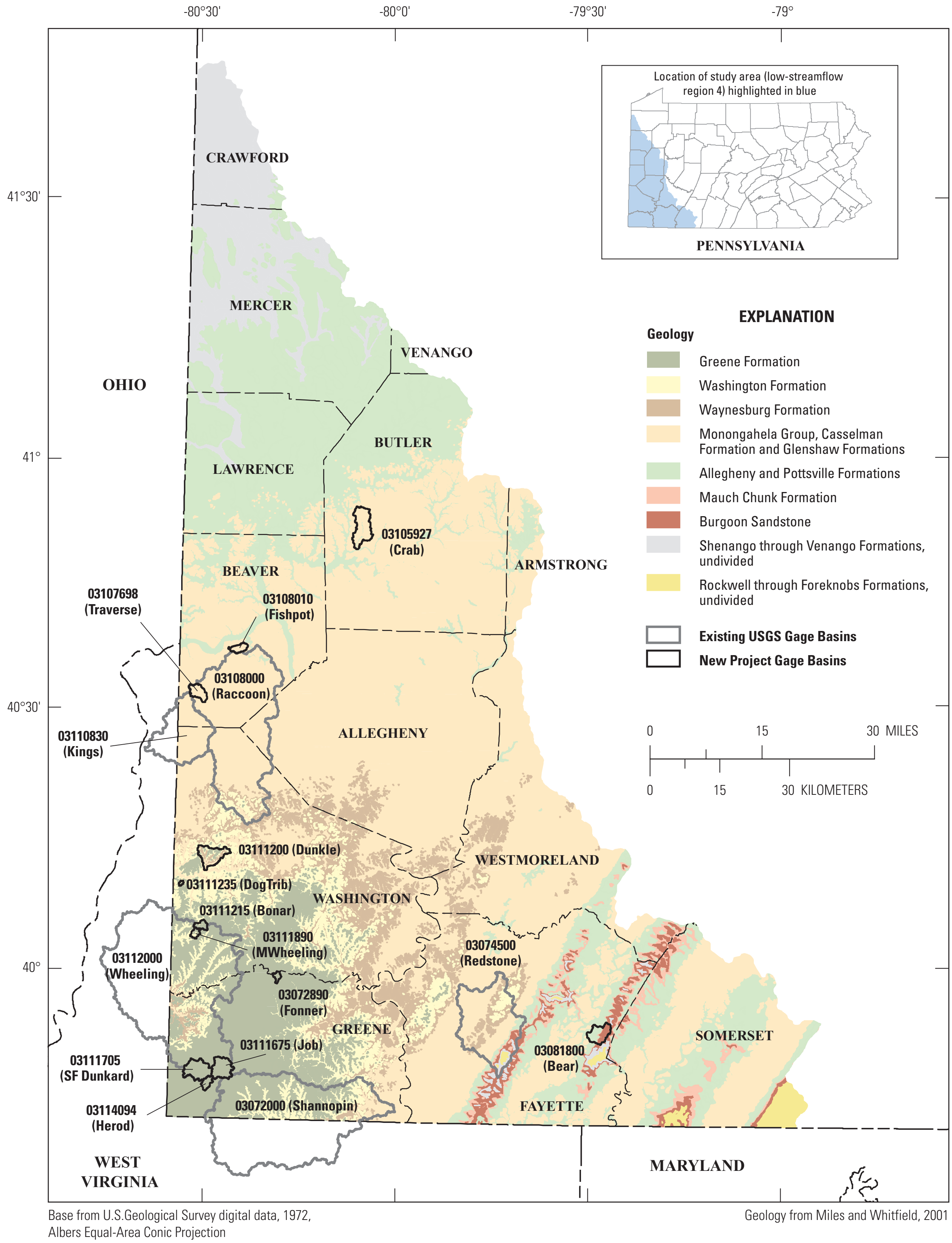

Figure 1. Location of existing and newly established streamgages in the study area in western Pennsylvania.

Table 1. Description of streamgages used in analysis, by county, in western Pennsylvania.

[USGS, U.S. Geological Survey; PA, Pennsylvania; WV, West Virginia; NLCD, National Land Cover Database; *, streamflow computed at all stages]

USGS station identifier	Station name	Station short name	Watershed area (square miles)	Pennsylvania county	Developed (urban) land, from NLCD (2011) (percent)	Forested area, from NLCD (2011) (percent)
03111675	* Job Creek at Delphene, PA	Job	6.57	Greene	5.5	87
03111705	* South Fork Dunkard Fork at Aleppo, PA	SF Dunkard	7.68	Greene	6.5	73
03114094	Herod Run near New Freeport, PA	Herod	1.79	Greene	5.2	80
03072890	Fonner Run near Deer Lick, PA	Fonner	0.99	Greene	3.1	90
03072000	* Dunkard Creek at Shannopin, PA[1]	Shannopin	229	Greene	6.5	78
03112000	* Wheeling Creek at Elm Grove, WV[1]	Wheeling	281	Greene/Washington	6.1	73
03111890	Middle Wheeling Creek near Claysville, PA	MWheeling	1.24	Washington	5.4	46
03111215	Bonar Creek near Claysville, PA	Bonar	1.62	Washington	12.4	51
03111235	Unnamed trib to Dog Run at Dunsfort, PA	DogTrib	0.28	Washington	1.5	79
03111200	* Dunkle Run near Claysville, PA	Dunkle	7.70	Washington	5.6	40
03110830	* Kings Creek at Weirton, WV[1]	Kings	48.9	Beaver/Washington	11.2	86
03107698	* Traverse Creek near Kendall, PA	Traverse	3.82	Beaver	6.7	66
03108010	Fishpot Run near Shippingport, PA	Fishpot	2.11	Beaver	22.0	61
03108000	* Raccoon Creek at Moffatts Mill, PA[1]	Raccoon	178	Allegheny/Beaver/Washington	12.6	64
03105927	* Crab Run near Connoquenessing, PA	Crab	10.0	Butler	10.5	53
03081800	* Bear Run at Kauffman, PA	Bear	5.77	Fayette	4.1	94
03074500	* Redstone Creek at Waltersburg, PA[1]	Redstone	73.7	Fayette	24.9	55

[1]Pre-existing streamgage, not established for this study.

Table 2. Description of newly established streamgages with the physiographic section and percentages of each underlying geologic formation, by county, in western Pennsylvania.

[USGS, U.S. Geological Survey; PA, Pennsylvania]

USGS station identifier	Station name	Pennsylvania county	Station short name	Physiographic section	Geologic unit closest to land surface from map of Miles and Whitfield (2001), as percent of watershed area									
					Greene Formation of Permian age	Washington Formation of Permian age	Waynesburg Formation of Permian and Pennsylvanian ages	Monongahela Group of Pennsylvanian age	Casselman Formation of Pennsylvanian age	Glenshaw Formation of Pennsylvanian age	Allegheny Formation of Pennsylvanian age	Pottsville Formation of Pennsylvanian age	Mauch Chunk Formation of Mississippian age	Burgoon Sandstone of Mississippian age
03111675	Job Creek at Delphene, PA	Greene	Job	Waynesburg Hills	100.0									
03111705	South Fork Dunkard Fork at Aleppo, PA	Greene	SF Dunkard	Waynesburg Hills	100.0									
03114094	Herod Run near New Freeport, PA	Greene	Herod	Waynesburg Hills	100.0									
03072890	Fonner Run near Deer Lick, PA	Greene	Fonner	Waynesburg Hills	100.0									
03111890	Middle Wheeling Creek near Claysville, PA	Washington	MWheeling	Waynesburg Hills	88.5	11.6								
03111215	Bonar Creek near Claysville, PA	Washington	Bonar	Waynesburg Hills	75.7	24.3								
03111235	Unnamed trib to Dog Run at Dunsfort, PA	Washington	DogTrib	Waynesburg Hills	55.8	38.9	5.3							
03111200	Dunkle Run near Claysville, PA	Washington	Dunkle	Waynesburg Hills	16.5	62.4	17.8	3.3						
03107698	Traverse Creek near Kendall, PA	Beaver	Traverse	Pittsburgh Low Plateau					85.6	14.4				
03108010	Fishpot Run near Shippingport, PA	Beaver	Fishpot	Pittsburgh Low Plateau					0.8	89.3	9.8			
03105927	Crab Run near Connoquenessing, PA	Butler	Crab	Pittsburgh Low Plateau						86.6	13.4			
03081800	Bear Run at Kauffman, PA	Fayette	Bear	Allegheny Mountain							37.6	17.4	8.0	37.0

Hirsch, 2002). This regression technique is commonly used for extending the length or filling missing periods of the streamflow record at a continuous-record streamgage. MOVE.1, which is referred to as the line of organic correlation, is preferred over more common linear regression techniques, such as ordinary least squares, because it preserves the inherent variance of streamflow data at the site to be estimated and results in an estimate of flow that is less biased than estimates from other methods. MOVE.1 is recommended when eight or more base-flow measurements are available for a partial-record streamgage and requires concurrent streamflow from a hydrologically similar index streamgage. The MOVE.1 method follows the equation

$$\hat{y} = \bar{y} + \frac{S_y}{S_x}\left(\hat{x} - \bar{x}\right) \quad (1)$$

where

- $\hat{y}$ is the estimated streamflow (transformed to log units) at the estimation site,
- $\bar{y}$ is the average of the observed streamflows (log units) at the estimation site,
- S_y is the standard deviations of the log transformed observed streamflows at the estimation site,
- S_x is the standard deviations of the log transformed observed streamflows at the index streamgage,
- $\hat{x}$ is streamflow (log units) at the index streamgage for which $\hat{y}$ is estimated, and
- $\bar{x}$ is the average of concurrent streamflows (log units).

MOVE.1 regressions were performed using the R statistical program (version 3.4.3) with the SMWRStats package (R Core Team, 2017; Lorenz, 2015) on $\log_{10}$-transformed data (referred to hereafter as "log transformed"). The following code within R was used.

```
library (smwrStats)
outputfile <- move.1 (estimation site
data ~ index streamgage data, data = data-
file, distribution = "commonlog")
```

Because log transformations are required, measurements of zero streamflow cannot be used (Curan and others, 2012). MOVE.1 regression output can be applied to the log-transformed index streamgage streamflow to estimate the streamflow at the estimation site.

Regression Diagnostics

To quantify MOVE.1 regression performance and aid in evaluation of the regression, three different regression diagnostics are presented, the Nash-Sutcliffe Efficiency, Pearson's correlation coefficient (r), and the prediction interval.

Nash-Sutcliffe Efficiency Coefficient

The Nash–Sutcliffe Efficiency (NSE) coefficient is used to assess the predictive power of hydrological models (Nash and Sutcliffe, 1970; McCuen and others, 2006; Jain and Sudheer, 2008). It is defined as

$$E = 1 - \frac{\Sigma_{t=1}^{T}\left(\hat{y}^t - y^t\right)^2}{\Sigma_{t=1}^{T}\left(y^t - \bar{y}\right)^2} \quad (2)$$

where

- E is Nash-Sutcliffe model efficiency,
- $\hat{y}$ is estimated value at time *t*,
- y is observed value at the estimation site at time *t*, and
- $\bar{y}$ is average of the observed values at the estimation site.

Krause and others (2005) describe the NSE as a value that can range from $-\infty$ to 1. An NSE value of 1.0 indicates a perfect fit between the estimated and observed values. An NSE value of zero indicates the goodness-of-fit is as good as using the mean of the observed values for the period, and a negative NSE value indicates that the mean of the observed values for the period provides a better fit than the individual estimated result. Differences between the observed and estimated values are calculated as squared values, and as a result, the model performance during extreme high or low streamflow is over-estimated or underestimated, respectively. For this study, the NSE was calculated on the log transformed values to reduce the sensitivity to extreme values (Krause and others, 2005).

Pearson's Correlation Coefficient

Pearson's correlation coefficient (r) measures the linear association between two variables (Helsel and Hirsch, 2002). It is defined as

$$r = \frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{x_i - \bar{x}}{S_x}\right) * \left(\frac{y_i - \bar{y}}{S_y}\right) \quad (3)$$

where

- r is Pearson's correlation coefficient,
- n is number of values,
- x_i is observed value at index streamgage for value *i*,
- $\bar{x}$ is average of the observed values at index streamgage,
- S_x is standard deviation of the observed values at index streamgage,
- y_i is observed value at the estimation site for value *i*,
- $\bar{y}$ is average of the observed values at the estimation site, and
- S_y is standard deviation of the observed values at estimation site.

The r value can range from 0 to 1; if two variables are perfectly correlated with a positive slope, then r = 1. The r value is sensitive to outliers and nonlinearity and thus is most useful when comparing log transformed streamflow.

Prediction Interval

Prediction intervals were computed for the MOVE.1 regressions. A prediction interval has a stated probability that a new data point with a specified magnitude will fall within it (Helsel and Hirsch, 2002). Both parametric and non-parametric methods are available for the calculation of prediction interval limits; however, the parametric method requires that the MOVE.1 regression residuals are normally distributed. A test for normalcy was accomplished on each MOVE.1 regression, and about one-third of the regressions examined had residuals (observed value minus estimated value) that were not normally distributed on the basis of skewness or kurtosis. For consistency among the numerous MOVE.1 regressions, the non-parametric prediction interval method was used. The equation to calculate the non-parametric prediction upper and lower interval limits is as follows (equations 4 and 5, respectively):

$$\hat{y} + e_{(L)} \quad (4)$$

$$\hat{y} + e_{(U)} \quad (5)$$

where

- $\hat{y}$ is estimated value of y given x_o,
- $e_{(L)}$ is the 1-α/2 quantile of the residuals, or the Lth ranked residual where $L = (n+1) * \alpha/2$. (n = count, α = probability exceedance), and
- $e_{(U)}$ is the α/2 quantile of the residuals, or the Uth ranked residual where $U = (n+1) * 1-\alpha/2$. (n = count, α = probability exceedance).

The 95-percent prediction interval was used in this study, meaning that there is a 95-percent probability that future estimated streamflow values will be contained within the upper and lower limits of the prediction interval, based on the regression calibration dataset. Prediction intervals were calculated for each estimation site using many index streamgages. A perfect relation between two sites would result in zero residual values for all data, and the resulting prediction interval would be zero. The smaller the prediction interval, the smaller the regression residual values are at a given confidence interval.

MOVE.1 Regression Comparison

The log prediction interval width is used as a qualitative measure of the MOVE.1 regression performance along with NSE and Pearson's correlation coefficient r values. Since non-parametric intervals are used, the prediction interval width is not symmetrical around the regression line; therefore, the prediction interval is presented in log space. Utilizing the prediction interval width in log space gives equal weight to the upper and lower prediction interval limits and thus is useful when making comparisons between MOVE.1 regressions. As described in the "Index-Gage Method Results" section, it was seen that in general when comparing various MOVE.1 regressions developed for one estimation site that has numerous index streamgages, the smallest log prediction interval width corresponded to the highest or second highest NSE and r values. This lends confidence that the log prediction interval width can be used as an additional variable for regression comparison.

Analysis of Streamflow Estimation

For the analysis of streamflow estimation, data were obtained and analyzed in a consistent manner for the 12 newly established and 5 existing streamgages in the study area. All data that were obtained at the streamgage were not used for analysis. Considerations were used in data selection such as whether the data were influenced by runoff and whether zero streamflow was observed. In practice, streamflow will be measured only periodically at an estimation site. However, the streamgages that were used in this analysis compute continuous streamflow from the stage, producing values of streamflow at 5-minute increments of time. To simulate the measurement constraints in practice, data were selected from the continuous record using specific criteria and by following various measurement schedules. Once the data were selected, MOVE.1 regressions were performed. Zero streamflow values were not used in the MOVE.1 regression but are important for evaluation purposes.

To improve the MOVE.1 regressions from streamgages with various watershed sizes, analysis includes only streamflow that was not affected appreciably by runoff and that could be considered base flow. Runoff-influenced streamflow for this study is defined operationally as streamflow on the day of precipitation plus streamflow on the following 2 days. The frequency of periodic streamflow measurements to best obtain the most relevant information without measuring continuously was determined and is described later in the "Frequency of Streamflow Measurements" section. Prediction intervals, NSE coefficients, and r values were computed. Evaluation of streamflow not used for MOVE.1 regression development was performed if streamflow data before May 1, 2015, were available for both streamgages. Results of the MOVE.1 regressions for all 12 newly established streamgages and selected regressions for previously established streamgages are discussed in the next sections.

Data Selection

The index-gage method for estimating streamflow requires that data be available for overlapping periods of record at two sites (the estimation site and the index streamgage). The following discussion focuses on the way periodic streamflow measurements made at various times can affect the relations developed with the index-gage method. The assumption is that the estimation site will not have continuous stage or streamflow data, but measurements will be made on a specified schedule. The index streamgage, however, will have stage measured, discrete streamflow computed every 5 or 15 minutes, and daily mean streamflow values computed. To simulate periodic streamflow measurements at an ungaged site of interest, discrete computed streamflow values from the estimation site were selected at prescribed time intervals (such as 9:00 a.m. every Monday). These discrete values were matched with same day (and time if discrete values were used) streamflows at the index streamgage, and analyses were run.

The following considerations will be discussed with respect to the index-gage method: (1) runoff-influenced streamflow, (2) zero streamflow at the estimation site and (or) index streamgage, (3) instantaneous or daily mean streamflow values to be used at the index streamgage, and (4) data-collection frequency for streamflow at the estimation site.

Runoff-Influenced Streamflow

The lack of continuous streamflow at the estimation site limits one's ability to understand the shape of a streamflow hydrograph during and after a rainfall event. It is recognized that the shape of the hydrograph is dependent on various basin characteristics, such as land use, geology, and topography, and there are studies that use these characteristics to assist in streamflow estimation (Stuckey, 2006). For the purposes of this study, streamflow alone is examined for use in MOVE.1 regressions, though basin characteristics can be used to explain regression variability. It is anticipated that the index streamgage and estimation site may be some distance away from each other and that rainfall amount and intensities may vary between streamgages. Even if the two streamgages are in close proximity to each other, the index streamgage and estimation site may have different watershed-area sizes or other basin characteristics that affect how the stream responds to a precipitation event, as determined by a local rain gage and (or) radar data. Streamflows at streamgages 03114094 (Herod) and 03111675 (Job) are shown in figure 2 as an

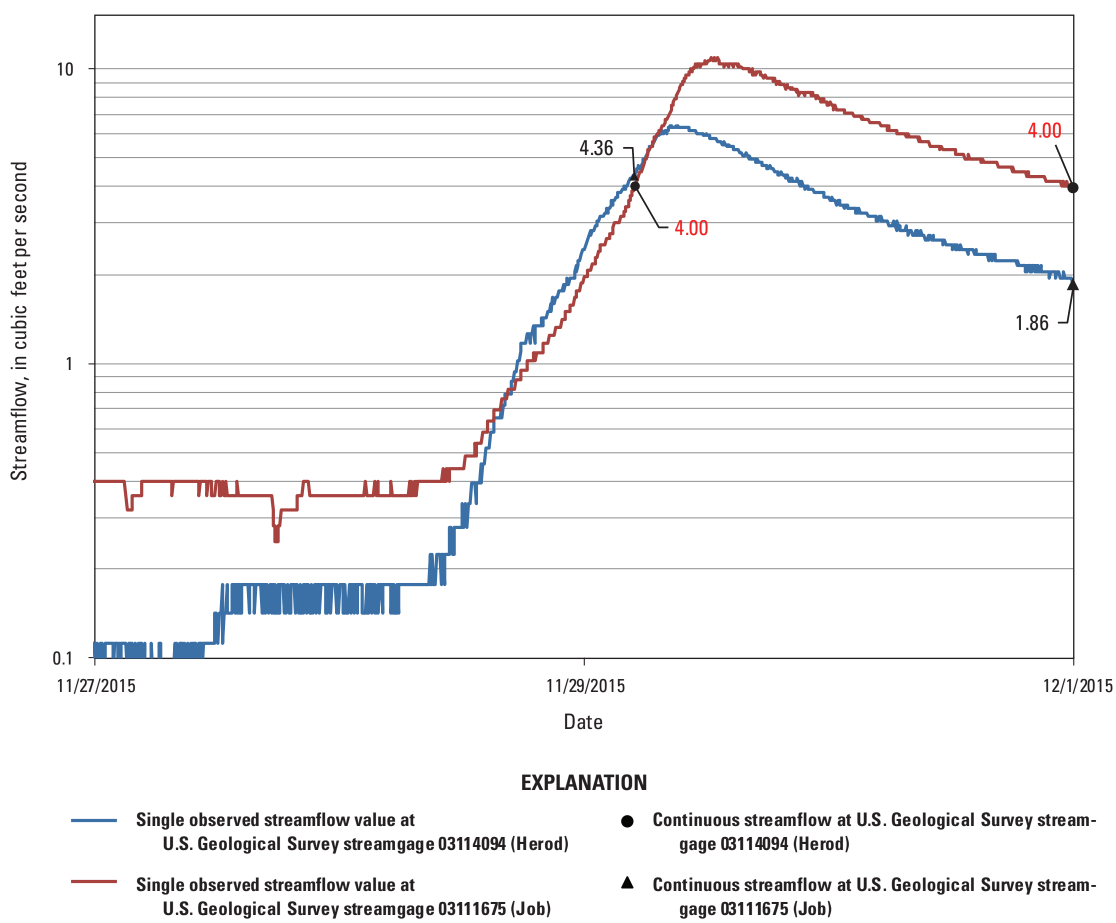

Figure 2. Streamflow at U.S. Geological Survey streamgages 03114094, Herod Run near New Freeport, and 03111675, Job Creek at Delphene, Pennsylvania, during a precipitation event.

example of this. The two streamgages are adjacent to one another and have watershed areas of about 1.8 mi^2 (03114094 Herod) and about 6.6 mi^2 (03111675 Job). Streamflows of 4 ft^3/s on the rising and falling limbs of the hydrograph for streamgage 03111675 (Job) are shown in figure 2 with black circles; for comparison, the streamflows at the same time for streamgage 03114094 (Herod) are shown with black triangles at 4.36 ft^3/s and 1.86 ft^3/s, respectively. In this example, if the streamflows at streamgage 03114094 (Herod) were estimated using data from streamgage 03111675 (Job), the index-gage method would not capture the differences in the response to the precipitation event that occurred on November 29, 2015, between the two streamgages.

To examine the potential effects of precipitation and runoff events more closely, relations were developed using MOVE.1 between estimation site 03111235 (DogTrib) and index streamgages 03111200 (Dunkle) and 03111890 (MWheeling) using (1) all concurrent streamflow data and (2) data with streamflow removed on the day precipitation occurred and the 2 days following the precipitation event. Six different MOVE.1 regressions were developed for each situation, one regression with all streamflow and five regressions with 100 random concurrent data points for a total of 12 regressions. Prediction intervals at the 95-percent confidence interval, NSE values, and the r value were computed for all MOVE.1 regressions. The NSE values were calculated using the same dataset for all 12 MOVE.1 regressions. This analysis was done at the two different streamgage pairs. Statistical summaries of the log prediction interval width and NSE values for the two streamgage pairs are shown in figure 3; (regression statistics are available in appendix 1.) For both sets of streamgage pairs, the NSE values for the two datasets (runoff and non-runoff influenced data) were similar, but the log prediction interval width was generally greater when the runoff-influenced periods were included, indicating greater uncertainty.

To minimize the effect of precipitation runoff in the watershed, runoff-influenced streamflow was not considered in further data analysis unless otherwise specified. Data on at least 3 days per precipitation event anywhere in a watershed, as determined by a local rain gage and (or) radar data, were removed from the streamflow record for each streamgage, including the day (or days) precipitation occurred and the 2 days following the precipitation event.

Zero Streamflow Values

During streamgage inspections, the gage height of zero streamflow (GZF) was determined by measuring the lowest point on the streamflow control such as rock riffle. When there was no streamflow over the control, as evidenced by the gage height being lower than the GZF, zero streamflow was calculated. The occurrence of zero flow does not necessarily mean that the stream was completely dry; pools of water may have been present in the stream channel. In addition, it is possible that there may have been a small amount of water leaking through the control; however, it was assumed to be negligible. The relatively short 18-month streamflow record indicates that it is not unusual for small streams in southwestern Pennsylvania not appreciably affected by human activities to have zero flow conditions during summer and autumn months.

Zero streamflows were not used in the MOVE.1 regression analysis. The MOVE.1 regression analysis utilizes log streamflow, thus a streamflow of zero is undefined and cannot be used. Setting zero streamflow to a very small number was attempted, but it was found that arbitrary numbers affected the MOVE.1 regression analysis. Even though zero streamflow cannot be estimated directly, the MOVE.1 regression equation can be rearranged to estimate the streamflow at the index streamgage at which the flow at the estimation site would be very close to zero. Data collected during the MOVE.1 regression development period can guide zero flow determination as well. When zero streamflows were reported at the estimation site, two values were noted: (1) the highest corresponding streamflow at the index streamgage ("highest index streamflow at zero," or HISAZ for purposes of this report) and (2) the highest value at the estimation site when the index streamgage streamflow was less than or equal to the HISAZ value. These two values are used for evaluation of streamflow after the MOVE.1 regression development period, as described in the "Evaluation of Streamflow Not Used for Regression Development" section that begins on page 33.

Instantaneous and Daily Mean Streamflow

Future application of the index-gage method will require periodic streamflow measurements typically made over a short period of time (approximately 1 hour or less) at an estimation site; however, the index streamgage may have instantaneous and daily mean streamflow time series. An analysis was done to determine the implications of using daily mean streamflow values computed at the index streamgage as opposed to 5- or 15-minute instantaneous values (with runoff-influenced streamflow removed). Daily mean streamflows are available for USGS streamgages on the National Water Information System NWISWeb (https://waterdata.usgs.gov/nwis) and may be easier to work with than instantaneous values where the time stamp of the value needs to be taken into consideration.

There does not appear to be a clear basis for using daily mean streamflow rather than instantaneous streamflow for the data comparison. Instantaneous streamflow values were used for this analysis when comparing data for 11 of the 12 newly established streamgages. The analysis using previously established index streamgages was completed using daily mean streamflow data that are publicly available. Additionally, daily mean streamflow values were used for one of the newly established streamgages (03072890, Fonner) when the instantaneous values were temperature affected and the daily mean value was considered a better value (Hittle, 2019b).

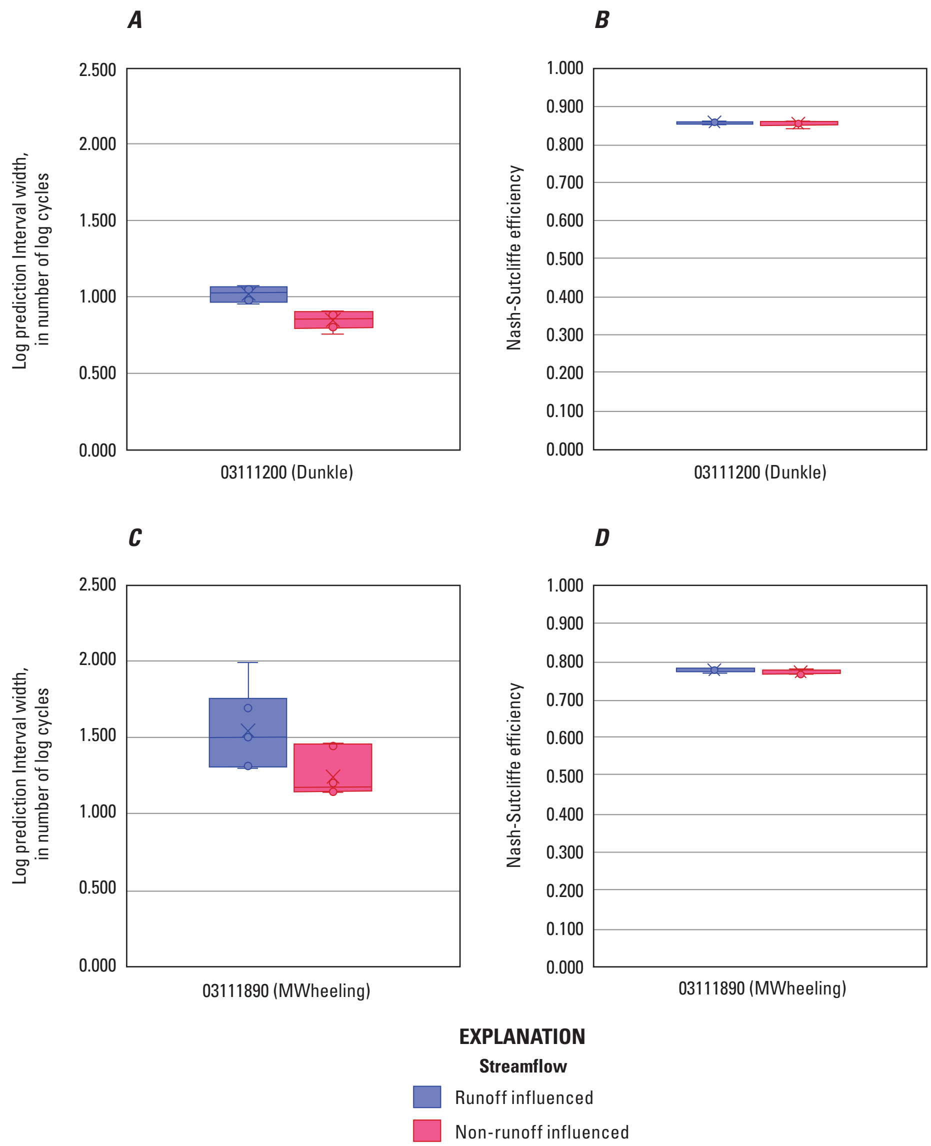

Figure 3. For U.S. Geological Survey (USGS) streamgage 03111235, Unnamed Trib to Dog Run at Dunsfort, Pennsylvania, *A*, log prediction interval width and *B*, Nash-Sutcliffe Efficiency values, as estimated using USGS streamgage 03111200, Dunkle Run near Claysville, Pennsylvania, and *C*, log prediction interval and *D*, Nash-Sutcliffe Efficiency values as estimated using USGS streamgage 03111890, Middle Wheeling Creek near Claysville, western Pennsylvania, for six MOVE.1 regressions with and without runoff-influenced streamflow.

Frequency of Streamflow Measurements

The current PADEP streamflow-measurement schedule starts about 2.5 years in advance of any longwall mining activity underneath a stream. Streamflow is measured prior to mining once a month for 2 years, weekly for 6 months, and daily for 2 weeks (Pennsylvania Department of Environmental Protection, 2005), regardless of the timing of antecedent precipitation. This schedule results in approximately 60 measurements made over 2.5 years at the site of interest. The purpose of examining streamflow-measurement schedules was to determine how to get the maximum amount of information from a prescribed measurement schedule while attempting to keep a similar number of measurements as the current PADEP schedule. The various streamflow-measurement schedules evaluated are listed in table 3. An example calendar of selected measurement schedules is shown in figure 4. These streamflow-measurement schedules were applied at three streamgage pairs. MOVE.1 regression diagnostic factors and results are discussed in the following paragraphs and presented in table 4 and figure 5.

Three streamgage pairs were analyzed to illustrate three different scenarios that could be seen in practice. (1) A MOVE.1 regression to estimate streamflow at streamgage 03111235 (DogTrib) using streamflow data from streamgage 03107698 (Traverse) represents the scenario where the

Table 3. Descriptions of streamflow-measurement schedules, including whether runoff-influenced streamflow was used in the schedule, an explanation of the schedule, whether it is possible to implement the schedule for data collection, and examples explaining the schedules.

Streamflow-measurement schedule identifier	Runoff-influenced streamflow included?	Streamflow-measurement schedule explanation	Is this schedule possible to implement for data collection?	Example
ALL_PO	No	Streamflow measurement made every 5 minutes	This scenario represents a continuous-record streamgage, not a periodically measured streamgage	If a day is not influenced by precipitation, every 5-minute data point in the day is used, so there would be 288 points for 1 day
PO1	No	One streamflow measurement per day every day when the streamflow is not affected by precipitation (the day of precipitation and 2 days following is considered affected by precipitation)	Yes	See figure 4, PO1 schedule in orange text
PO2	No	One streamflow measurement per day on days 1,3,5,7,10,13,16 and every 3 days after when the streamflow is not affected by precipitation (the day of precipitation and 2 days following is considered affected by precipitation)	Yes	See figure 4, PO2 schedule in dark blue text
PO3	No	One streamflow measurement every month for 2 years, one streamflow measurement a week for 6 months, one streamflow measurement a day for 2 weeks	Yes	Using only streamflow not influenced by precipitation, the DEP schedule was followed. This schedule has fewer measurements than expected because many days in the final 2 weeks may have been precipitation influenced
PO4	No	One streamflow measurement once a week on the same day. If no stream-flow measurement is able to be obtained due to precipitation, the first non-runoff influenced day is measured, then immediately back to regular schedule	Yes	See figure 4, PO4 schedule in light blue text

Table 3. Descriptions of streamflow-measurement schedules, including whether runoff-influenced streamflow was used in the schedule, an explanation of the schedule, whether it is possible to implement the schedule for data collection, and examples explaining the schedules.—Continued

Streamflow-measurement schedule identifier	Runoff-influenced streamflow included?	Streamflow-measurement schedule explanation	Is this schedule possible to implement for data collection?	Example
PO5 (1–2)	No	Every month for 2 years, the first (PO5-1) or second (PO5-2) non-runoff influenced days are measured as described in PO2. For 6 months, all days as described in PO2 are measured.	Yes	See figure 4, PO5 schedule in green text
PO6	No	Every month, the first non-runoff influenced days are measured as described in PO2; however, if only one measurement is made (due to precipitation), the next set of non-runoff influenced days are measured until at least day 1, and day 3 are measured	Yes	See figure 4, PO6 schedule in purple text
PO7	No	Every month, only the first non-runoff influenced days are measured as described in PO2 that results in measuring at least day 1 and day 3	No - It would not be possible to predict 3 days ahead if rain would fall, and if a measurement was made, one would use it, mimicing PO6	See figure 4, PO7 schedule in grey text
PO8	No	Every month, streamflow measurements are made on the PO2 schedule so the longest period of non-runoff influenced streamflow is measured but the same numbered day is not measured twice. This could result in measurements being made after several precipitation events in one month	Yes	See figure 4, PO8 schedule in red text
DEP (1–4)	Yes	One streamflow measurement every month for 2 years, one streamflow measurement a week for 6 months, one streamflow measurement a day for 2 weeks	Yes	The same day each week was chosen. This is accomplished 4 times, starting on a different day of the week each time

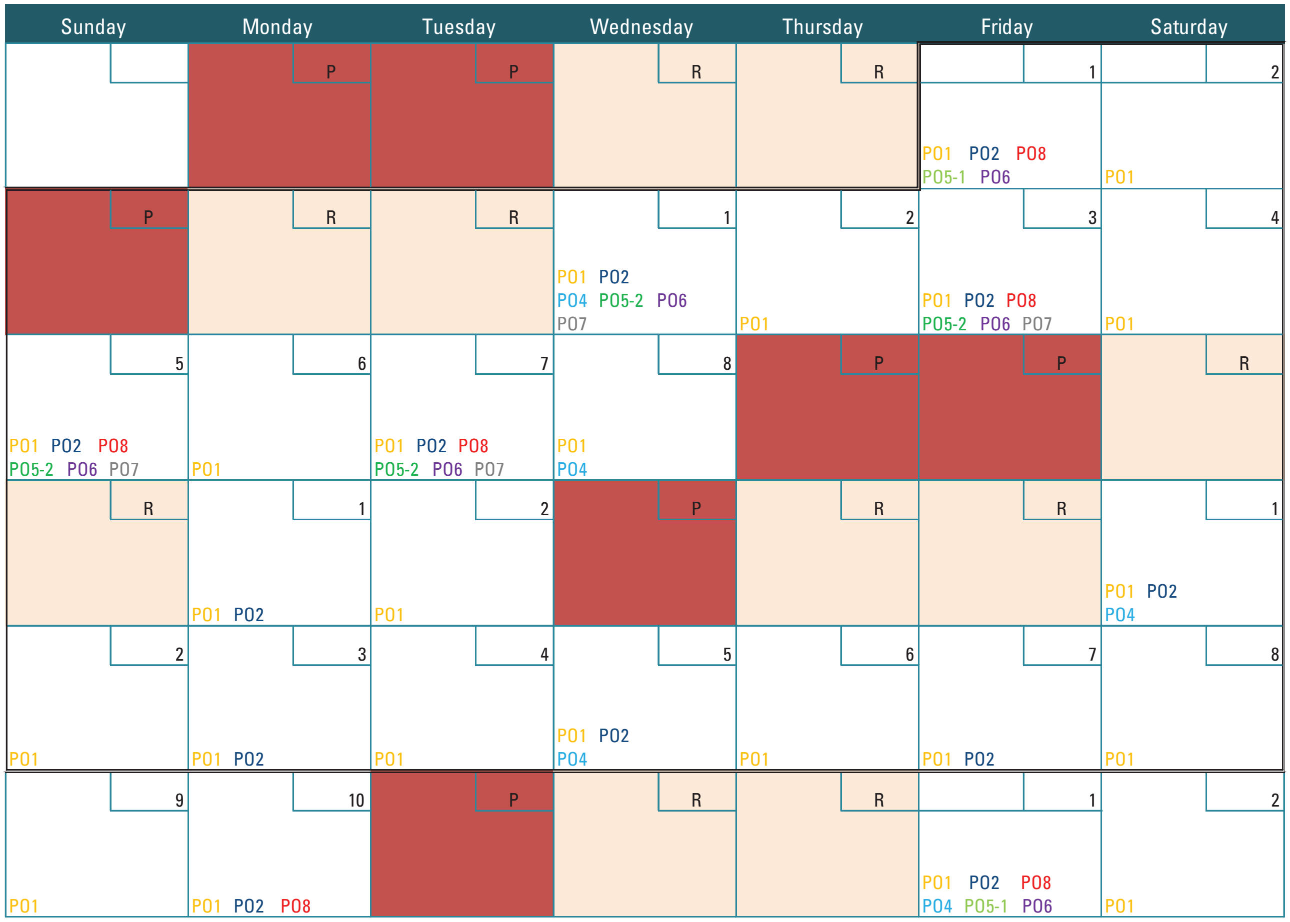

Figure 4. Example calendar of measurement schedules during a hypothetical month. The text within the calendar indicates whether a streamflow measurement should be made on that day according to selected measurement schedules. Measurement schedules are color coded to enhance readability. (PO1, measurement schedule; 1–10, number of days for which streamflow is no longer influenced by runoff; R, streamflow influenced by runoff; P, precipitation observed; = (double line), delineates 1 month)

estimation site (DogTrib) experiences zero streamflow. (2) A MOVE.1 regression to estimate streamflow at streamgage 03111200 (Dunkle, where zero streamflow was not recorded) using streamflow data from streamgage 03107698 (Traverse) represents a scenario that has several outliers, likely owing to localized conditions or uncertain shift application. (3) A MOVE.1 regression to estimate streamflow at streamgage 03107698 (Traverse, where zero streamflow was not recorded) using streamflow at streamgage 03108010 (Fishpot) represents a scenario that does not appear to have outliers.

The ALL_PO streamflow-measurement schedule mimics a continuous-record streamgage with 5-minute data collected but with no runoff-influenced streamflow included in the analysis. The MOVE.1 regression results from this schedule serve as a standard to which all other measurement schedules can be compared with regard to regression prediction intervals and zero streamflow. As can be seen in table 4, there are log prediction interval widths for some schedules that are smaller than the ALL_PO value. A small log prediction interval width indicates better agreement between the streamgages based on the calibration data collected and results in a better MOVE.1 regression than is produced when the entire dataset is sampled.

Zero Streamflow Recorded at the Estimation Site

On the basis of the analysis of measurement frequency, only measurement schedules that do not include runoff-influenced streamflow are discussed here. The prediction of zero streamflow at an estimation site requires a streamflow-measurement frequency that is likely to include zero streamflow during the MOVE.1 regression development period. To do this, a measurement scenario that measures the longest non-runoff influenced period needs to be used. Three of the streamflow-measurement schedules (PO5, PO6, and PO7) did not include any zero streamflow values for the estimation site; therefore, they were excluded from further

Table 4. Results of MOVE.1 regression diagnostic factors, using a 95-percent confidence interval, for 14 measurement schedules for three streamgage pairs in western Pennsylvania. The PO1, PO2, and PO8 schedules are highlighted because they best represent the scenario where the estimation site recorded days of zero streamflow.

[ft^3/s, cubic feet per second; USGS, U.S. Geological Survey; *, zero streamflow, not observed at the estimation site during the model development period; n/a, datapoints selected for this measurement schedule did not include zero streamflow at the estimation site even though zero streamflow was observed during the model development period; brown highlighted schedules are those that best represent the scenario where the estimation site recorded days of zero streamflow; log, logarithm base 10]

Streamflow-measurement schedule	Number of streamflow measurements	Number of measurements used in analysis	Coefficient of correlation r	Nash-Sutcliffe Efficiency value (computed on a mutual dataset)	Width of log prediction interval (number of log cycles)	Back-transformed Prediction Interval Limits at 1.00 ft^3/s		Highest index streamflow at estimated streamflow of zero (ft^3/s)
						Lower prediction interval limit	Upper prediction interval limit	
USGS streamgage 03111235, Unnamed trib to Dog Run at Dunsfort, streamflow estimated by using USGS streamgage 03107698, Traverse Creek near Kendall								
ALL_P0	53,937	49,575	0.901	0.819	1.213	0.310	5.068	0.57
PO1	193	181	0.905	0.814	1.354	0.256	5.789	0.47
PO2	114	108	0.908	0.815	1.322	0.292	6.127	0.38
PO3	37	36	0.895	0.815	1.327	0.273	5.805	0.23
PO4	71	68	0.904	0.818	1.353	0.273	6.150	0.38
PO5-1	51	51	0.896	0.822	1.206	0.292	4.694	n/a
PO5-2	46	45	0.907	0.821	1.093	0.287	3.559	0.23
PO6	73	73	0.906	0.818	1.230	0.278	4.722	n/a
PO7	51	51	0.913	0.816	1.135	0.324	4.421	n/a
PO8	58	55	0.906	0.816	1.283	0.271	5.204	0.38
DEP-1[1]	61	61	0.895	0.814	1.450	0.144	4.060	n/a
DEP-2[1]	61	60	0.838	0.806	1.699	0.190	9.487	0.18
DEP-3[1]	61	58	0.863	0.812	1.334	0.221	4.779	2.35
DEP-4[1]	60	59	0.873	0.822	1.221	0.293	4.883	0.23
USGS streamgage 03111200, Dunkle Run near Claysville, streamflow estimated by using USGS streamgage 03107698, Traverse Creek near Kendall								
ALL_P0	67,976	67,976	0.898	0.793	0.783	0.426	2.585	*
PO1	246	246	0.886	0.778	0.854	0.396	2.833	*
PO2	144	144	0.882	0.786	0.876	0.393	2.952	*
PO3	46	46	0.944	0.759	0.830	0.386	2.605	*
PO4	72	72	0.885	0.776	1.056	0.323	3.673	*
PO5-1	63	63	0.901	0.803	1.094	0.245	3.037	*
PO5-2	62	62	0.933	0.787	0.836	0.423	2.905	*
PO6	90	90	0.852	0.804	0.909	0.310	2.513	*
PO7	69	69	0.886	0.801	0.809	0.353	2.272	*
PO8	76	76	0.870	0.801	1.152	0.247	3.500	*
DEP-1[1]	61	61	0.929	0.748	0.868	0.354	2.618	*
DEP-2[1]	59	59	0.928	0.800	0.796	0.463	2.894	*
DEP-3[1]	61	61	0.932	0.756	0.960	0.405	3.692	*
DEP-4[1]	64	64	0.901	0.736	1.255	0.286	5.151	*
USGS streamgage 03107698, Traverse Creek near Kendall, streamflow estimated by using USGS streamgage 03108010, Fishpot Run near Shippingport								
ALL_P0	72,244	72,244	0.933	0.872	0.777	0.431	2.650	*
PO1	259	259	0.930	0.873	0.778	0.422	2.523	*
PO2	150	150	0.927	0.873	0.807	0.402	2.579	*
PO3	45	45	0.927	0.863	0.745	0.436	2.423	*
PO4	85	85	0.923	0.874	0.768	0.411	2.411	*

Table 4. Results of MOVE.1 regression diagnostic factors, using a 95-percent confidence interval, for 14 measurement schedules for three streamgage pairs in western Pennsylvania. The PO1, PO2, and PO8 schedules are highlighted because they best represent the scenario where the estimation site recorded days of zero streamflow.—Continued

[ft^3/s, cubic feet per second; USGS, U.S. Geological Survey; *, zero streamflow, not observed at the estimation site during the model development period; n/a, datapoints selected for this measurement schedule did not include zero streamflow at the estimation site even though zero streamflow was observed during the model development period; brown highlighted schedules are those that best represent the scenario where the estimation site recorded days of zero streamflow; log, logarithm base 10]

Streamflow-measurement schedule	Number of streamflow measurements	Number of measurements used in analysis	Coefficient of correlation r	Nash-Sutcliffe Efficiency value (computed on a mutual dataset)	Width of log prediction interval (number of log cycles)	Back-transformed Prediction Interval Limits at 1.00 ft^3/s		Highest index streamflow at estimated streamflow of zero (ft^3/s)
						Lower prediction interval limit	Upper prediction interval limit	
PO5-1	79	79	0.926	0.867	0.818	0.417	2.745	*
PO5-2	84	84	0.941	0.866	0.801	0.441	2.787	*
PO6	86	86	0.917	0.873	0.798	0.384	2.415	*
PO7	68	68	0.92	0.870	0.856	0.375	2.691	*
PO8	78	78	0.925	0.871	0.878	0.372	2.804	*
DEP-1[1]	62	62	0.956	0.871	0.702	0.396	1.998	*
DEP-2[1]	64	64	0.915	0.864	1.018	0.418	4.353	*
DEP-3[1]	64	64	0.931	0.874	0.834	0.400	2.727	*
DEP-4[1]	62	62	0.956	0.872	0.697	0.472	2.347	*

[1]Schedules include runoff-influenced streamflow.

measurement-schedule analyses. Streamflow-measurement schedules PO3 and PO4 also were excluded from further measurement-schedule analysis because of the high probability of missing zero streamflow days. The other streamflow-measurement schedules (PO1, PO2, PO8) included days with zero streamflow values, although the HISAZ values as compared to the ALL-PO schedule were less.

The MOVE.1 regression developed with data from the PO8 streamflow-measurement schedule produced log prediction interval widths similar to those from the MOVE.1 regression developed with data from the ALL_PO schedule when estimating streamflow at site 03111235 (DogTrib) using streamflow at streamgage 03107698 (Traverse). The HISAZ value and the log prediction interval width from the MOVE.1 regression developed with data from the PO8 schedule (0.38 ft^3/s and 1.283 log cycles, respectively) were comparable to those from the regression developed with data from the ALL_PO schedule (0.57 ft^3/s and 1.213 log cycles, respectively), and the number of required streamflow measurements was similar to that for the DEP schedules.

Zero Streamflow Not Recorded at Estimation Site

On the basis of the analysis of the streamgage pairs in the previous section where streamflow at the estimation site went to zero, the PO1, PO2, and PO8 streamflow-measurement schedules are the focus of additional analysis. Estimated streamflows in relation to observed streamflows at streamgage 03111200 (Dunkle) and the 95-percent prediction intervals for the MOVE.1 regressions developed with data from the PO1, PO2, and PO8 streamflow-measurement schedules are shown in figure 5. For any estimation site, a crucial factor in determining the optimum streamflow-measurement schedule is ensuring data are collected during as many non-runoff periods as possible and for the longest period possible. However, it does not appear that measurements are needed every day during the entire non-runoff influenced period. This is evidenced by the similarity between the log prediction interval width of the MOVE.1 regression developed with data from the PO2 schedule (0.876 log cycles) and that of the PO1 schedule (0.854 log cycles) for 03107698 (Traverse) as estimated using 03111200 (Dunkle) (table 4). However, the log prediction interval width for the MOVE.1 regression developed with data from the PO8 schedule (1.152 log cycles) is larger than those developed with data from the PO1 and PO2 schedules. The same outliers were observed in the MOVE.1 regressions using data from the PO2 and PO8 schedules (fig 5); however, the larger log prediction interval width can be explained by the fact that there are more streamflow measurements in the regression calibration dataset (144 streamflow measurements) for the PO2 streamflow-measurement schedule compared to the PO8 schedule (76 streamflow measurements). Thus, the MOVE.1 regression residual chosen for the log prediction interval width was different for the two datasets.

Measurement schedule data for streamflow estimated at streamgage 03107698 (Traverse) using streamflow at streamgage 03108010 (Fishpot) show trends in the log prediction interval widths similar to those for streamgage 03111200 (Dunkle). The log prediction interval widths are similar for the MOVE.1 regressions developed with data from

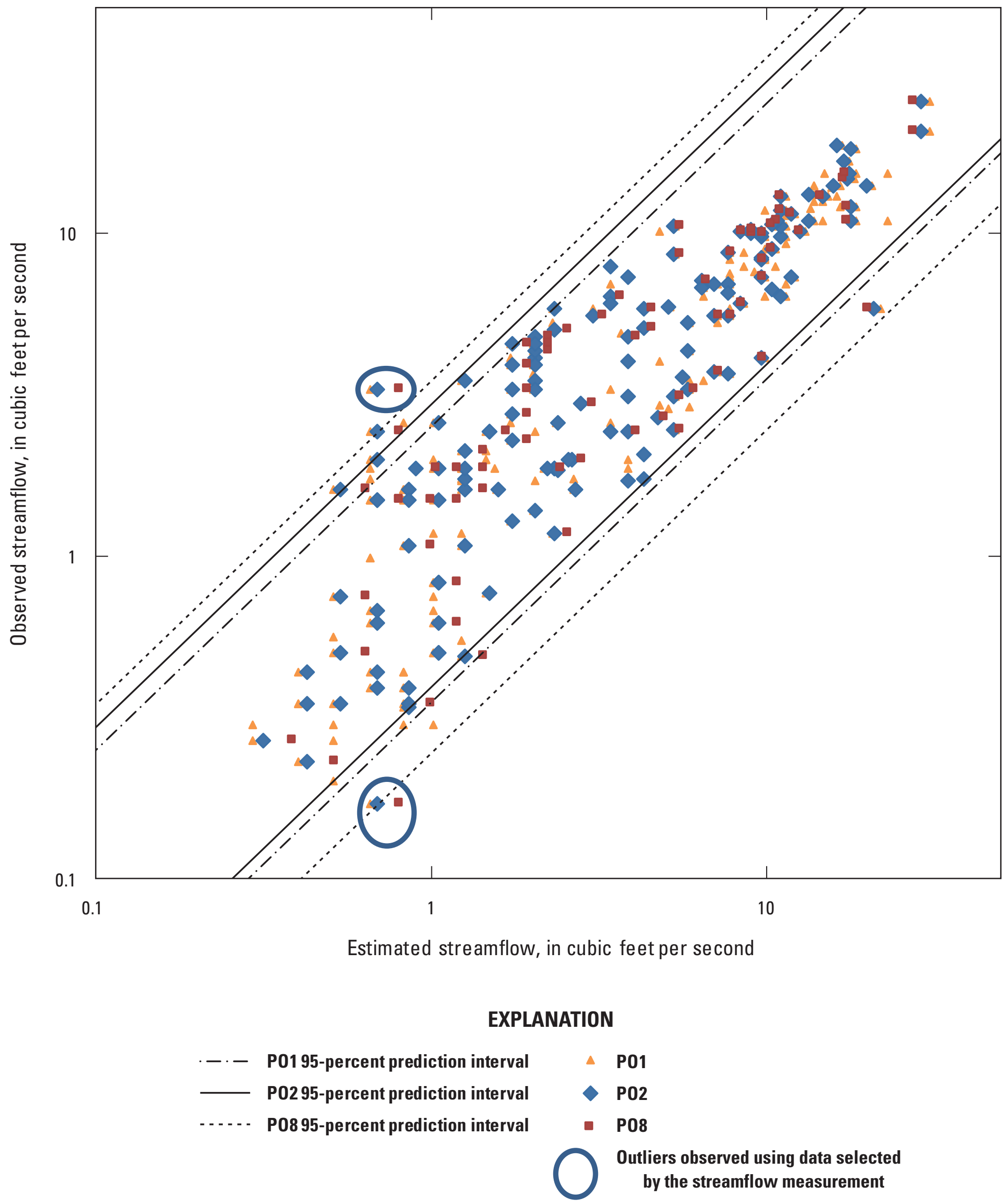

Figure 5. Observed streamflow in relation to estimated streamflow at U.S. Geological Survey (USGS) streamgage 03111200, Dunkle Run near Claysville (Dunkle), western Pennsylvania, for streamflow-measurement schedules PO1, PO2, and PO8 with the 95-percent prediction intervals. Streamflow at USGS 03111200 (Dunkle) was estimated using streamflow at USGS 03107698, Traverse Creek near Kendall.

the PO2 schedule (0.807 log cycles) and the PO1 schedule (0.777 log cycles) but lower than the log prediction interval width for the MOVE.1 regressions developed with data from the PO8 data (0.878 log cycles).

Current PADEP Schedule

To examine what is currently required, MOVE.1 regressions were produced with data selected for the current PADEP schedule labeled DEP. MOVE.1 regressions produced with data from the DEP schedule were examined with four different regressions starting on any day of the week (DEP-1, DEP-2, DEP-3, and DEP-4). These four scenarios (DEP-1 to DEP-4) emphasize data at the end of the analysis period, in which more than one-half of the measurements are collected in the last 6 months, and a one-quarter of them are collected in the last 2 weeks. Despite the inclusion of runoff-influenced streamflow, the DEP schedule sometimes resulted in smaller log prediction interval widths than the ALL_PO schedule. This was seen in the MOVE.1 regression to estimate streamflow at 03107698 (Traverse) using streamflow at 03108010 (Fishpot) using the DEP-1 and DEP-4 scenarios, which produced smaller log prediction interval widths. When zero streamflow at the estimation site is considered, the DEP-1 scenario missed instances where zero streamflow occurred, which is considered a critical piece of information for future streamflow examination.

Streamflow-Measurement Summary

A graphical summary of the log prediction interval width produced by MOVE.1 regressions with data from streamflow-measurement schedules All_PO, DEP, PO1, PO2, and PO8 is shown in figure 6. The symbol for the DEP schedule shows the maximum and minimum prediction interval widths because this schedule was examined using four different MOVE.1 regressions for the four scenarios run (DEP-1 to DEP-4). In general, figure 6 shows that the MOVE.1 regressions produced with data from the PO1 and PO2 schedules resulted in log prediction interval widths at the 95-percent confidence level that are similar to each other and larger than the widths from regressions produced with data from the ALL_PO schedule. The MOVE.1 regression prediction interval width using data from the PO8 schedule was larger than that from the ALL_PO data regression but fell either above or below the prediction interval widths for the regressions produced with data from the PO1 and PO2 schedules. For MOVE.1 regressions produced with data from the PO1, PO2, and PO8 schedules, the NSE values were within 0.02, indicating the data selected by these schedules produced

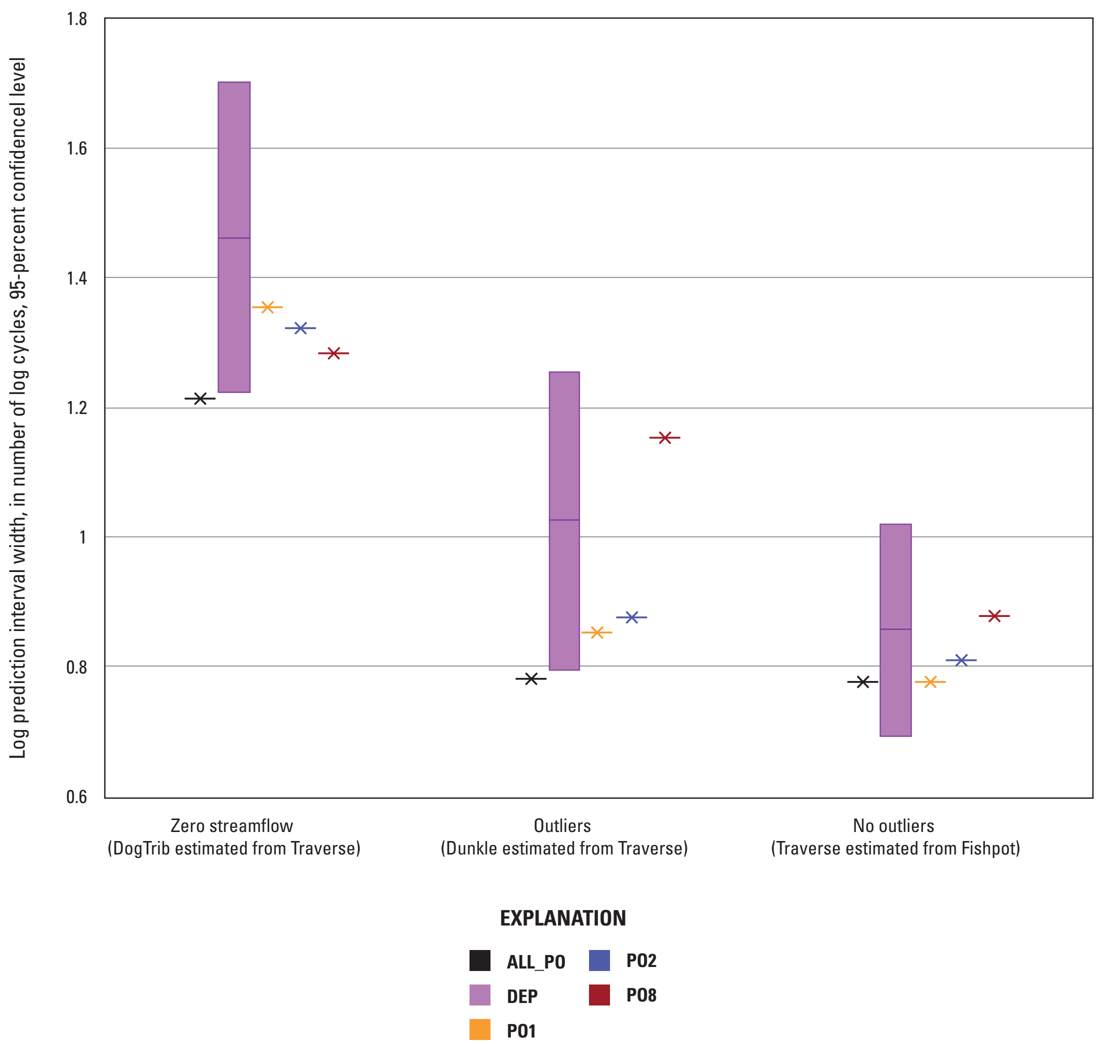

Figure 6. Prediction interval widths for the Zero streamflow example for U.S. Geological Survey (USGS) streamgage 03111235, Unnamed trib to Dog Run at Dunsfort (DogTrib), estimated using streamflow at USGS streamgage 03107698, Traverse Creek near Kendall (Traverse); Outliers example for USGS streamgage 0311200, Dunkle Run near Claysville (Dunkle), estimated using streamflow at USGS streamgage 03107698, Traverse Creek near Kendall; and No outliers example for USGS streamgage 03107698, Traverse Creek near Kendall, estimated using streamflow at USGS streamgage 03108010 Fishpot Run near Shippingport (Fishpot), western Pennsylvania. The DEP streamflow-measurement schedule is shown with the highest and lowest log prediction interval widths because this schedule was analyzed four times using different data. The ALL_PO, PO1, PO2, and PO8 streamflow-measurement schedules were each analyzed only once.

similar regressions. Data from the DEP schedule were examined using four different regressions starting on any day of the week. The differences in the log prediction interval widths indicate that the data selected by these scenarios for the current PADEP schedule included various outliers, depending on the day the measurement schedule was started. Interestingly, these scenarios measured runoff-influenced data; however, two of the DEP MOVE.1 regression prediction interval widths (DEP-1 scenario and the DEP-4 scenario for estimation site 03108010 [Fishpot] estimated by index streamgage 03107698 [Traverse]) were lower than the ALL_PO data regression prediction interval width, indicating it is not only the runoff influence that affected the prediction interval width; otherwise, all interval widths would be larger. The distribution of the measurement selection (concentrating most of the measurements within 6 months versus spacing the measurements evenly throughout the regression development period) also seems to play a part in the prediction interval width.

For this study, the PO2 schedule was used to select data for MOVE.1 regression development to capture all non-runoff influenced streamflow periods during the regression development period. This schedule was used to eliminate a potential source of error when comparing multiple index streamgages for use with an estimation site and to assure that the lowest streamflow was sampled. In the PO8 schedule, the lowest streamflows may not be measured if the longest non-runoff influenced period occurs at the beginning of the month and the lowest streamflow occurs later. This is one of the cautions of using the PO8 schedule for data selection; the range and number of outliers can change depending on whether the PO8 schedule started at the beginning of a month or in the middle of a month.

Index-Gage Method Results

Once the streamflow-measurement schedule for analysis was determined, regressions using MOVE.1 were developed for all streamgage pairs to determine which index streamgage best estimated streamflow at the estimation site. The log prediction interval width, NSE, and correlation coefficient (r) were used to select the best index streamgage. The width of the log prediction interval provided an indication of the uncertainty associated with the MOVE.1 regression; the smaller the log prediction interval width, the better the streamgage regression. This was generally confirmed with the NSE and r values computed with each MOVE.1 regression. An analysis was done to determine whether watershed size or distance might affect the selection of the best index streamgage. Non-runoff influenced data from May 2015 to March 2017 were used for all streamgages. A summary of all data is presented in the remainder of this section. The MOVE.1 regression diagnostics for all streamgage pairs are shown in table 5. The log prediction interval width is listed for each streamgage pair; the number in red is the lowest value for a particular streamgage. For any one estimation site, the highest NSE value corresponds to the first or second lowest log prediction interval width. However, the lowest log prediction interval width was not the same for every newly established gage; it ranged from 0.609 log cycles at 03107698 (Traverse) to 1.451 log cycles at 03114094 (Herod). Further, NSE and log prediction interval widths do not correspond between estimation sites. For instance, an NSE value of 0.841 corresponds to a log prediction interval width of 1.410 log cycles at station 03111675 (Job) when the index streamgage is 03111705 (SF Dunkard). When the same index streamgage (SF Dunkard) was used to estimate streamflow at 03111200 (Dunkle), the NSE value was 0.602, and the log prediction interval width was 1.129 log cycles. The MOVE.1 regressions developed using SF Dunkard as the index streamgage produced lower values for NSE and log prediction interval width for estimation site 03111200 (Dunkle) than for estimation site 03111675 (Job), indicating that even though the regression fit at Dunkle was not as good, a smaller log prediction interval width was produced. Differences in lowest log prediction interval width appear to correspond to the range in log-transformed streamflows observed at the estimation site during the regression development period. The lowest and highest non-runoff influenced streamflow values that were observed at each estimation site from May 1, 2015, to March 31, 2017, are shown in table 6. The log range in streamflow at estimation site 03111200 (Dunkle) is less than that at estimation site 03111675 (Job). Of the newly established sites, those in Greene County have the largest range in log streamflow, whereas those in Washington County have middle ranges in log streamflow.

MOVE.1 Regression Discussion

Development of MOVE.1 regressions using all the newly established sites as estimation sites revealed that there was not one index streamgage that was ideal for use with all estimation sites in the study area. Two aspects of the estimation site/index streamgage relations can be easily discerned— distance between streamgages (table 7) and the watershed-area ratio of the streamgages. These aspects are examined in relation to the index-gage method performance.

Distance from the index streamgage in relation to the log prediction interval width for 12 newly established streamgages is shown in figure 7. For purposes of this illustration, any log prediction interval width greater than 1.7 is shown as a value of 1.7. For 10 of 12 newly established sites, using the closest streamgage as the index streamgage produced MOVE.1 regressions with the first or second smallest log prediction interval width except for 03072890 (Fonner) and 03105927 (Crab).

Streamflow statistics can be transferred from a gaged site to an ungaged site on the same stream within a certain watershed-area ratio. A previous study by Sloto and others (2017) showed that for most transferred statistics, the watershed-area ratio 0.33–3.0 performs as well as, if not better than, the more traditional ratios of 0.5–1.5 or 2.0. For this study, the streamgages were evaluated on how well they estimate base flow at a periodically measured site based on prediction

Table 5. Summary of MOVE.1 regression coefficient of correlation, Nash-Sutcliffe Efficiency value, and log prediction interval width for streamgage pairs in western Pennsylvania.

[PI, prediction interval; r, correlation coefficient; NSE, Nash-Sutcliffe Efficiency value; *red* italicized font indicates the smallest log predicition interval width, the largest correlation coefficient, or the largest NSE value; x, the estimation site and index streamgage are the same streamgage; -, the index streamgage was not used to estimate streamflow at the estimation site]

Index streamgage	Estimation site											
	03072890			03081800			03105927			03107698		
	PI width (number of log cycles)	r	NSE	PI width (number of log cycles)	r	NSE	PI width (number of log cycles)	r	NSE	PI width (number of log cycles)	r	NSE
03072890	x	x	x	1.295	0.874	0.874	1.670	0.821	0.644	1.099	0.827	0.653
03081800	1.642	0.888	0.776	x	x	x	1.463	0.864	0.727	0.921	0.896	0.792
03105927	1.949	0.821	0.643	1.119	0.864	0.727	x	x	x	0.738	0.937	0.873
03107698	1.770	0.827	0.653	1.026	0.896	0.792	*1.055*	*0.937*	*0.873*	x	x	x
03108010	2.220	0.717	0.434	1.348	0.823	0.646	1.655	0.871	0.742	0.774	0.935	0.871
03111200	2.033	0.840	0.681	1.393	0.822	0.644	1.636	0.847	0.694	0.859	0.896	0.792
03111215	1.382	0.860	0.719	1.193	0.880	0.760	1.521	0.888	0.776	1.005	0.888	0.775
03111235	1.577	0.863	0.725	1.155	0.882	0.763	1.724	0.856	0.713	0.972	0.908	0.816
03111675	2.150	0.716	0.432	1.506	0.830	0.660	1.648	0.834	0.668	1.358	0.831	0.661
03111705	2.227	0.710	0.419	1.188	0.842	0.685	1.460	0.878	0.755	1.060	0.849	0.698
03111890	1.625	0.884	0.767	*0.823*	*0.935*	*0.869*	1.223	0.906	0.813	0.785	0.925	0.850
03114094	2.202	0.667	0.334	1.181	0.821	0.642	1.236	0.825	0.649	1.070	0.837	0.674
[1]03072000	1.752	0.821	0.641	-	-	-	-	-	-	-	-	-
[1]03074500	-	-	-	0.906	0.926	0.853	-	-	-	-	-	-
[1]03108000	-	-	-	-	-	-	-	-	-	0.661	0.955	0.909
[1]03110830	-	-	-	-	-	-	-	-	-	*0.609*	*0.972*	*0.945*
[1]03112000	*1.230*	*0.898*	*0.796*	-	-	-	-	-	-	0.909	0.898	0.797

Table 5. Summary of MOVE.1 regression coefficient of correlation, Nash-Sutcliffe Efficiency value, and log prediction interval width for streamgage pairs in western Pennsylvania.—Continued

[PI, prediction interval; r, correlation coefficient; NSE, Nash-Sutcliffe Efficiency value; *red* italicized font indicates the smallest log predicition interval width, the largest correlation coefficient, or the largest NSE value; x, the estimation site and index streamgage are the same streamgage; -, the index streamgage was not used to estimate streamflow at the estimation site]

Index streamgage	Estimation site											
	03108010			03111200			03111215			03111235		
	PI width (number of log cycles)	r	NSE	PI width (number of log cycles)	r	NSE	PI width (number of log cycles)	r	NSE	PI width (number of log cycles)	r	NSE
03072890	1.340	0.717	0.434	1.098	0.834	0.668	1.231	0.861	0.721	1.317	0.861	0.722
03081800	1.105	0.823	0.646	1.139	0.822	0.644	1.506	0.880	0.760	1.369	0.882	0.763
03105927	1.126	0.871	0.742	1.078	0.851	0.702	1.467	0.888	0.776	1.602	0.856	0.712
03107698	0.726	*0.935*	*0.871*	0.800	0.895	0.790	1.370	0.887	0.775	1.319	0.908	0.816
03108010	x	x	x	1.048	0.847	0.694	1.670	0.796	0.591	1.485	0.822	0.645
03111200	1.064	0.847	0.694	x	x	x	1.479	0.886	0.772	*0.990*	*0.929*	*0.857*
03111215	1.127	0.796	0.591	1.019	0.885	0.771	x	x	x	1.247	0.886	0.773
03111235	1.054	0.822	0.645	*0.649*	*0.930*	*0.859*	1.329	0.886	0.773	x	x	x
03111675	1.465	0.744	0.488	1.336	0.793	0.587	1.447	0.866	0.731	1.422	0.845	0.690
03111705	1.151	0.788	0.576	1.129	0.801	0.602	1.447	0.874	0.748	1.278	0.827	0.654
03111890	1.016	0.846	0.692	1.027	0.865	0.730	*1.047*	0.931	0.861	1.221	0.886	0.772
03114094	0.999	0.820	0.641	0.940	0.771	0.541	1.353	0.763	0.527	1.466	0.770	0.541
[1]03072000	-	-	-	-	-	-	-	-	-	-	-	-
[1]03074500	-	-	-	-	-	-	-	-	-	-	-	-
[1]03108000	*0.713*	0.912	0.824	0.873	0.915	0.830	-	-	-	1.345	0.866	0.732
[1]03110830	-	-	-	-	-	-	-	-	-	1.271	0.881	0.761
[1]03112000	1.190	0.840	0.682	0.852	0.912	0.823	1.074	*0.937*	*0.873*	1.261	0.912	0.822

Table 5. Summary of MOVE.1 regression coefficient of correlation, Nash-Sutcliffe Efficiency value, and log prediction interval width for streamgage pairs in western Pennsylvania.—Continued

[PI, prediction interval; r, correlation coefficient; NSE, Nash-Sutcliffe Efficiency value; *red* italicized font indicates the smallest log predicition interval width, the largest correlation coefficient, or the largest NSE value; x, the estimation site and index streamgage are the same streamgage; -, the index streamgage was not used to estimate streamflow at the estimation site]

Index streamgage	Estimation site											
	03111675			03111705			03111890			03114094		
	PI width (number of log cycles)	r	NSE	PI width (number of log cycles)	r	NSE	PI width (number of log cycles)	r	NSE	PI width (number of log cycles)	r	NSE
03072890	2.460	0.702	0.405	2.871	0.710	0.419	1.171	0.880	0.759	2.278	0.667	0.334
03081800	2.397	0.832	0.663	2.321	0.842	0.685	1.105	0.926	0.851	1.703	0.864	0.729
03105927	2.132	0.834	0.668	2.244	0.881	0.761	1.014	0.906	0.813	1.675	0.826	0.652
03107698	2.357	0.831	0.661	2.296	0.849	0.698	0.962	0.924	0.848	1.784	0.837	0.674
03108010	2.760	0.744	0.488	2.748	0.788	0.576	1.340	0.846	0.692	1.607	0.841	0.681
03111200	2.401	0.793	0.587	2.555	0.801	0.602	1.295	0.866	0.732	1.786	0.771	0.541
03111215	1.903	0.865	0.729	2.299	0.874	0.748	*0.926*	0.931	0.861	1.906	0.763	0.527
03111235	2.066	0.845	0.690	2.165	0.828	0.656	1.100	0.886	0.772	1.830	0.769	0.538
03111675	x	x	x	1.674	0.921	0.841	1.585	0.839	0.677	1.529	0.877	0.754
03111705	*1.410*	*0.921*	*0.841*	x	x	x	1.289	0.849	0.699	*1.451*	*0.927*	*0.854*
03111890	2.339	0.845	0.690	2.430	0.849	0.699	x	x	x	1.714	0.821	0.642
03114094	1.411	0.878	0.755	*1.536*	*0.927*	*0.854*	1.152	0.821	0.642	x	x	x
[1]03072000	1.424	0.914	0.829	1.962	0.885	0.771	1.101	0.919	0.840	1.603	0.841	0.682
[1]03074500	-	-	-	-	-	-	-	-	-	-	-	-
[1]03108000	-	-	-	-	-	-	-	-	-	-	-	-
[1]03110830	-	-	-	-	-	-	-	-	-	-	-	-
[1]03112000	1.443	0.905	0.809	2.161	0.888	0.776	0.965	*0.939*	*0.879*	1.656	0.800	0.599

[1]Pre-existing streamgage, not established for this study.

Table 6. Estimation sites, by county in western Pennsylvania, with the lowest and highest non-runoff influenced observed streamflow, May 1, 2015–March 31, 2017, and logarithmic transformed streamflow and streamflow range difference.

[*, indicates during the model development period, zero streamflow was observed; **; indicates only non-runoff influenced streamflow is considered; ft^3/s, cubic foot per second]

Streamgage	County	Lowest observed **streamflow (ft^3/s)	Highest observed **streamflow (ft^3/s)	Log base 10 transformed lowest observed **streamflow	Log base 10 transformed highest observed **streamflow	Difference between log base 10 transformed highest and lowest observed **streamflow
03108010	Beaver	0.07	8.56	−1.1549	0.9325	2.0874
03107698	Beaver	0.13	19.90	−0.8861	1.2989	2.1849
03081800	Fayette	0.22	34.84	−0.6576	1.5421	2.1997
03111200	Washington	0.23	38.90	−0.6383	1.5899	2.2282
03111890	Washington	0.01	4.96	−2.0000	0.6955	2.6955
03111215	Washington	*0.01	8.65	−2.0000	0.9370	2.9370
03111235	Washington	*0.001	1.197	−3.0000	0.0781	3.0781
03111675	Greene	*0.01	24.94	−2.0000	1.3969	3.3969
03072890	Greene	*0.001	3.174	−3.0000	0.5016	3.5016
03111705	Greene	*0.01	33.45	−2.0000	1.5244	3.5244
03114094	Greene	*0.01	42.70	−2.0000	1.6304	3.6304
03105927	Butler	0.02	71.97	−1.6990	1.8572	3.5561

interval width, regardless of location or watershed-area ratio. Figure 8 shows the watershed-area ratio of the estimation gage to the index gage versus log prediction interval width. The shaded area between the red lines represents where the index streamgage watershed area is 0.33 to 3 times the size of the estimation site. The streamgages outside the shaded area performed as well as those within it, and there does not appear to be any pattern between watershed-area ratio and log prediction interval widths (figure 8). An example is the streamflow relation between streamgage 03111235 (DogTrib) as estimated by streamgage 03112000 (Wheeling), with a watershed-area ratio of 0.001 and a log prediction interval width of 1.261 log cycles which makes it the fourth smallest log prediction interval width of the 14 index sites that were analyzed (table 5; Hittle, 2019c).

The distance between the streamgage pairs appears to be a major contributing factor to how well the index streamgage can estimate streamflow at the estimation site. The closest streamgage to estimation sites 03072890 (Fonner) and 03105927 (Crab) is more than 10 miles away, and using the index streamgage closest to the estimation streamage did not produce MOVE.1 regressions having the first or second smallest log prediction interval widths. To further explore the distance issue, only index streamgages that were greater than 10 miles from the estimation site were examined. In this case, the closest streamgage produced MOVE.1 regressions with the first or second smallest prediction intervals for only 5 of 11 estimation sites; for 1 estimation site (03111705, SF Dunkard), all log prediction interval widths were greater than 1.7 log cycles. This indicates that it is ideal to have an index streamgage within about 10 miles of the site of interest but by no means indicates that acceptable prediction interval widths cannot be produced using streamgages further away.

Representative Index Streamgages

In the previous section "MOVE.1 Regression Discussion," we looked at how factors related to the watershed area and location of the index streamgage are related to the MOVE.1 regression performance at one estimation site. The analysis in this section examines how one index streamgage relates to a number of estimation sites. The estimation sites are discussed in four county groups, (1) Washington County, (2) Beaver County, (3) Greene County and (4) Butler and Fayette Counties. As was discussed in the "Index-Gage Method Results" section beginning on page 19, the log prediction interval width cannot be used to look at the performance of one index streamgage for multiple estimation sites because the range of flow at the estimation site will influence this number. Therefore, the estimation sites are broken up into groups to determine the best index streamgage for an area as determined by log prediction interval width.

The log prediction interval widths from the MOVE.1 regressions that were produced for each index streamgage are shown in figure 9. On the basis of the MOVE.1 regression log prediction interval widths, the streamflows at streamgages in Washington County are generally well estimated. MOVE.1 regressions using streamgages 03112000 (Wheeling), 03111890 (MWheeling), and 03111215 (Bonar) as index streamgages produced log prediction interval widths less than 1.3 log cycles for all the Washington County streamgages.

Table 7. Distance between the watershed area centroids for pairs of U.S. Geological Survey streamgages in western Pennsylvania.

[x, the estimation site and index streamgage are the same streamgage; -, the index streamgage was not used to estimate streamflow at the estimation site]

Index streamgage	Distance, in miles											
	Estimation site											
	03072890	03081800	03105927	03107698	03108010	03111200	03111215	03111235	03111675	03111705	03111890	03114094
03072890	x	44.1	60.9	39.8	43.5	18.6	13.0	17.4	14.3	16.2	12.4	16.8
03081800	44.1	x	72.1	69.6	70.8	54.7	55.3	59.7	51.0	54.1	55.9	52.2
03105927	60.9	72.1	x	31.1	21.7	49.1	59.0	54.1	74.6	75.8	59.0	77.1
03107698	39.8	69.6	31.1	x	7.5	22.4	31.1	26.1	50.3	50.3	32.3	52.2
03108010	43.5	70.8	21.7	7.5	x	28.0	37.3	32.9	55.3	55.9	38.5	57.8
03111200	18.6	54.7	49.1	22.4	28.0	x	9.9	5.6	28.6	28.6	10.6	29.8
03111215	13.0	55.3	59.0	31.1	37.3	9.9	x	6.5	19.3	19.3	1.6	21.7
03111235	17.4	59.7	54.1	26.1	32.9	5.6	5.6	x	24.9	24.9	6.8	26.1
03111675	14.3	51.0	74.6	50.3	55.3	28.6	19.3	24.9	x	3.1	18.0	2.5
03111705	16.2	54.1	75.8	50.3	55.9	28.6	19.3	24.9	3.1	x	18.0	2.5
03111890	12.4	55.9	59.0	32.3	38.5	10.6	1.6	6.8	18.0	18.0	x	19.9
03114094	16.8	52.2	77.1	52.2	57.8	29.8	21.7	26.1	2.5	2.5	19.9	x
[1]03072000	19.2	-	-	-	-	-	-	-	11.0	13.4	27.8	11.7
[1]03074500	-	14.8	-	-	-	-	-	-	-	-	-	-
[1]03108000	-	-	-	7.4	10.6	17.5	-	22.3	-	-	-	-
[1]03110830	-	-	-	6.0	-	-	-	20.1	-	-	-	-
[1]03112000	14.4	-	-	40.2	46.8	19.0	10.0	14.4	12.5	11.3	8.5	13.2

[1]Pre-existing streamgage, not established for this study.

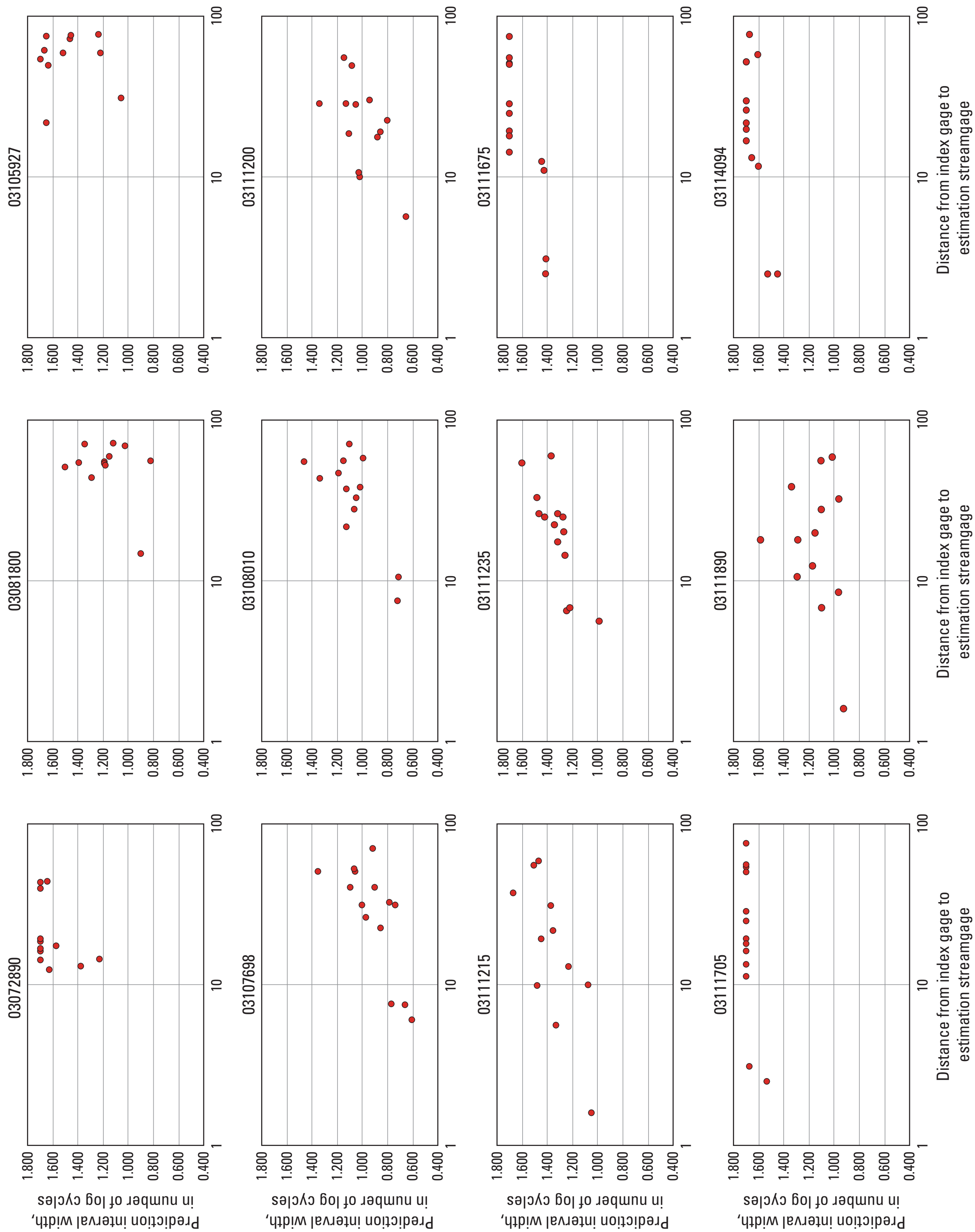

Figure 7. Distance (on log scale) from the estimation site to the index streamgage in relation to the log prediction interval width for each of the 12 newly established streamgages, in western Pennsylvania.

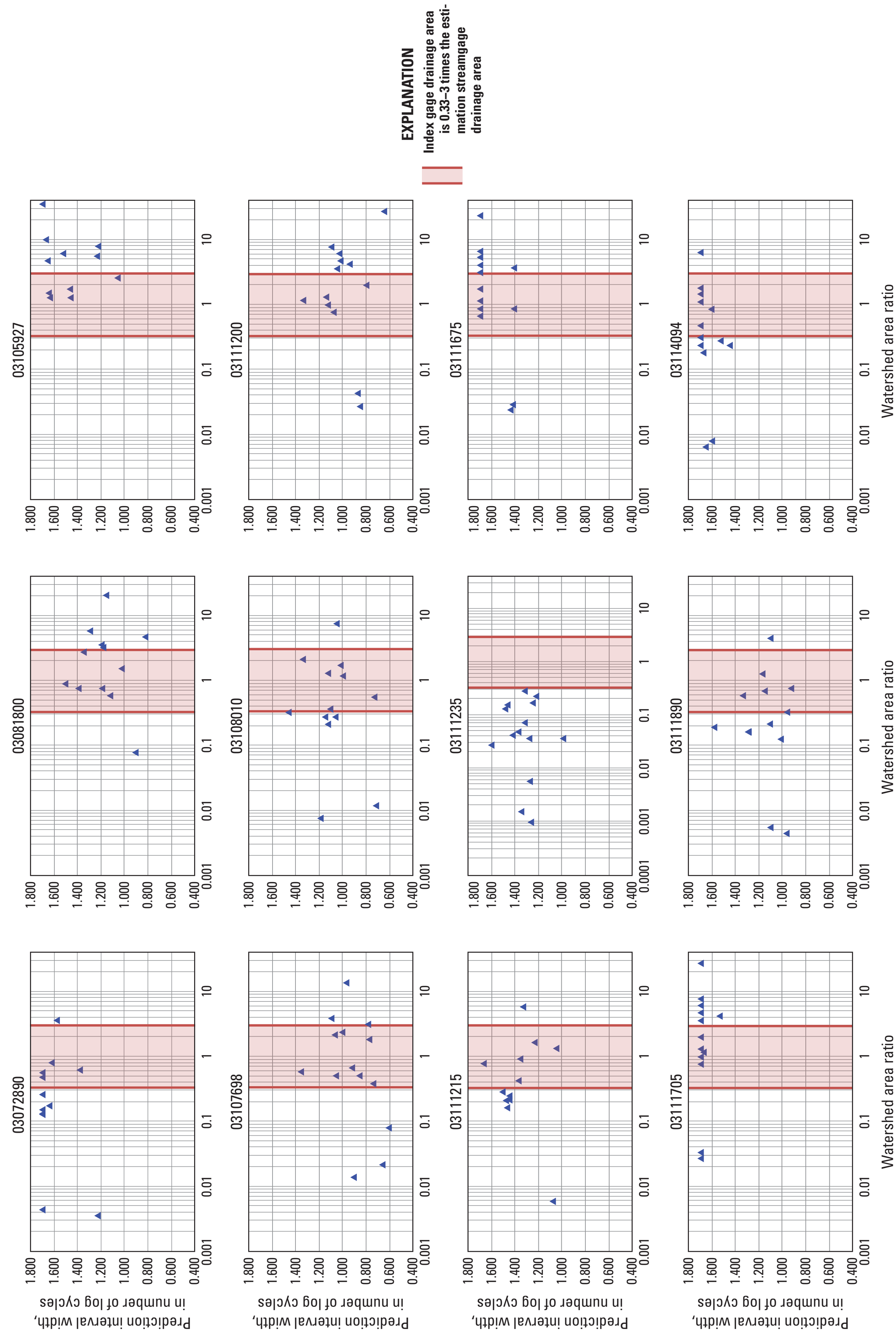

Figure 8. Ratio of the estimation site watershed area to the index streamgage watershed area for the 12 newly established streamgages in western Pennsylvania in relation to the log prediction interval width. The shaded area between the red lines represents the area where the index streamgage watershed area is 0.33 to 3 times the size of the estimation site watershed area.

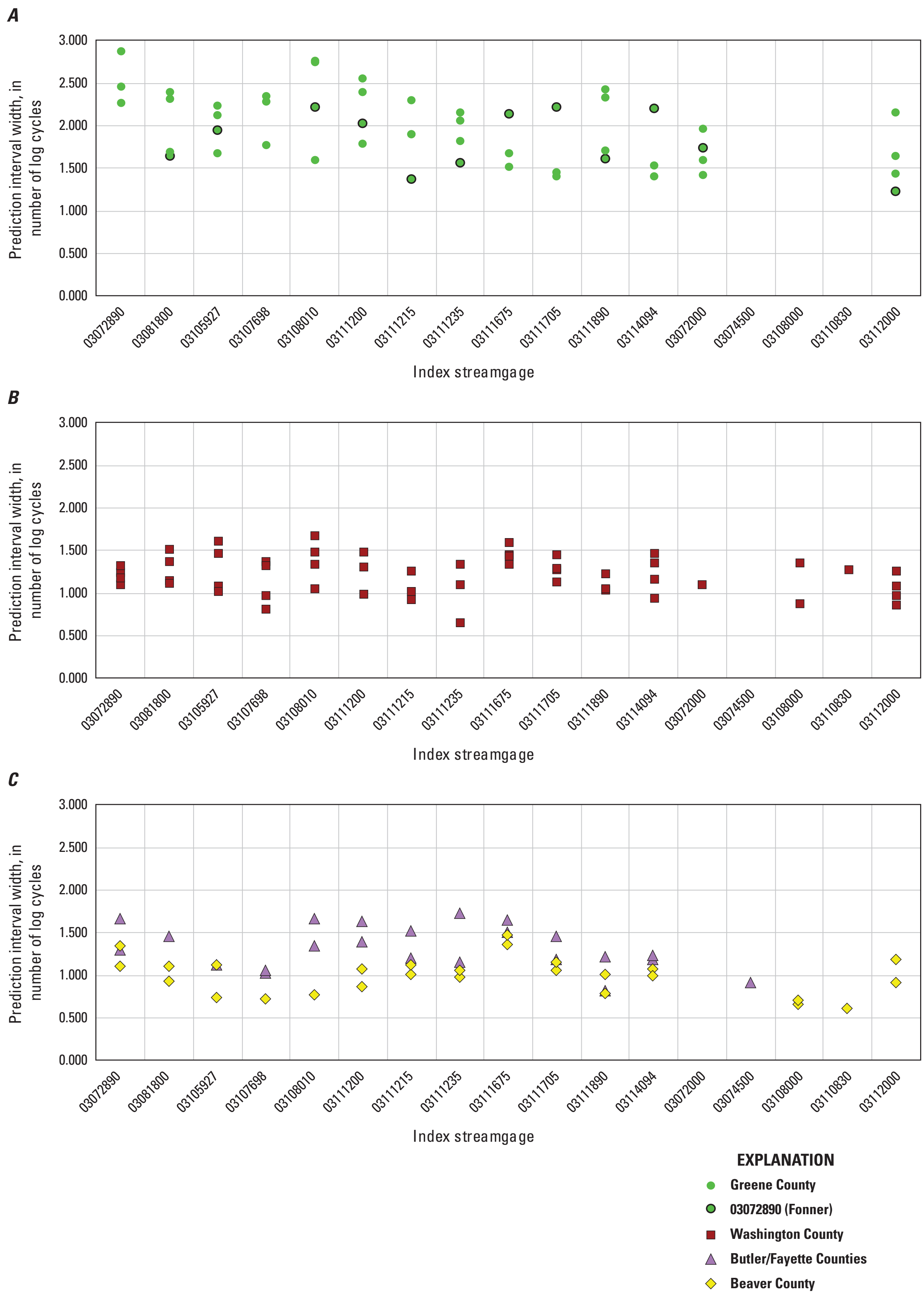

Figure 9. Log prediction interval widths calculated from the MOVE.1 regressions for selected index streamgages in *A*, Greene County, *B*, Washington County, and *C*, Beaver/Fayette/Butler Counties, western Pennsylvania.

This may indicate that these streamgages represent streamflow well for Washington County streams.

The estimation sites in Greene County (depicted in green in fig. 9) using streamgages 03114094 (Herod) and 03111705 (SF Dunkard) as index streamgages produced the smallest log prediction interval widths when streamgage 03072890 (Fonner; circled in black in fig. 9) is excluded as an estimation site. This may indicate that these streamgages represent streamflow well for Greene County streams. For Greene County, the previously established streamgages—03072000 (Shannopin) and 03112000 (Wheeling)—performed adequately as index streamgages, but the results were not consistent. Consequently, for a site of interest in Greene County, MOVE.1 regressions need to be developed using a newly established streamgage and a previously established streamgage to determine the best index streamgage.

Although the streamgages identified previously in the section produced the smallest consistent log prediction interval widths, this study has shown that, in general, MOVE.1 regressions for an estimation site can be developed using any streamgage in the area surrounding the estimation site. The NSE coefficients (table 5) computed from the MOVE.1 regression show that when station 03072890 (Fonner) is not included as an index streamgage, 9 of the 12 estimation sites have values greater than 0.50 from all index streamgages, giving a qualitative indication that a relation between the stations is possible. The Greene County estimation sites, however, produce MOVE.1 regressions with the largest log prediction intervals when the index streamgage is not in Greene County. In addition to the streamflow range discussed in the "Index-Gage Method Results" on page 19, examining the continuous record of the newly established estimation sites and concentrating on the base-flow characteristics of the streamgages may provide insight for further analysis.

Base-Flow Characteristics of the Newly Established Streamgages

Examining the base-flow characteristics of the 12 newly established streamgages can provide further insight into the streamgage relations and possibly help in identifying areas where future index streamgages should be placed or retained. Base flow is the sustained streamflow of the stream in the absence of direct runoff (U.S. Geological Survey, 2017) and is mostly attributed to groundwater entering the stream under natural conditions. Within the study area, there are differences in physical characteristics, such as land use, geologic formation, and climate, that could cause differences in base-flow characteristics of the 12 small streams. The base flow of a stream can be affected by underground mining activities that change the groundwater elevation or alter groundwater divides. Although loss of base flow (zero streamflow) in small headwater streams can be a natural occurrence during seasonally dry periods, subsidence due to mining may enhance the effect by inducing fracturing, increasing hydraulic conductivity, and increasing the capacity of the subsurface to store water. Greater hydraulic conductivity and subsurface storage may lower groundwater levels in the affected area, resulting in the reduction or removal of the base-flow component of streamflow and extending periods of zero streamflow when runoff and recharge from precipitation are minimal.

Streamflow records were analyzed to document base-flow characteristics of the small watersheds. The contribution of base flow was investigated by analysis of streamflow records at continuous-record streamgages (hydrograph analysis). The base flow of streams draining small watersheds was determined with the computerized base-flow separation method PART (Rutledge, 1998) by use of the USGS Groundwater Toolbox (Barlow and others, 2015). Although PART is not recommended for watershed areas less than 1 mi^2 and other methods of base-flow separation are available, PART was chosen because it has been recently applied in Pennsylvania (McCoy and others, 2015; Reese and Risser, 2010). Hydrographs of daily mean streamflow from continuous-record streamgages were separated into base flow and direct runoff components. Daily mean streamflows at the 12 newly established sites (table 2) were analyzed. An example of hydrograph separation by the PART method is shown for the streamflow record for estimation site 03111675 (Job) during 2015 (fig. 10).

The streamgages used for the base-flow analysis, along with some watershed characteristics and underlying geology, are listed in table 2. Records of daily mean streamflow were available from August 2014 through December 2016 for some streamgages, but the data were not complete for all streamgages for that entire period. To compare conditions among all 12 small watersheds, the period of concurrent record from June 18, 2015, through December 31, 2016, was used, except for the derivation of master-recession curves, for which all available data were used. The results of the comparisons would likely differ if streamflow records of longer duration were available. Two base-flow analysis techniques were examined, base-flow-duration curves and the median recession index (K). These analyses were done with the use of the USGS Groundwater Toolbox (Barlow and others, 2015).

Base-Flow Duration Curves

A base-flow duration curve illustrates the percentage of time a given streamflow is likely to be equaled or exceeded. Base-flow duration curves for streamflow in the 12 small watersheds (normalized for watershed area) were plotted for the period of concurrent record from June 18, 2015, through March 31, 2017 (fig. 11). The base-flow duration curves show variation among the streamgages, although the streamgages could be divided into three groups, as shown in figure 11 by the different line colors.

One factor that might be contributing to base-flow differences seen in figure 11 is the bedrock geology, particularly at the Greene County sites (table 2). Watersheds of the four Greene County streams (depicted in red in fig. 11) are underlain entirely by bedrock of the Greene Formation. The Greene

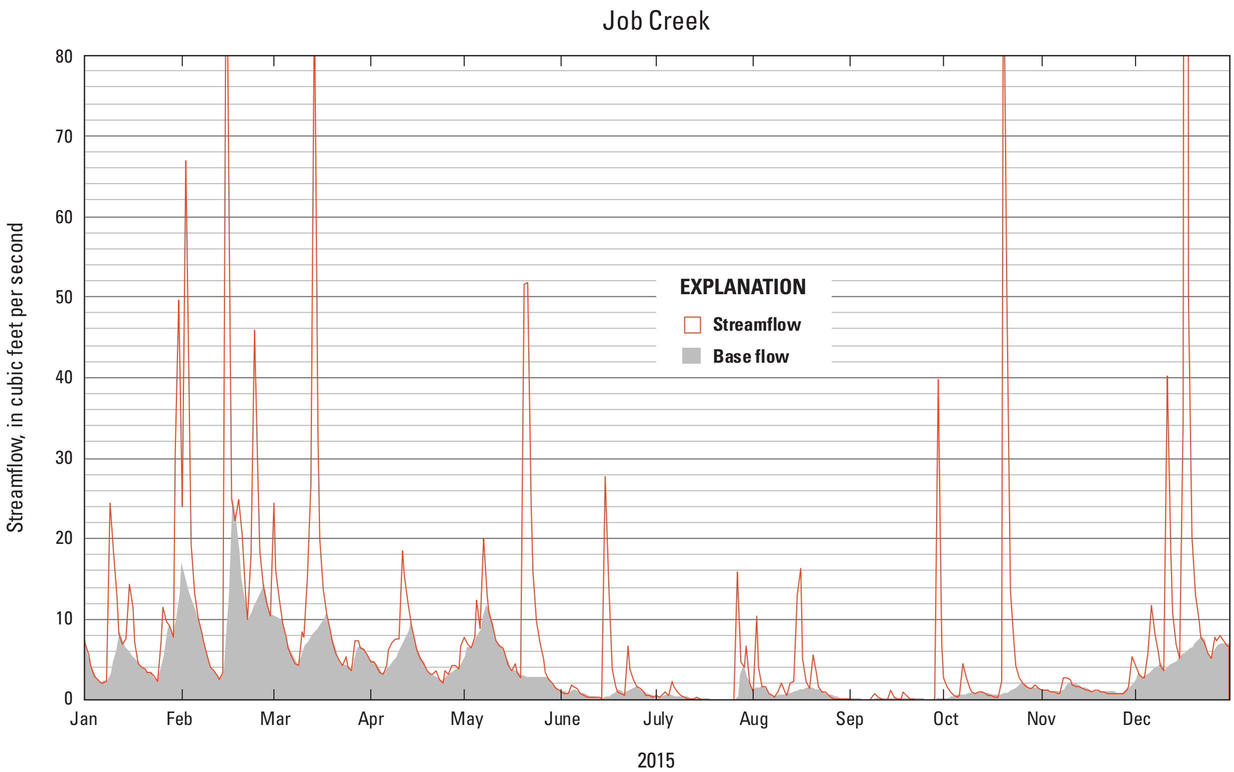

Figure 10. Example of hydrograph separation using the PART method and the daily streamflow record for U.S. Geological Survey estimation site 03111675, Job Creek at Delphene, western Pennsylvania, during 2015.

Formation of Permian age is known to be a poor aquifer that often does not provide even the small quantities of groundwater to wells needed for domestic use (Stoner and others, 1987). It is probable that the Greene Formation provides less groundwater discharge to streams per square mile of watershed than other older geologic formations in the study area. The 03111890 (MWheeling) and 03111215 (Bonar) streamgages, which have higher base-flow yields (base flow per square mile) than the Greene County sites, are mostly underlain by the Greene Formation (75 percent or greater), which may account for the lower base-flow yields than those sites to the north. Streamgage 03111235 (DogTrib) goes dry about 5 percent of the year and could have been grouped with the streamgages shown in blue (fig. 11) because it followed their trend approximately 87 percent of the time. It is not unexpected that streamflow in a watershed area of this size could go to zero owing to underflow that is not measured by the streamgage. In the future, it would not be possible to establish base-flow duration curves for a periodically measured stream; however, these graphs depicting base-flow yields could lend themselves to the identification of 2 or 3 groups of streamgages that would relate best to each other. Index streamgage establishment could then be guided by placing streamgages in the area generally represented by the grouped streamgages.

Median Recession Index

The master recession curve (MRC) for a stream is a plot of streamflow recession over time (Q/t) during periods when the stream is chiefly sustained by base flow. It provides an average characterization of base-flow response developed by assembling multiple segments of continuous recession from the streamflow hydrograph that represents a period greater than any single recession in the recorded data. The rate of base-flow decline shown by the MRC is related to the transmissivity and subsurface storage of the aquifer beneath the watershed, among other factors (Rutledge, 1998).

The MRC for the 12 streams draining small watersheds was determined using a computer program called RECESS (Rutledge, 1998) as implemented in the USGS Groundwater Toolbox (Barlow and others, 2015). The program computes an equation for the MRC and the median recession index (K), which is the median slope of multiple streamflow-recession periods selected for each stream (table 8). Specifically, the value of K is the median time in days for the streamflow to decline one log cycle (after the influence of surface runoff or interflow has ceased) for the multiple recession segments analyzed. A smaller K value indicates that the base flow in the watershed decreases faster than that in a watershed with a larger K value. A smaller K value could also indicate the watershed may experience zero flow before another watershed

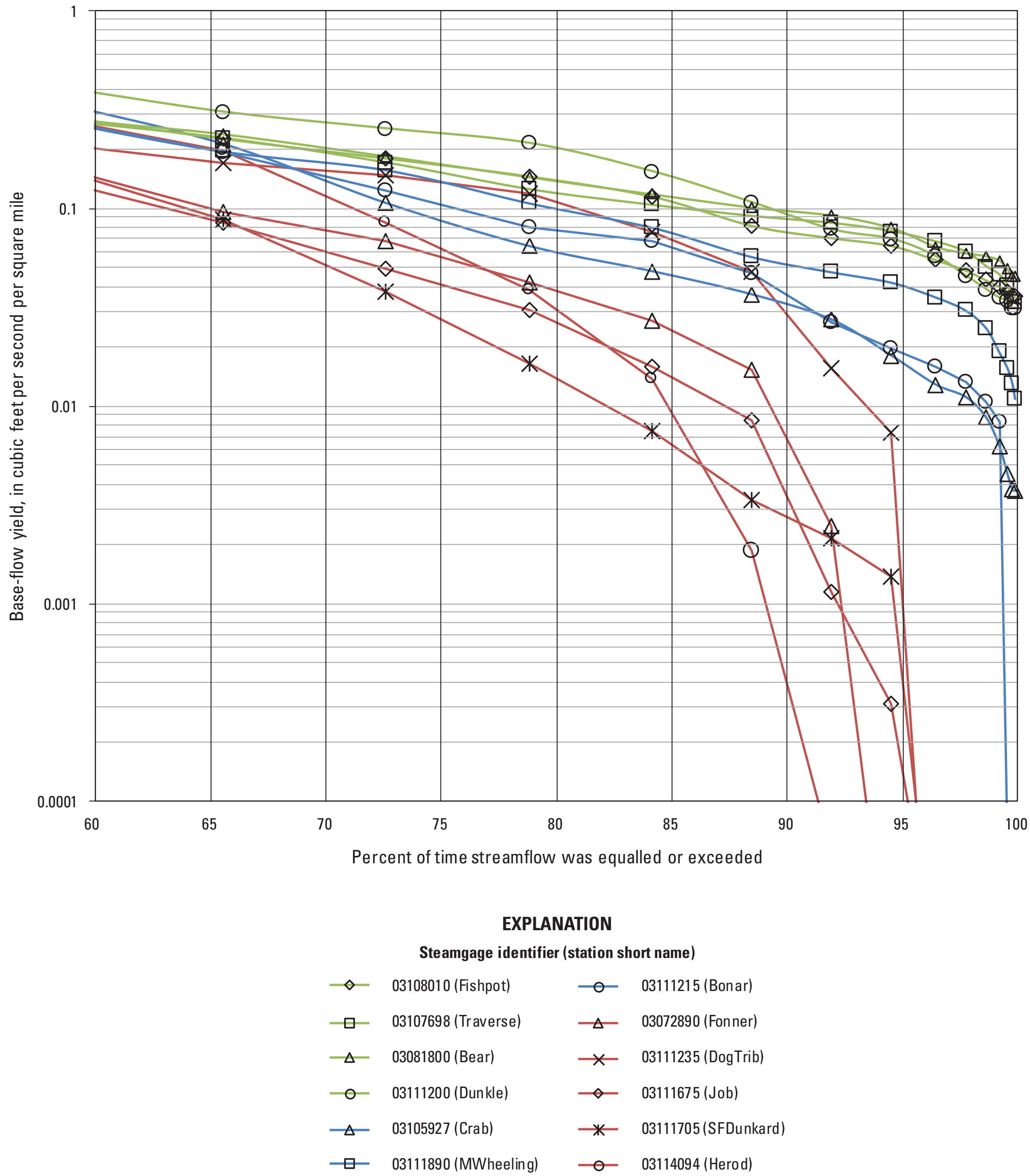

Figure 11. Base-flow duration curves for 12 small watersheds in western Pennsylvania plotted for the period of concurrent record from June 18, 2015, through March 31, 2017. The three colors of lines present a visual grouping of the streamgages.

Table 8. Median recession index (K) in days per log (base 10) cycle of streamflow for newly established streamgages in western Pennsylvania, by county.

[USGS, U.S. Geological Survey]

USGS station identifier	Station name	Pennsylvania county	Median recession index (K), in days per log (base 10) cycle of streamflow
03111675	Job Creek at Delphene	Greene	11.35
03111705	South Fork Dunkard Fork at Aleppo	Greene	14.82
03114094	Herod Run near New Freeport	Greene	12.23
03072890	Fonner Run near Deer Lick	Greene	14.63
03111890	Middle Wheeling Creek near Claysville	Washington	17.08
03111215	Bonar Creek near Claysville	Washington	21.64
03111235	Unnamed trib to Dog Run at Dunsfort	Washington	14.34
03111200	Dunkle Run near Claysville	Washington	25.5
03107698	Traverse Creek near Kendall	Beaver	16.68
03108010	Fishpot Run near Shippingport	Beaver	18.96
03105927	Crab Run near Connoquenessing	Butler	13.69
03081800	Bear Run at Kauffman	Fayette	22.35

of similar size with a larger K value. Periods of streamflow recession from the months of September through May were examined using the period of record available for each streamgage. Recession segments during June–August were not used to avoid periods when the recessions could be strongly affected by evapotranspiration.

With periodic measurement only, MRCs cannot be obtained. However, Eng and Milly (2007) describe the technique of using measurements spaced apart on a recession curve to estimate the K value. Using two measurements of base flow on successive days after cessation of surface runoff and interflow, the recession index can be estimated as

$$K = \Delta t / (log Q_1 - log Q_2) \quad (6)$$

where

- K is the recession index, in days per log (base 10) cycle of streamflow;
- Q_1 is the base flow measured in the stream at time 1, in ft^3/s;
- Q_2 is the base flow measured at a later time 2, in ft^3/s; and
- Δt is the time between $Q1$ and $Q2$, in days.

This is an estimate of K based on two values; however, using the PO2 streamflow-measurement schedule, it is possible that numerous values on a recession curve can be determined. The following technique was used to determine an estimate of K from a recession curve. Log streamflow from a recession period was plotted against the day from the streamflow-measurement schedule (day 1, day 3, day 5, and so on from the PO2 schedule), and a linear trend line and associated equation were developed. The equation was then reversed to estimate the days when streamflow would be 10.00 ft^3/s and 100.0 ft^3/s; the number of days for streamflow to drop one log cycle (for example, the number of days for the logarithm of flow to drop from 3 to 2) is the K value for that period.

With continuous streamflow record, the recession trend is determined by evaluating relatively large recession events over a period long enough to measure the recession over a complete log cycle to determine an overall recession trend. For streamgages with periodic streamflow measurements only, it may not be possible to measure multiple days in a row, depending on precipitation patterns. This implies judgment will be needed in selecting the recession periods for evaluation on the basis of partial record, realizing there will be great variability in estimates of K for one streamgage. For example, figure 12 shows the K value computation for streamgage 03111235 (DogTrib) for three recession periods greater than 3 days during non-summer months (so evapotranspiration would not be an issue). Estimates of K ranged from 14 to 24 days per log cycle of streamflow. However, these snapshots of K values can be useful in predicting how well two streamgages relate to each other. Analyzing the same recession periods at 03111890 (Middle Wheeling), the K values ranged from 18 to 24 days per log cycle of streamflow (fig. 12 *A*, *B*, *C*). The K values in April and November are very similar but not those in February. One would predict that the relation between the streamgages should be stronger in November and April than in February on the basis of this recession data.

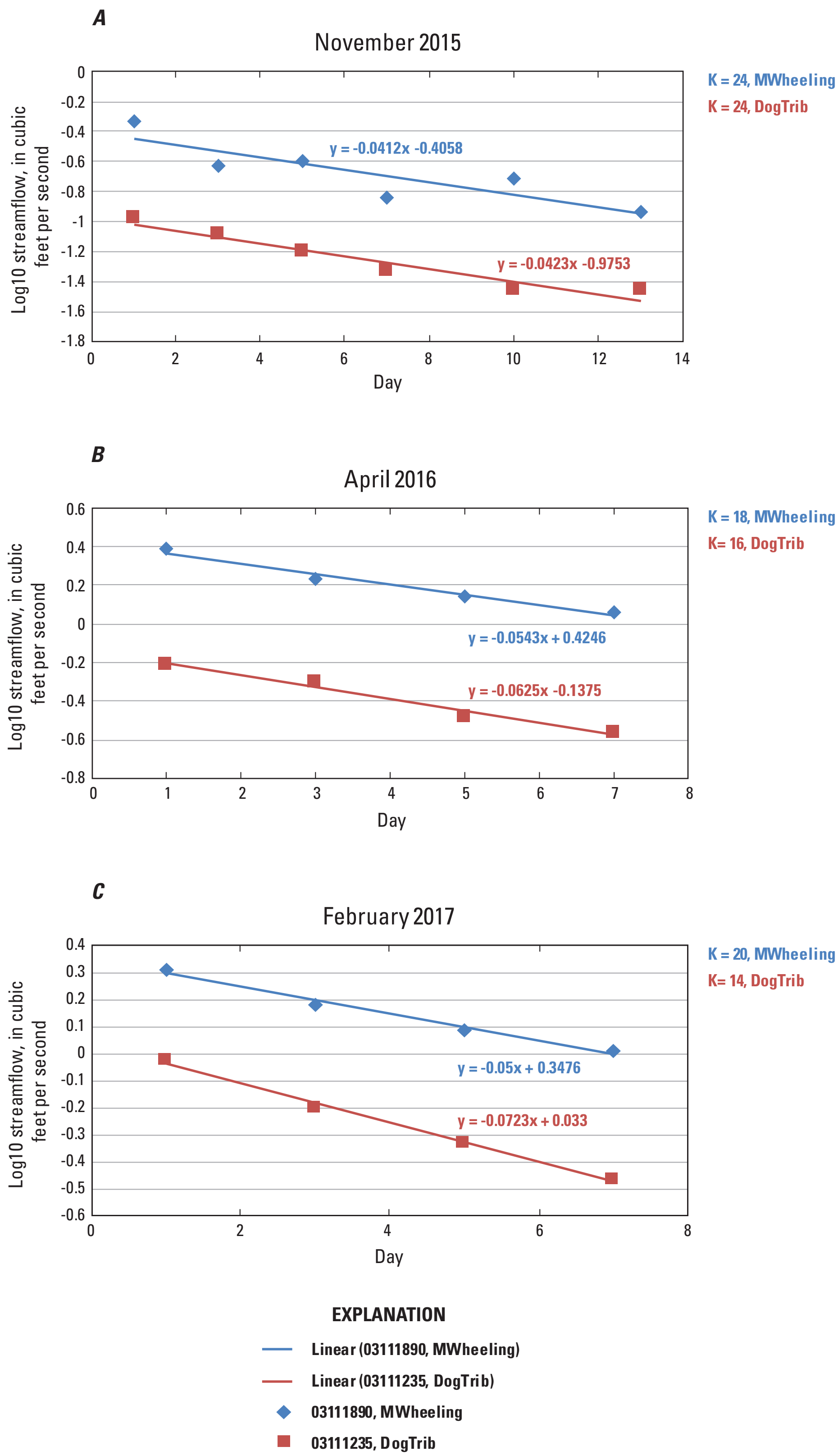

Figure 12. Median Recession Index (K) for recession periods in *A*, November 2015, *B*, April 2016, and *C*, February 2017 at U.S. Geological Survey streamgage 03111235, Unnamed trib to Dog Run at Dunsfort (DogTrib) and U.S. Geological Survey streamgage 03111890, Middle Wheeling Creek near Claysville (MWheeling) in western Pennsylvania. The simple linear equation for DogTrib is shown in red, and the equation for MWheeling is shown in blue.

Evaluation of Streamflow Not Used for Regression Development

An independent streamflow dataset (evaluation dataset) that was collected outside the regression development period was used to evaluate the MOVE.1 regression models. Observed streamflow at the estimation site was evaluated to determine whether the streamflow was within the log prediction interval width calculated from the observed streamflow at the index streamgage. If the observed streamflow at the estimation site is outside the calculated prediction interval, then there is a 95-percent chance that it is outside the range of values observed during the regression development period.

Evaluation of zero streamflow at the estimation site is not accomplished with the MOVE.1 regression, but from observed streamflow measurements during the regression development period. During evaluation, if zero streamflow occurs at the estimation site while the index streamflow is at or below the HISAZ value, it means this condition was observed during the regression development period. If the index streamflow was above the HISAZ value, this condition was not observed during the regression development period, and further evaluation not discussed here is necessary. Another piece of information related to zero flow that is not accomplished with the MOVE.1 regression is the highest streamflow at the estimation site when the streamflow at the index streamgage is at or below the HISAZ value. If streamflow at the index streamgage is below the HISAZ value and the observed streamflow at the estimation site also is below that HISAZ value, it means this condition has been observed during the regression development period. Even though the condition was observed during the regression development period, it may fall outside the prediction interval. If this occurs, further evaluation of the data point may be necessary.

For this study, the evaluation dataset was streamflow data from September 2014 to April 2015. As described in the “Frequency of Streamflow Measurement” section, the PO2 streamflow-measurement schedule was used to select streamflow values for the evaluation dataset. An example of streamflow estimated at streamgage 03072890 (Fonner) using streamflow at streamgage 03112000 (Wheeling) is shown in figure 13. There is a 95-percent probability that estimated streamflow data will be contained within the prediction intervals. Four observations plotted outside of the prediction intervals. For the data on November 28, 2014, the observed streamflow at streamgage 03072890 (Fonner) is 0.249 ft^3/s. The upper 95-percent prediction limit computed for an index streamflow of 38.3 ft^3/s is 0.140 ft^3/s. The observed streamflow is greater than the prediction limit and, thus, is outside of the 95-percent prediction interval. The data on November 15, 2014, have the opposite scenario; observed streamflow is less than the lower prediction limit. However, one more piece of information is available. For this streamflow measurement, the observed streamflow at the estimation site is 0.001 ft^3/s, and the observed streamflow at the index streamgage is 26.3 ft^3/s, which is less than the HISAZ value of 30.3 ft^3/s. The lower MOVE.1 regression prediction limit is 0.005 ft^3/s (greater than the observed streamflow of 0.001 ft^3/s at the estimation site), and thus the estimation streamflow is outside the prediction interval. However, looking at all the data from the regression development period where streamflow at the index streamgage was at or less than 30.3 ft^3/s, the highest streamflow at the estimation site is 0.086 ft^3/s. Given that this estimation streamflow scenario occurred during the regression development period but falls outside the MOVE.1 regression prediction interval, this data point may need further evaluation. This example (Hittle, 2019d) and evaluation spreadsheets for all MOVE.1 regressions for streamgage pairs with data available before May 2015 are fully illustrated in the companion data release for this report (Hittle, 2019a). If 03112000 (Wheeling) were continued as an index streamgage, the streamflow should be periodically evaluated to ensure that it has not been affected by a basin changing event warranting the development of a new MOVE.1 regression.

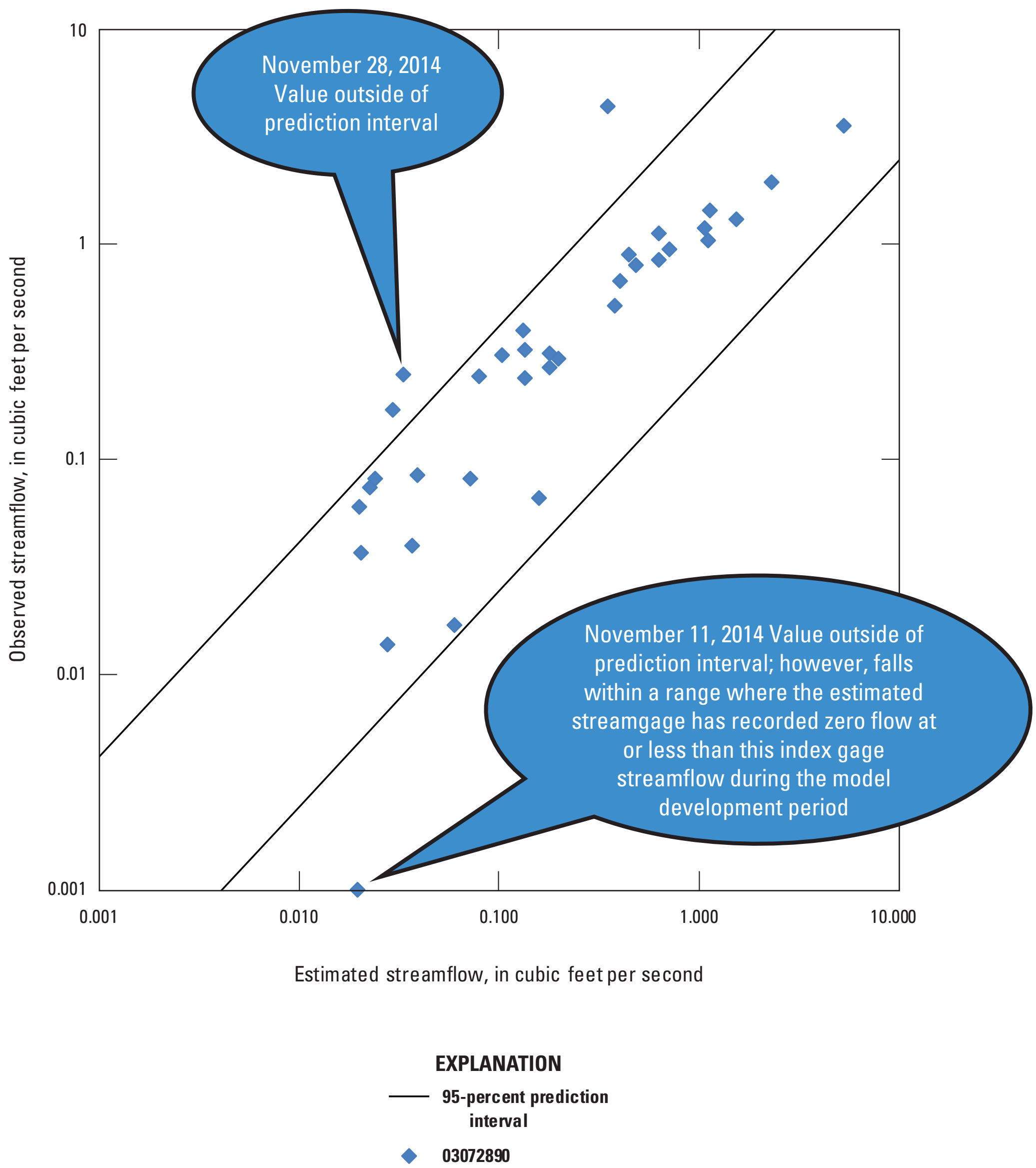

Figure 13. Estimated streamflow in relation to observed streamflow at U.S. Geological Survey (USGS) streamgage 03072890, Fonner Run near Deer Lick (Fonner), western Pennsylvania, with the 95-percent prediction intervals. Streamflow at USGS streamgage 03072890 (Fonner) was estimated using streamflow at USGS streamgage 03112000 Wheeling Creek at Elm Grove, West Virginia.

Accuracy and Limitations

There are many important limitations and considerations for the data collected for this project and the applicability of this technique for the future. The first limitation is how the streamflow for the index streamgage and estimation site was obtained. Streamflow at the newly established streamgages was calculated using a stage-streamflow rating that was developed from several streamflow measurements made over the course of the project. Streamflow measurements also were used to shift the rating to account for minor changes in the stream control over time. There is no way to know exactly when the stage–discharge relation changed between field visits; therefore, the best hydrologic judgment was used when applying shifts. This is a source of uncertainty at any location and can be minimized in the future by making more frequent measurements or establishing permanent control structures, such as a weir, where practical. This source of uncertainty is present for the index streamgage and estimation site, whereas in the future, the uncertainty associated with application of shifts will be present only at the index streamgage because the estimation site will have only periodic measurements.

Omitting the runoff-influenced streamflow data in developing the MOVE.1 regressions limits the range of streamflow used in future predictions because there is no mechanism to predict runoff-influenced streamflow when that streamflow was not part of the regression development. Although the MOVE.1 regressions were developed with limited data owing to the time constraint of this project (about 2 years), observations from the evaluation dataset generally fell within the 95-percent prediction intervals. Localized rain events that affect one watershed more than another will always occur and can result in data falling outside the prediction intervals. Thus, it is important to realize that the prediction interval is a statistic and will not capture every relation between two streamgages. An example of localized rain events affecting the relation between two streamgages is illustrated by the estimation of site 03111235 (DogTrib) from index streamgage 03111215 (Bonar). An analysis of all newly established streamgages used as index streamgages to estimate streamflow at 03111235 (DogTrib) shows streamgage 03111215 (Bonar) was the fifth best index streamgage, as determined by examining the prediction interval width, and the second closest at 6.5 miles (tables 5 and 7). The observed streamflow in relation to estimated streamflow for streamgage 03111235 (DogTrib) is shown in figure 14. Two data points that are outside the 95-percent prediction interval (data points circled in red) occurred on July 18, 2016, and September 14, 2016. The position of the data points is explained by storms that concentrated over the watershed of streamgage 03111215 (Bonar) during July 14–15 and September 10, 2016; however, the storms did not affect the 03111235 (DogTrib) watershed. There could be some geographic feature located to the west of the streamgages that funnels storms particularly over the 03111215 (Bonar) watershed. If that is the case, it would be evidenced by a larger prediction interval width that would account for more data points that do not appear to follow the general trend. Any data point that is above the upper prediction interval limit indicates that the observed streamflow at a streamgage is higher than expected. This is the case for the data point enclosed in a red triangle.

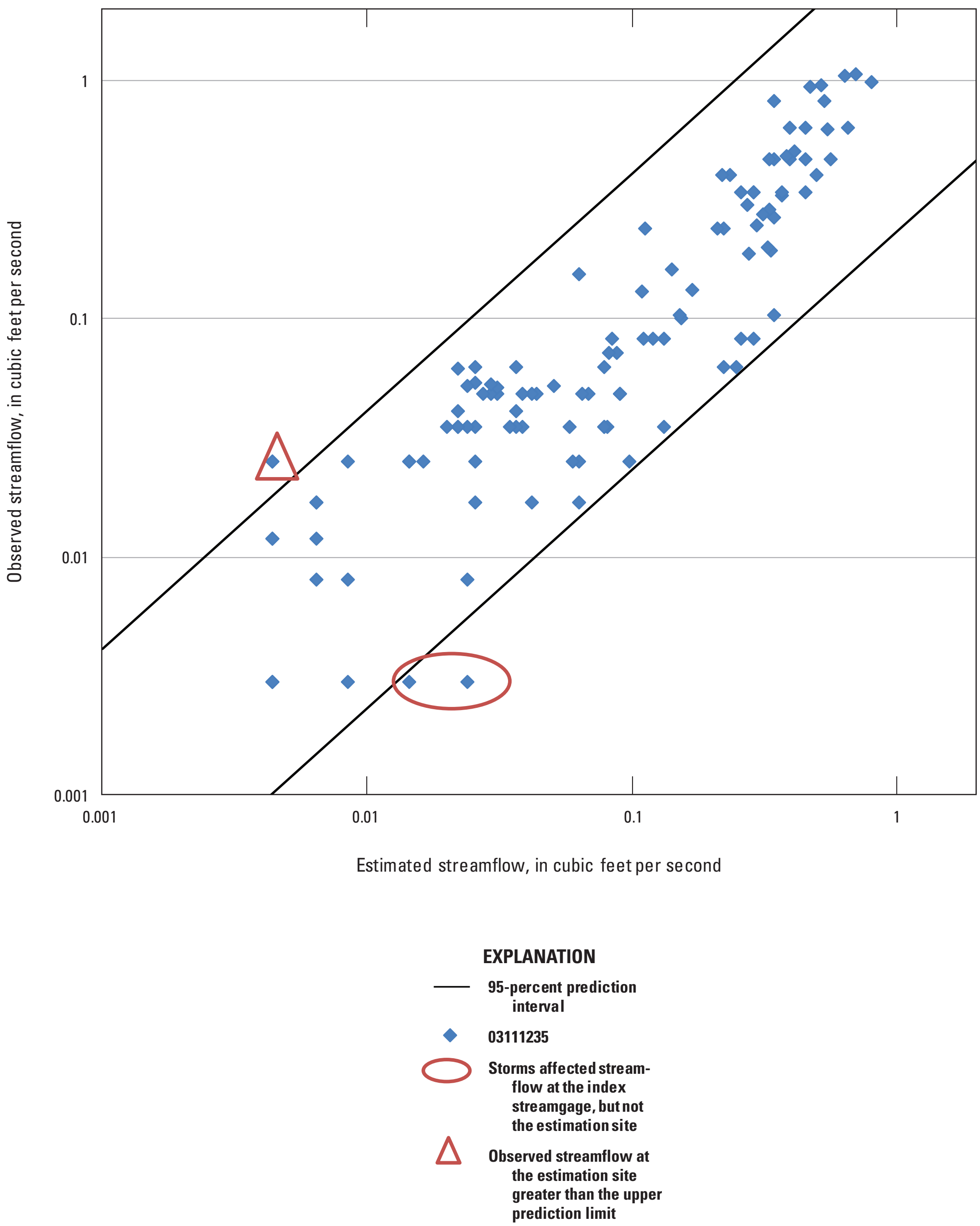

Figure 14. Estimated streamflow in relation to observed streamflow at U.S. Geological Survey (USGS) streamgage 03111235 Unnamed trib to Dog Run at Dunsfort (DogTrib), western Pennsylvania, with the 95-percent prediction intervals. Streamflow at USGS streamgage 03111235 (DogTrib) was estimated using streamflow at USGS streamgage 03111215 Bonar Creek near Claysville.

Application of Techniques to Estimate Natural Streamflow at an Ungaged Site

The techniques described earlier in this report to estimate non-runoff influenced base flow in small watersheds in western Pennsylvania, based on the index-gage method, are illustrated in this section. At the estimation site, streamflow measurements are obtained following the PO2 schedule for about 2.5 years (a measurement is made starting 3 days after a precipitation event [considered day 1] and continuing on subsequent days 3, 5, 7, 10, 13, 16, and every third day until another precipitation event occurs). Rainfall in the area ideally is determined using a local rain gage or historical radar data. A MOVE.1 regression is developed that relates streamflow at the estimation site to streamflow at a nearby streamgage (index streamgage). The precipitation record is examined to assure that runoff-influenced streamflow at the index streamgage is not used. The associated 95-percent prediction intervals and the median recession index (K) also are produced for the regression development period. Lastly, streamflow measurements collected following the PO2 schedule for an additional amount of time (independent dataset not used in regression development) are evaluated.

All data used to develop the MOVE.1 regressions and the resulting regression output, including diagnostics, are detailed in a companion data release (Hittle, 2019a). For example, spreadsheet “Index Streamgage 03111705, Estimation Site 03111675; Data, Regression Models, Evaluation.xlsx” (Hittle, 2019e) was developed by using streamgage 03111705 (SF Dunkard) as the index streamgage and streamgage 03111675 (Job) as the estimation site. Streamflow measurements were selected at the estimation site for the period of May 1, 2015 – March 31, 2017, according to the PO2 schedule. Instantaneous streamflow for that period were matched to streamflow observed at the index streamgage. Observed values from the estimation site were examined for zero streamflow. Because zero streamflow was measured at the estimation site, the HISAZ value and the highest estimated value at or less than the HISAZ value were recorded for use in data evaluation. All streamflow data selected during the regression development period, minus periods of zero streamflow, were used for MOVE.1 regression development. Using the R statistical program (version 3.4.3) with the SMWRStats package (R Core Team, 2017; Lorenz, 2015), a MOVE.1 regression analysis was done using log transformed streamflow data. From this MOVE.1 regression, streamflow at the estimation site is estimated and 95-percent prediction intervals are determined. Regression residuals were examined to determine whether parametric or non-parametric prediction intervals need to be utilized for evaluation. In this case, the test located on the “Model Development (nonparamet)” tab indicates the residuals were not normally distributed; therefore, the nonparametric prediction intervals are used on the “Evaluation” tab.

Data that were collected outside the regression development period are evaluated using the developed MOVE.1 regression. Streamflow estimates at the estimation site, along with the non-parametric 95-percent prediction intervals, are computed using the MOVE.1 regression. A determination can then be made as to whether the streamflow observed at the estimation site falls within the prediction intervals or whether the observed streamflow at the index streamgage is less than the HISAZ value when zero streamflow was observed at the estimation site.

Other information that could be analyzed are the K values for multiple recession periods. For the regression development period, plots were developed of streamflow-measurement day in relation to log streamflow for every recession period that had data recorded for at least 7 days. A simple trend line was calculated along with a trend-line equation for each recession period to calculate the K (recession index) value. Sites that have similar K values should have streamflows during non-runoff periods that are more strongly correlated than streamflows at sites with dissimilar K values.

Summary and Conclusions

A study was conducted by the U.S. Geological Survey, in cooperation with the Pennsylvania Department of Environmental Protection (PADEP), to develop a method for estimating base flow at an ungaged, periodically measured site in the bituminous coal region of southwestern Pennsylvania and adjacent states. This report describes an index-gage method that can be used to estimate streamflow that is predominately unaffected by human activities (such as mining) and not influenced by runoff at a periodically measured site (referred to as the “estimation site”) as a function of streamflow measured at a streamgage site (referred to as the “index streamgage”). The index-gage method employs a regression technique known as Maintenance of Variance, Type 1 (MOVE.1). The period for this study was about 2.5 years, and the number of discrete streamflow measurements initially examined (60) followed current recommendations by PADEP (DEP schedule) for measuring streams that will be undermined by longwall mining. The PADEP requires that streamflow be measured prior to mining once a month for 2 years, weekly for 6 months, and daily for 2 weeks (Pennsylvania Department of Environmental Protection, 2005).

Twelve streamgages with watershed areas less than 10 square miles were established for this study, with most established within Greene and Washington Counties, Pennsylvania. Stage data were collected for the entire period of operation at all 12 streamgages. However, streamflow was computed only for medium to low streamflow at 6 streamgages (partial-record streamgages), whereas streamflow was computed at all stages at the other 6 streamgages (continuous-record streamgages). Data from five previously established continuous-record streamgages with watershed areas ranging from 48.9 to 281 square miles were also used in analyses in this study.

Runoff-influenced streamflow data, defined in this study as streamflow on the day of a precipitation event and 2 days following the precipitation event, were not used in MOVE.1 regression analysis. Once the runoff-influenced data were removed, the remaining streamflow data were analyzed to determine whether daily mean or instantaneous streamflow values would be used for the index streamgage. The analyses did not show a clear advantage to using instantaneous or daily mean streamflow data, so both daily and instantaneous data were used for analyses.

Ten different streamflow-measurement schedules were examined to determine how best to obtain information about the relation between streamflows at two sites when only periodic measurements were made at one site, while maintaining the number of measurements similar to the number PADEP currently (2016) requires. The PO2 schedule (a streamflow measurement is made starting 3 days after a precipitation event [considered day 1], then every other day to day 7, then every third day [days 3, 5, 7, 10, 13, 16, …] until another precipitation event occurs) was used to select data for analysis. Though the number of measurements is greater than 60, this schedule sampled all non-runoff influenced streamflow periods within a month and yielded a good chance of including the lowest streamflow for the regression development period. Thus, when examining relations between all streamgages, the larger dataset was used (PO2 schedule) to have a good chance of including the lowest streamflow.

In general, when a streamflow-measurement schedule that targets the lowest streamflows and includes measurements made only during non-runoff streamflow periods is used, the MOVE.1 regressions developed are comparable to using one streamflow measurement per day with the runoff-influenced streamflow removed, as described by the Nash-Sutcliffe Efficiency values. The resulting log prediction interval widths varied at the 95-percent confidence interval. When similar data, sampled following three different measurement schedules, were used, the number of streamflow measurements included in the dataset, based on the schedule selected, caused different ranked residuals to be used in calculating the prediction interval limits. When the number of measurements was similar to the number currently (2016) in the PADEP schedule, satisfactory results were obtained with the PO8 schedule that targets measurements that occur every other day for 7 days then every third day during non-runoff periods, with the exception that a given day sequence number (1, 3, 5, 7, … days after cessation of runoff) is sampled only once in a month. It is acknowledged that the lowest streamflow at the estimation site may not be measured if the longest non-runoff influenced period occurred at the beginning of the month and streamflow wasn’t measured again, even though the streamflow was lower. Additionally, the range and number of outliers could change if the PO8 schedule were started at the beginning or end of a month.

The distances between the estimation site and the index streamgage was a factor related to how well streamflow was estimated at the estimation site. For all of the newly established streamgages used as estimation sites, except 2, the best index streamgage, as indicated by the log prediction interval width, was 1 of the 2 streamgages closest to the estimation site. For the remaining two sites, the closest index streamgage was more than 10 miles away. For the study area, this could indicate that an ideal index streamgage would be within 10 miles but does not imply that a satisfactory relation cannot be developed with a streamgage further away.

The ratio of the watershed area of the estimation site to that of the index streamgage was compared to the prediction interval width. No relation between the two variables could be determined from the graphical analysis. Size of the index-gage watershed does not appear to affect the MOVE.1 regression log prediction interval width. MOVE.1 regression prediction intervals for the existing streamgages are comparable to the prediction intervals for the newly established streamgages, even though the watershed area of the existing streamgage was many times greater.

Index streamgages with the smallest prediction intervals could make ideal index streamgages for future estimation of streamflow in small watersheds in western Pennsylvania. Using the Washington County streamgages 03111890 (MWheeling), 03111215 (Bonar), and previously established streamgage 03112000 (Wheeling) as index streamgages produced MOVE.1 regressions with the smallest prediction interval widths for most of the streamgages in the county, despite their distances from the estimation sites. In Greene County, streamgages 03114094 (Herod) and 03111705 (SF Dunkard) produced MOVE.1 regressions with the smallest log prediction interval widths of the three streamgages clustered together, which includes 03111675 (Job). Even though the streamgages with the smallest prediction interval widths appear to be the best fit as index streamgages for their areas, for this study it was found that streamflow for a site of interest can be estimated by using streamflow (non-runoff influenced) at an index streamgage regardless of the distance to the estimation site, recognizing that the further the sites are from each other, the more the variation in precipitation and geology will affect the relation. Using a streamflow-measurement schedule that captures numerous non-runoff periods (PO8 or PO2), base flow at a site can be estimated with the index-gage method. In addition, upper and lower prediction limits can be calculated to give an indication of uncertainty in the estimates.

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Appendix 1.

Table 1.1 Results of MOVE.1 regression diagnostics for streamflow at U.S. Geological Survey streamgage 03111235 (DogTrib) streamflow estimated by using U.S. Geological Survey streamgages 03111200 (Dunkle) and 03111890 (MWheeling) with and without runoff-influenced streamflow.

Table 1.1 Results of MOVE.1 regression diagnostics for streamflow at U.S. Geological Survey streamgage 03111235 (DogTrib) streamflow estimated by using U.S. Geological Survey streamgages 03111200 (Dunkle) and 03111890 (MWheeling) with and without runoff-influenced streamflow.

[ft^3/s, cubic feet per second]

Runoff-influenced streamflow included in regression?	Regression number	Logarithm (base 10) prediction interval range (number of log cycles)	Nash-Sutcliffe Efficiency value	Correlation coefficient (r)	Highest streamflow at index streamgage when the estimation site was zero (HISAZ) (ft^3/s)
U.S. Geological streamgage 03111235 (DogTrib) streamflow estimated by using U.S. Geological Survey Streamgage 03111200 (Dunkle)					
Yes	ALL	0.998	0.861	0.913	2.59
Yes	r1	1.048	0.862	0.879	0.56
Yes	r2	0.972	0.853	0.925	0.62
Yes	r3	1.042	0.860	0.924	0.83
Yes	r4	1.062	0.858	0.893	0.99
Yes	r5	0.950	0.860	0.928	0.35
No	ALL_PO	0.802	0.859	0.884	0.99
No	r6	0.752	0.860	0.901	0.83
No	r7	0.904	0.861	0.905	0.49
No	r8	0.880	0.857	0.908	0.68
No	r9	0.821	0.843	0.922	0.42
No	r10	0.897	0.862	0.923	0.44
U.S. Geological streamgage 03111235 (DogTrib) streamflow estimated by using U.S. Geological Survey Streamgage 03111890 (MWheeling)					
Yes	ALL	1.313	0.783	0.868	0.16
Yes	r1	1.503	0.779	0.848	0.13
Yes	r2	1.684	0.782	0.850	0.08
Yes	r3	1.491	0.779	0.792	0.05
Yes	r4	1.296	0.777	0.879	0.09
Yes	r5	1.984	0.782	0.814	0.08
No	ALL_PO	1.152	0.776	0.877	0.13
No	r6	1.437	0.783	0.873	0.08
No	r7	1.145	0.767	0.885	0.09
No	r8	1.453	0.777	0.863	0.06
No	r9	1.136	0.779	0.883	0.08
No	r10	1.213	0.769	0.899	0.11

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Publishing support provided by the
West Trenton Publishing Service Center

Hittle and Risser—**Estimation of Base Flow on Ungaged, Periodically Measured Streams in Small Watersheds in Western Pennsylvania**—Scientific Investigations Report 2018–5150

ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20185150