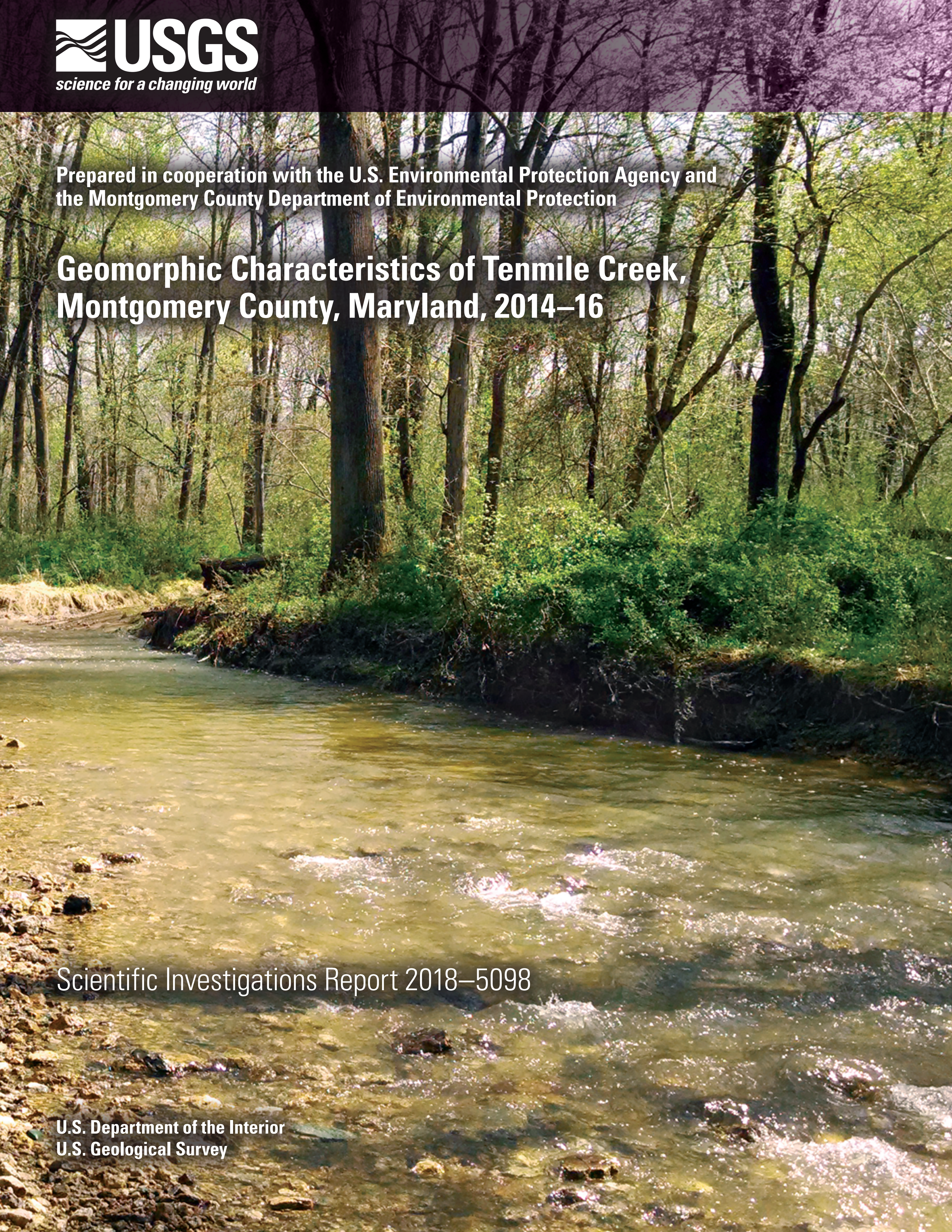

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Prepared in cooperation with the U.S. Environmental Protection Agency and
the Montgomery County Department of Environmental Protection

Geomorphic Characteristics of Tenmile Creek, Montgomery County, Maryland, 2014–16

Scientific Investigations Report 2018–5098

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

Cover. Photograph showing Tenmile Creek, looking upstream near U.S. Geological Survey streamflow-gaging station 01644388. Photograph by Michael A. Clark, U.S. Geological Survey, May 1, 2014.

Geomorphic Characteristics of Tenmile Creek, Montgomery County, Maryland, 2014–16

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U.S. Department of the Interior
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Contents

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic yard (yd^3)	0.7646	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile ($[ft^3/s]/mi^2$)	0.01094	cubic meter per second per square kilometer ($[m^3/s]/km^2$)
foot per second (ft/s)	0.3048	meter per second (m/s)
inch per hour (in/h)	0.0254	meter per hour (m/h)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	metric ton (t)
	Force	
pound per square foot (lb/ft^2)	4.882	kilogram per square meter (kg/m^2)
	Density	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)

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

$$°F = (1.8 \times °C) + 32.$$

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

$$°C = (°F - 32) / 1.8.$$

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).

Elevation, as used in this report, refers to distance above the vertical datum.

Water year is defined as the 12-month period beginning October 1 and ending September 30. The water year is designated by the calendar year in which it ends. For example, the year beginning October 1, 2015 and ending September 30, 2016 is called “water year 2016.”

Abbreviations

DEP	Montgomery County Department of Environmental Protection
d50	Median particle diameter
I-270	Interstate 270
NAD 83	North American Datum of 1983
NAVD 88	North American Vertical Datum of 1988
R^2	Coefficient of determination
RSE	Residual standard error
SPA	Special Protection Area
EPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

Geomorphic Characteristics of Tenmile Creek, Montgomery County, Maryland, 2014–16

By Edward J. Doheny and S. Matthew Baker

Abstract

Data collected from April 2014 through September 2016 were used to assess geomorphic characteristics and geomorphic changes over time in a selected reach of Tenmile Creek, a small rural watershed near Clarksburg, Maryland. Longitudinal profiles of the channel bed, water surface, and bank features were developed from field surveys. Changes in cross-section geometry between field surveys were documented. Grain-size distributions for the channel bed were developed from pebble counts. Continuous-record streamflow and precipitation data were also collected in the Tenmile Creek watershed and used to supplement the geomorphic analyses.

The Rosgen system of stream classification was used to classify the stream channel according to morphological measurements of slope, entrenchment ratio, width-to-depth ratio, sinuosity, and median particle diameter of the channel materials. Boundary shear stress near the U.S. Geological Survey (USGS) streamflow-gaging station was assessed by using hydraulic variables computed from the cross-section surveys and slope measurements derived from crest-stage gages and temporary data loggers installed along the study reach.

Analysis of the longitudinal profiles indicated relatively small changes in the percentage and distribution of riffles, pools, and runs in the study reach between April 2014 and March 2015. More noticeable changes were observed during surveys conducted in March 2016 and September 2016. The channel-bed slope showed a net reduction over time from 0.0072 to 0.0040 feet per foot (ft/ft). The low-flow water-surface slope also showed a net reduction over time from 0.0065 to 0.0045 ft/ft. Net aggradation in the lower section of the study reach combined with net degradation in the upper section of the study reach contributed to the net reduction in channel-bed and water-surface slope. The large storm and resulting flood on July 30, 2016 was a major factor in observed changes in the longitudinal profiles between the March 2016 and September 2016 surveys.

Comparison of data from the cross-sectional surveys indicated vertical changes in all cross sections, with more extreme changes observed between surveys in the lower section of the study reach due in part to alternating periods of net storage and transport of sand. Lateral erosion was not a major factor in the study reach, with the exception of cross section Dd, where considerable lateral erosion was documented during the study period. The flood that resulted from the large storm on July 30, 2016 was a major factor in some of the vertical changes observed in the channel bed of the study reach cross sections.

Particle-size analyses of the channel bed from pebble counts indicated median particle diameters ranging from 15.5 millimeters (mm) to 23.1 mm, which is characterized as medium to coarse gravel. Sand percentages ranging from 3.4 percent to 16.4 percent of the total counts were observed over time. Net increases in storage of fine sediment in the reach were observed between April 2014 and March 2016, and a considerable reduction in storage was observed between March 2016 and September 2016.

The Tenmile Creek stream channel was classified as a C4 channel, based on morphological descriptions from the Rosgen system of stream classification. The C4 classification describes a single-thread channel with a slight entrenchment ratio; a moderate to high width-to-depth ratio; moderate to high sinuosity; a water-surface slope of less than 2 percent; and a median particle diameter in the gravel range of 2 to 64 mm.

The analysis of boundary shear stress indicated a range of 0.35 to 1.18 pounds per square foot for instantaneous streamflow ranging from 79 to 2,860 cubic feet per second during the study period. The relation between discharge and boundary shear stress for Tenmile Creek was compared to similar relations that were previously developed for Minebank Run, a small, urban watershed in the eastern section of the Piedmont Physiographic Province in Baltimore County, Md. that was physically restored during 2004–05. The comparison indicated a much flatter slope in the relation for Minebank Run in both its unrestored and restored conditions. This difference in the relations indicates that the erosive power in the urban watershed of Minebank Run is much more sensitive to increases in discharge magnitude than in the non-urban watershed of Tenmile Creek.

Introduction

Tenmile Creek (referred to locally as Ten Mile Creek), a small, rural watershed in Montgomery County, Maryland, is just to the west of Clarksburg, Md., and drains approximately 5.41 square miles (mi^2). Tenmile Creek is a tributary of Little Seneca Lake, a reservoir that was built on Little Seneca Creek during the early 1980s, and completed in 1983 as an emergency water supply for the metropolitan Washington, D.C. region. The Seneca Creek watershed ultimately drains to the Potomac River and the Chesapeake Bay.

The Montgomery County Council has designated the Tenmile Creek watershed as one of five Special Protection Areas (SPAs) in the County. Under County law, an SPA is defined as a part of Montgomery County that has high quality, or unusually sensitive, water resources or other environmental features, and those resources or features would be negatively affected by land-use change unless extraordinary or special protective measures are taken (Montgomery County Department of Environmental Protection, 2017). In October 2010, the U.S. Geological Survey (USGS), Maryland-Delaware-D.C. Water Science Center established a continuous-record streamflow-gaging station on the lower section of Tenmile Creek to monitor the inflows into Little Seneca Lake. In June 2013, a second streamflow-gaging station was installed and activated farther upstream on Tenmile Creek in a location closer to selected areas of the watershed where future development is planned. In February 2014, the USGS, in cooperation with the U.S. Environmental Protection Agency (EPA), and the Montgomery County Department of Environmental Protection (DEP) began a study to (1) further enhance hydrologic monitoring in the Tenmile Creek watershed with the installation of two continuous-record precipitation gages, and (2) document geomorphic characteristics of the stream channel in a selected reach of Tenmile Creek, prior to any additional development of the watershed.

As part of this study, continuous-record streamflow data were collected at one location in the study reach, whereas continuous-record precipitation data were collected in two locations in the Tenmile Creek watershed. Geomorphic data collected in the study reach included surveyed elevations of the channel bed, water surface, and bank features, surveyed cross sections, pebble counts of the channel-bed material for grain-size analyses, and high-water marks from storm-runoff events in the watershed. The high-water mark data were supplemented with continuous-stage data from HOBO (Onset Computer Corporation, Bourne, Massachusetts) pressure-transducer data loggers that were placed alongside a series of three **crest-stage gages**[1] in the study reach.

These data were used to assess geomorphic characteristics and changes over time in the Tenmile Creek study reach. Analyses conducted for this report include: a comparison of longitudinal profiles of the channel bed and water surface over time; a comparison of cross-section geometry at seven locations in the study reach over time; a comparison of grain-size distributions of the channel bed over time; classification of the study reach according to the Rosgen system of stream classification (Rosgen, 1994, 1996); and computations of **boundary shear stress** based on cross-section geometry and water-surface slope in the vicinity of the streamflow-gaging station. The shear-stress computations for Tenmile Creek were compared to those previously published for Minebank Run, a small, urban watershed in the eastern section of the Piedmont Physiographic Province in Baltimore County, Maryland (Doheny and others, 2007; Doheny and others, 2012).

Purpose and Scope

The purpose of this report is to document a baseline geomorphic assessment of an approximately 1,000-foot (ft) reach of Tenmile Creek. Data collected from **water years** 2014 through 2016 were used to assess the geomorphic characteristics in the study reach. Data collection in the study reach occurred on four occasions between April 2014 and September 2016. Data collected included cross-section surveys of the stream channel, longitudinal-profile surveys of the study reach, pebble counts of the channel bed, and collection of high-water marks with supplemental stage data for computing water-surface slopes.

The techniques used for geomorphic data collection are described. The analyses included (1) development of longitudinal profiles of the channel bed, water surface, and channel features, (2) documentation of cross-section geometry in seven permanent cross sections that were set up in the study reach, (3) development of grain-size distributions of the channel bed in the cross-section locations, and (4) boundary shear stress computations based on cross-section geometry and water-surface slope in the vicinity of the continuous-record streamgage.

The report presents comparisons of these analyses over time to document and assess baseline conditions for channel geometry, longitudinal profile, and bed-material composition. The Tenmile Creek stream channel was also classified by using the Rosgen system of classification for natural rivers (Rosgen, 1994). The report also presents some comparisons of boundary shear stress computations for Tenmile Creek with those previously published for Minebank Run, a small, urban watershed in the eastern section of the Piedmont Physiographic Province in Baltimore County, Md. (Doheny and others, 2007; Doheny and others, 2012).

Description of Tenmile Creek Watershed

Tenmile Creek is a 5.41-mi^2 subwatershed of Little Seneca Creek in the northwestern section of Montgomery County, Md. (fig. 1). The Tenmile Creek subwatershed lies between 39° 12′ 27″ and 39° 14′ 57″ north latitude, and between 77° 16′ 43″ and 77° 20′ 08″ west longitude, within the western section of the Piedmont Physiographic Province,

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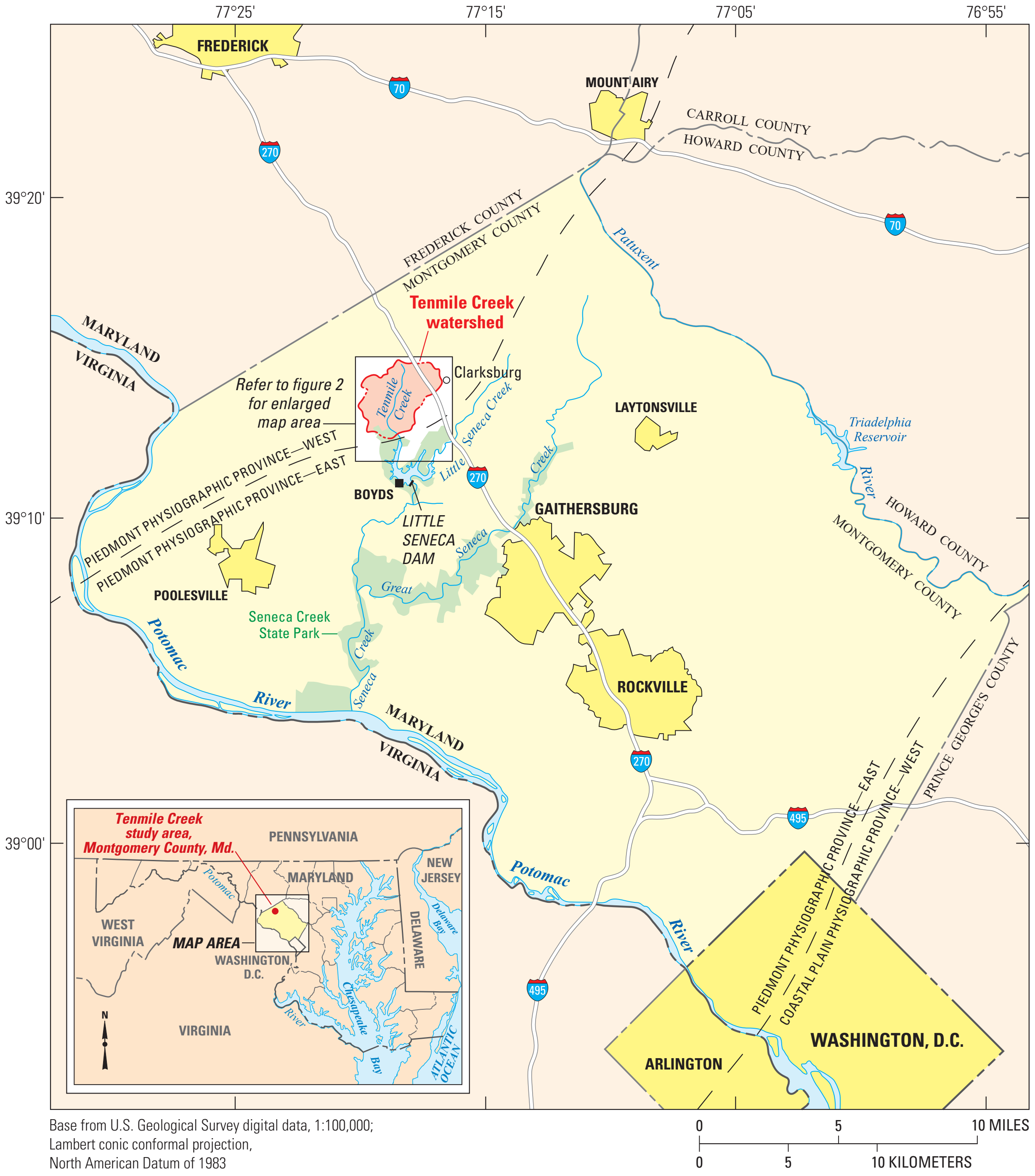
[1] Words in **bold** are defined in the glossary section of the report.



Base from U.S. Geological Survey digital data, 1:100,000;
Lambert conic conformal projection,
North American Datum of 1983

Figure 1. Location of Tenmile Creek watershed, Montgomery County, Maryland.

just northwest of the boundary between the eastern and western sections of the Piedmont (Reger and Cleaves, 2008). The headwaters of Tenmile Creek originate near Thompsons Corner, Md., approximately 2 miles (mi) northwest of Clarksburg. The stream flows south for about 2.5 mi, and drains into Little Seneca Lake approximately 1.9 mi northeast of the town of Boyds, Md.

Prior to 1983, when the dam that created Little Seneca Lake was completed, Tenmile Creek flowed for an additional length of about 1.85 mi before its confluence with Little Seneca Creek. The dam permanently submerged this downstream section of the stream channel, and approximately 2.14 mi^2 of drainage area from Tenmile Creek is now direct drainage into Little Seneca Lake since the construction of the dam.

The watershed is underlain by the Western Piedmont Metasedimentary Rocks, including two geologic formations composed of late Pre-Cambrian crystalline rocks. The first is the Ijamsville Phyllite, which consists of blue, green, or purple phyllite and phyllitic slate, with interbedded metasiltstone and **metagraywacke** (Maryland Geological Survey, 1968a). The second is the Marburg Formation, which consists of bluish-gray to silvery-green, fine-grained, muscovite-chlorite-albite-quartz schist, with interbedded quartzite (Maryland Geological Survey, 1968b).

The Tenmile Creek watershed ranges in elevation from about 540 to 680 ft above the North American Vertical Datum of 1988 (NAVD 88) at the drainage boundaries, to about 400 to 600 ft above NAVD 88 at the bottom of the stream valley. **Relief** ranges from about 30 ft to 140 ft in most areas of the watershed. Average annual precipitation in the watershed totals about 44 inches (in.), based on 30-year mean annual precipitation normals between 1981 and 2010 (PRISM Climate Group, 2018; U.S. Geological Survey, 2012).

Land use in the watershed is classified as about 52.4 percent forest, about 42.6 percent agricultural, and about 5.0 percent impervious area, based on Maryland 2010 land-use data (Maryland Department of Planning, 2018; U.S. Geological Survey, 2012). Much of the existing impervious area is in the headwaters, where Interstate 270 (I-270) traverses the watershed.

Description of Study Area

The Tenmile Creek study reach drains the upper 3.37-mi^2 section of the watershed (fig. 2). The length of the study reach is approximately 1,000 ft. Land use in this section of the Tenmile Creek watershed is approximately 43.3 percent forest, 6.0 percent impervious area, and the remainder is mostly agricultural, based on Maryland 2010 land-use data (Maryland Department of Planning, 2018; U.S. Geological Survey, 2012).

Sinuosity of the stream channel in the study reach is low (less than 1.2). The reach includes three mostly straight segments, and two locations with larger meanders, which coincide with an eroded channel bed and noticeable presence of **cut banks**.

The stream channel in the study reach ranges from about 35 to 45 ft in width, and the bed is gently sloped. The **left bank** (east bank) ranges in height from about 3 to 4.5 ft, with a broad, wooded overbank area that allows flood flows to spread out in the valley. The **right bank** (west bank) of the channel and overbank is confined by a wooded hillslope through the majority of the reach (fig. 3). The stream can carry large amounts of woody debris at times because of the large percentages of forested areas that surround the stream channel.

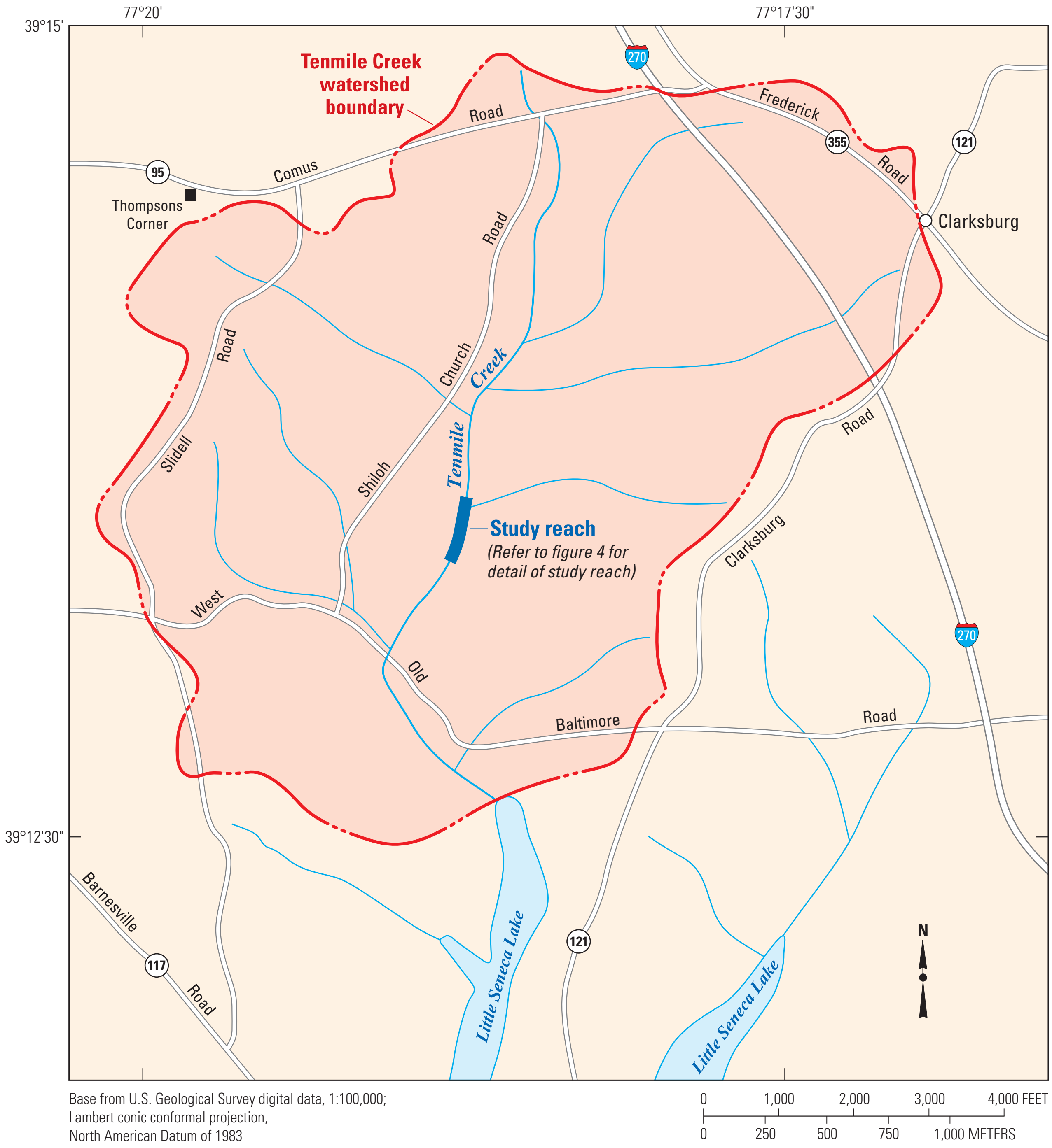
Bed material in the study reach consists of a mixture of sand, gravel, and cobbles, which is typical of many Piedmont stream channels in Maryland (McCandless and Everett, 2002). Bank material includes some deposits of sand and gravel, with greater percentages of silt and clay than in the channel bed.

Methods of Data Collection

Geomorphic data were collected in the Tenmile Creek study reach to quantify stream-channel dimension and profile, and to assess changes to the stream channel over time. A **continuous-record streamflow-gaging station** (USGS station number 01644388, Tenmile Creek near Clarksburg, Md.) recorded 5-minute unit-value stage data, allowing computation of corresponding discharge data in the Tenmile Creek study reach since June 2013 (U.S. Geological Survey, 2017a). Two continuous-record precipitation stations recorded 15-minute unit-value precipitation data in the Tenmile Creek watershed since June 2014 (U.S. Geological Survey, 2017b, 2017c). Surveys were conducted to document cross-section geometry and changes in channel geometry over time. Surveys of the longitudinal profile were also conducted to determine the elevations of channel features throughout the study reach. Pebble counts were conducted to determine grain-size distributions of the surficial bed material (Doheny and Baker, 2018). High-water marks were noted in three crest-stage gage locations in the study reach to determine the water-surface slope during storm events. The high-water marks were supplemented with continuous data from three HOBO pressure-transducer data loggers that provided continuous stage data at the crest-stage gage locations during the storm and flood of July 30, 2016. This allowed the water-surface slope to be determined on a continuous basis during the rise, peak, and recession of the storm.

Streamflow

Since June 2013, continuous-record streamflow data have been computed for USGS station 01644388 in the Tenmile Creek study reach using standard USGS streamflow-gaging techniques (Carter and Davidian, 1968; Buchanan and Somers, 1968, 1969; Sauer and Turnipseed, 2010; Turnipseed and Sauer, 2010). Periodic direct measurements of streamflow were made at a range of gage heights to develop a **stage-discharge rating** for the stream. The stage-discharge rating was used with the continuous record of gage heights from the



Base from U.S. Geological Survey digital data, 1:100,000;
Lambert conic conformal projection,
North American Datum of 1983

Figure 2. Detailed view of Tenmile Creek watershed and study reach, Montgomery County, Maryland.

Figure 3. View looking downstream at lower section of Tenmile Creek study reach. Photograph by Edward Doheny, U.S. Geological Survey, April 24, 2014.

station to determine the discharge continuously at 5-minute intervals. **Daily mean discharges** were computed for each day of the water year using the continuous discharge record. Streamflow statistics for USGS station 01644388, Tenmile Creek near Clarksburg, Md. for water years 2013 through 2016 are presented in table 1 (U.S. Geological Survey, 2017a).

Precipitation

Since June 2014, continuous-record precipitation data have been collected at two locations in the Tenmile Creek watershed to supplement streamflow and geomorphic data collection in the study reach. Mass-volume precipitation gages were used for data collection to enhance data accuracy during snow and ice periods, and data were collected at 15-minute intervals. A summary of maximum and minimum annual precipitation, maximum daily precipitation, and **maximum precipitation intensity** by water year for the two continuous-record precipitation gages in the Tenmile Creek watershed is presented in table 2.

Annual precipitation recorded in the Tenmile Creek watershed during the study period was slightly below normal during the 2015 water year, and slightly above normal during the 2016 water year (table 2). Annual precipitation totals are not presented for the 2014 water year because data were only collected from June through September. The storm of July 30, 2016 was the largest precipitation event experienced in the watershed during the study period. Daily precipitation during the storm ranged from 4.43 to 5.05 in., with most of the rain falling in one 3-hour period (U.S. Geological Survey, 2017b, 2017c).

Table 1. Summary of streamflow statistics for U.S. Geological Survey station 01644388, Tenmile Creek near Clarksburg, Maryland, water years 2013–16.

[mi^2, square mile; ft^3/s, cubic foot per second; (ft^3/s)/mi^2, cubic foot per second per square mile]

Station 01644388, Tenmile Creek near Clarksburg, Maryland	Water years 2013–16
Drainage area (mi^2)	3.37
Annual mean discharge (ft^3/s)	4.53
Highest annual mean discharge (ft^3/s)	5.73 (2014)
Lowest annual mean discharge (ft^3/s)	3.59 (2015)
Highest daily mean discharge (ft^3/s)	190.0 (June 10, 2013)
Lowest daily mean discharge (ft^3/s)	0.10 (Sept. 26, 2016)
Maximum instantaneous peak flow discharge (ft^3/s)	2,860 (July 30, 2016)
Minimum instantaneous low flow discharge (ft^3/s)	0.08 (Sept. 25–26, 2016)
Annual runoff (inches)	17.8
Annual runoff ([ft^3/s]/mi^2)	1.31

Table 2. Summary of continuous-record precipitation data recorded in the Tenmile Creek watershed, June 2014 through September 2016.

Precipitation category	U.S. Geological Survey station 391328077185901, Tenmile Creek precipitation gage at Slidell, Maryland	U.S. Geological Survey station 391407077174001, Tenmile Creek precipitation gage at Clarksburg, Maryland
Maximum annual precipitation (inches)	46.85 (2016)	50.29 (2016)
Minimum annual precipitation (inches)	42.01 (2015)	43.40 (2015)
Maximum daily precipitation (inches)	4.43 (July 30, 2016)	5.05 (July 30, 2016)
Maximum 15-minute precipitation intensity for 2014 water year (inches/hour)	3.28 (Aug. 3, 2014)	2.72 (Aug. 21, 2014)
Maximum 15-minute precipitation intensity for 2015 water year (inches/hour)	4.44 (Sept. 29, 2015)	4.76 (Sept. 29, 2015)
Maximum 15-minute precipitation intensity for 2016 water year (inches/hour)	4.24 (July 30, 2016)	3.92 (July 30, 2016)

Table 3. Dates, locations, and longitudinal stationing used for longitudinal-profile surveys in the Tenmile Creek study reach, 2014–16.

[ft, feet]

Date of survey	Starting station (ft)	Starting location	Ending station (ft)	Ending location	Reach length (ft)
April 24, 2014	4,964	Bottom of riffle, about 510 ft downstream of gage	5,868	Top of riffle, about 400 ft upstream of gage	904
March 31, 2015	4,990	Bottom of pool, about 480 ft downstream of gage	5,982	Top of pool, about 510 ft upstream of gage	992
March 30, 2016	4,960	Bottom of pool, about 510 ft downstream of gage	5,978	Top of pool, about 510 ft upstream of gage	1,018
September 14, 2016	4,997	Bottom of pool, about 475 ft downstream of gage	5,941	Top of pool, about 470 ft upstream of gage	944

Longitudinal Profiles

The longitudinal profile of the Tenmile Creek study reach was surveyed four times during the study period (April 2014, March 2015, March 2016, and September 2016) to determine the relative elevations and consistency of channel features. The methods that were used are described in Leopold (1994) and in Doheny and others (2007). The reach where the longitudinal-profile surveys were conducted began approximately 2,200 ft upstream from the road crossing at West Old Baltimore Road, and extended upstream approximately 900 to 1,000 ft (fig. 2). Channel-bed and water-surface elevations were surveyed along the study reach, as were channel features such as **point-bar** surfaces, **terraces**, and top-of-bank elevations. Elevations were vertically referenced to NAVD 88. All surveys were conducted using the same longitudinal stationing so that comparisons of profiles from different surveys would be possible. Survey elevations were measured at break points between **riffles**, **pools**, and **runs** in order to define these features individually. Distances were measured along the **thalweg** between surveyed points on the streambed, which allowed for definition of the lengths and distribution of riffles, pools, and runs in the reach. Point-bar surfaces, terraces, and top-of-bank elevations were also surveyed in selected locations where the features were clearly identifiable (Doheny and others, 2007). Dates, locations, and longitudinal stationing used for the longitudinal-profile surveys in the Tenmile Creek study reach are summarized in table 3.

Cross Sections

Permanent cross sections were established in the Tenmile Creek study reach to determine cross-section geometry and to assess physical changes in the stream channel over time. Seven cross sections were established with monumented endpoints over a distance of approximately 850 ft within the study reach (fig. 4). The reach also contained the continuous-record streamflow-gaging station, 01644388, Tenmile Creek near Clarksburg, Md. The cross sections were established in straight sections of the channel, or in straight sections between meanders, and were aligned perpendicular to flow direction

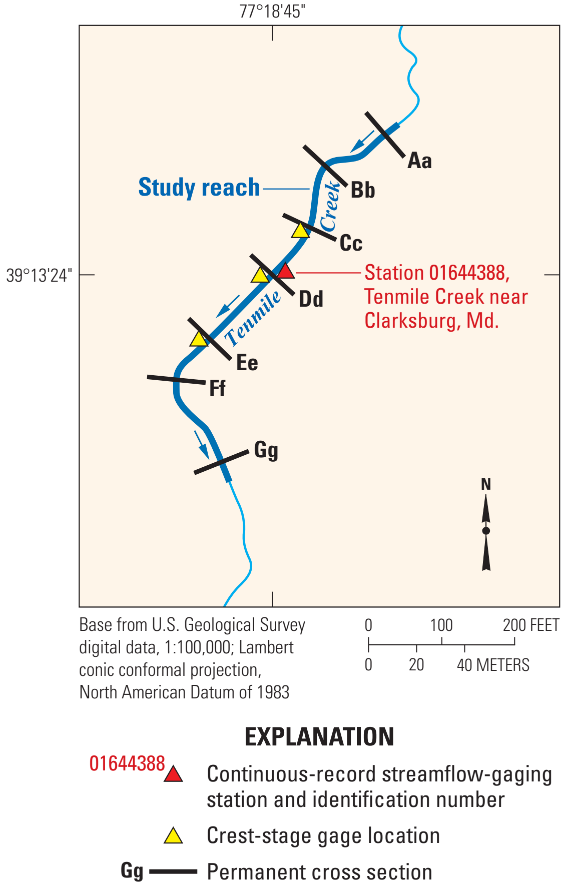


Figure 4. Locations of permanent cross sections that were established in the Tenmile Creek study reach, 2014.

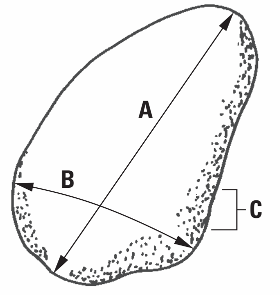
View looking downstream from cross section Aa. Photograph by Edward Doheny, U.S. Geological Survey, March 30, 2015.

View looking upstream from cross section Gg. Photograph by Edward Doheny, U.S. Geological Survey, March 30, 2015.

in the channel. The cross sections were vertically referenced to NAVD 88 and were initially surveyed in April 2014. The cross sections were re-surveyed in March 2015, March 2016, and again in September 2016 after the storm and flood of July 30, 2016 (table 1). Basic station information for the seven permanent cross sections in the Tenmile Creek study reach is summarized in table 4.

Pebble Counts

The composition of the channel bed within the study reach was characterized using pebble counts of the surficial channel-bed sediments at each cross section. One-hundred-particle pebble counts were collected throughout the entire length of the main channel at each of the seven permanent cross sections in April 2014, March 2015, March 2016, and September 2016. The pebble counts were made by randomly picking up particles from the channel bed at an interval of about 1 particle per ft of cross section, and measuring the intermediate axis of the particle that is picked up (fig. 5) (Leopold, 1994; Harrelson and others, 1994; Doheny and others, 2007). The particle sizes were tallied according to size class (silt, sand, gravel, or cobble) and used to directly determine grain-size distributions for the surface of the channel bed at each cross section, and for the study reach (Wentworth, 1922; Guy, 1969). An example of a grain-size distribution and computation of **percent finer** from a pebble count at cross section Dd in the Tenmile Creek study reach on April 23, 2014 is shown in table 5. A plot of the grain-size distribution developed from the pebble count at cross section Dd is shown in figure 6.



A = Longest axis (length)
B = Intermediate axis (width)
C = Shortest axis (thickness)

Figure 5. Examples of longest, intermediate, and shortest axes for measuring median particle diameter of pebbles during pebble counts.

Table 4. Basic station information for permanent cross sections in the Tenmile Creek study reach.

[ft, foot; lat, latitude; long, longitude; °, degrees; ', minutes; ", seconds]

Cross section	Longitudinal station (ft)	Description of cross section location	Left cross section endpoint lat-long (° ' ")	Right cross section endpoint lat-long (° ' ")
Aa	5,862.0	Straight	39 13 27.2 77 18 42.6	39 13 27.8 77 18 42.7
Bb	5,733.0	Upstream of meander	39 13 26.5 77 18 43.1	39 13 26.9 77 18 44.1
Cc	5,574.0	Downstream of meander	39 13 25.3 77 18 44.4	39 13 25.8 77 18 45.9
Dd	5,452.0	Straight	39 13 24.4 77 18 45.7	39 13 24.6 77 18 46.1
Ee	5,329.0	Straight	39 13 23.2 77 18 46.0	39 13 23.2 77 18 47.0
Ff	5,225.0	Upstream of meander	39 13 22.5 77 18 47.5	39 13 23.2 77 18 47.6
Gg	5,015.0	Downstream of meander	39 13 21.0 77 18 46.3	39 13 20.8 77 18 47.5

Table 5. Grain-size distribution and computation of percent finer from pebble count at Cross Section Dd, Tenmile Creek study reach, April 23, 2014.

[mm, millimeter; %, percent; --, not applicable]

Particle description	Particle size limit (mm)	Item count	Cumulative percent finer (%)
Silt	0.062	0	0
Sand	2	18	18.0
Very fine gravel	4	5	23.0
Fine gravel	8	15	38.0
Medium gravel	16	25	63.0
Coarse gravel	32	21	84.0
Very coarse gravel	64	13	97.0
Small cobbles	128	3	100.0
Large cobbles	256	0	100.0
Small boulders	512	0	100.0
Medium boulders	1,024	0	100.0
Large boulders	2,048	0	100.0
Very large boulders	4,096	0	100.0
TOTAL	**--**	**100**	**--**

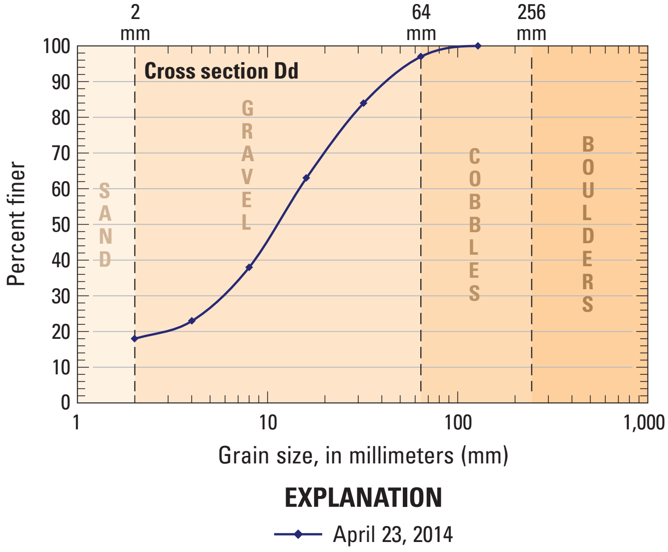


Figure 6. Grain-size distribution developed from the pebble count at cross section Dd, Tenmile Creek study reach, April 23, 2014.

Note: Grain-size classes were defined by Wentworth (1922).

High-Water Marks

High-water marks were obtained along the study reach during water years 2014 through 2016 from crest-stage gages that were installed at selected locations (Buchanan and Somers, 1968; Sauer and Turnipseed, 2010). The reach in the vicinity of the streamflow-gaging station was relatively straight, and crest-stage gages were installed at the approximate locations of cross sections Cc, Dd, and Ee.

The high-water marks were used along with data from the continuous-record streamflow-gaging station to determine peak water-surface elevations that occurred in the study reach between site visits. The crest-stage gages were serviced every 1–2 months and after major storm events. All high-water marks that were registered on each crest-stage gage were documented and logged. The hydrographs from the continuous-record streamflow-gaging station were referenced to determine the date of the storm that left each high-water mark, and the peak discharge associated with that storm (Doheny and others, 2007).

The distance between crest-stage gages along the thalweg of the stream channel was measured so that water-surface slopes could be determined at a range of stages and discharges by use of the high-water marks. A crest-stage gage that was used for obtaining high-water marks in the Tenmile Creek study reach is shown in figure 7.

In May 2016, non-vented, internally logging pressure transducers, HOBO U-20L-01 water-level data loggers, were installed at the three crest-stage gage locations to supplement high-water mark data collected from the crest-stage gages. These loggers were used to generate additional time-series stage data that could be used to compute water-surface slope for multiple points on a storm hydrograph, instead of only for the peak. The sensors were configured to record absolute pressure (atmospheric pressure plus water-column pressure) at 5-minute intervals. The absolute-pressure data were converted to water level, or stage, using atmospheric-pressure data collected at the continuous-record streamflow-gaging station (Freeman and others, 2004; Jastram, 2014). The plus or minus 0.03-ft accuracy of these sensors does not meet the USGS Office of Surface Water accuracy requirement of plus or minus 0.01 ft for stage sensors at continuous-record streamflow-gaging stations (Sauer, 2002). However, for this data-collection effort, these sensors were used only to supplement data from the crest-stage gages in the study reach, and not as the source of primary data for computation of the streamflow records at the continuous-record streamflow-gaging station.

Figure 7. Crest-stage gage for obtaining high-water marks in the Tenmile Creek study reach. Photograph by Michael A. Clark, U.S. Geological Survey, May 1, 2014.

Geomorphic Characteristics

Geomorphic data collected during water years 2014 through 2016 were used to assess geomorphic characteristics and changes over time in the Tenmile Creek study reach (Doheny and Baker, 2018). Geomorphic characteristics that were assessed included: (1) longitudinal profiles of the channel bed, water surface, and bank features; (2) changes in cross-section geometry; (3) grain-size analyses of the channel bed; (4) classification of a selected section of the reach according to the Rosgen system of stream classification (Rosgen 1994, 1996); and (5) analysis of boundary shear stress based on cross-section geometry and water-surface slope in the vicinity of the streamflow-gaging station.

Longitudinal Profiles

Longitudinal profiles of the channel bed, water surface, point bar, terrace, and top-of-bank elevations were developed for the Tenmile Creek study reach on the basis of field surveys that were conducted in April 2014, March 2015, March 2016, and September 2016. Slopes of the water surface and channel bed were determined by use of simple linear regression. Percentages of riffles, pools, and runs were determined for each profile based on the stream length of each feature relative to the length of the surveyed reach (Doheny and others, 2007; Doheny and others, 2012). The profiles were analyzed to determine differences in the distribution and locations of riffles, pools, and runs throughout the study reach over time. A plot of the longitudinal profile that was developed from the April 2014 survey of the study reach is shown in figure 8.

The longitudinal profiles show three depositional features in the main channel along the study reach; a terrace and two point-bar features (fig. 8). The presence of these features indicates that despite small percentages of impervious area in the watershed (5 to 6 percent), the stream channel may have adjusted itself to disturbances in the watershed. Such disturbances might include the initial construction of I-270 during the 1950s and subsequent implementation of large areas of pavement in the headwater areas, or increased sediment supply to the stream channel over time from farming in the watershed.

Slopes were computed for the channel bed and water surface for each of the four longitudinal profiles surveyed between April 2014 and September 2016. The results are shown in table 6.

Table 6. Slopes of channel bed and water surface in the Tenmile Creek study reach from longitudinal-profile surveys, 2014–16.

[ft/ft, feet per foot]

Date of survey	Channel bed (ft/ft)	Water surface (ft/ft)
April 24, 2014	0.0072	0.0065
March 31, 2015	0.0062	0.0058
March 30, 2016	0.0061	0.0060
September 14, 2016	0.0040	0.0045

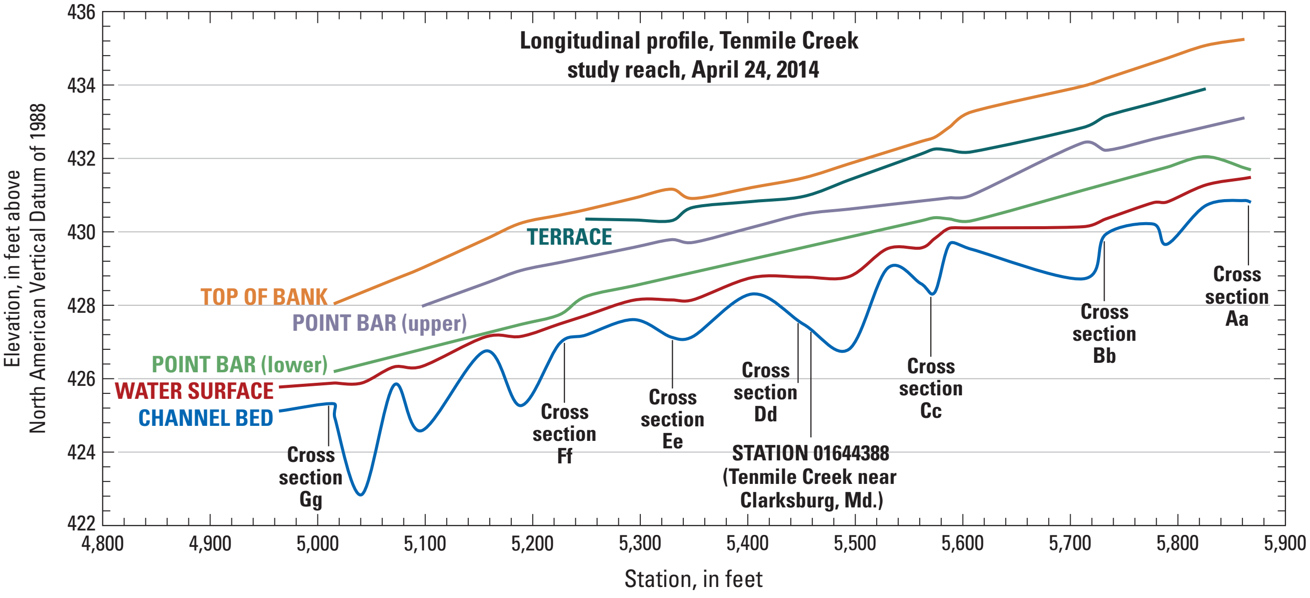


Figure 8. Longitudinal profile of channel features in the Tenmile Creek study reach from field survey conducted on April 24, 2014.

Between April 2014 and September 2016, the slopes of the channel bed and water surface decreased by 44.4 percent and 30.8 percent, respectively. The slopes showed only slight differences between the March 2015 and March 2016 surveys, but changed considerably between the March 2016 and September 2016 surveys. Decreases in the channel-bed and water-surface slopes indicate an increase in the prevalence of pools, and a decrease in riffles in the study reach over time (Leopold, 1994). Net aggradation in the lower section of the study reach combined with net degradation in the upper section of the study reach may also have contributed to the net reduction in channel-bed and water-surface slope. Runoff from the storm and flood of July 30, 2016 was the likely cause of changes in channel-bed and water-surface slopes in the study reach between March 2016 and September 2016.

Data from the longitudinal-profile surveys were also used to determine the percentages of riffles, pools, and runs in the study reach, and whether those percentages and the spatial distribution of the features varied or remained constant during the study period. The computed percentages are shown in table 7. The spatial distribution of riffles, pools, and runs that were determined from the longitudinal-profile surveys between April 2014 and September 2016 is shown in figure 9.

Considerable changes are evident in the percentages of riffles, pools, and runs during the study period (table 7). Riffle percentages decreased from about 56.1 percent to about 32.1 percent, whereas pool percentages increased from about 42.5 percent to about 66.1 percent. Although there was a notable increase in run percentages between the March 2015 and March 2016 surveys, overall run percentages during the study period only increased from about 1.4 to 1.8 percent.

A slight decrease in riffle percentages with a corresponding increase in pool percentages was observed between April 2014 and March 2015. In March 2016, a large drop in riffle percentages was observed with a corresponding increase in run percentages. Pool percentages also increased slightly. In September 2016, pool percentages increased considerably with a corresponding decrease in run percentages. Riffle percentages increased very slightly.

Because pool and run features are associated with smaller stream slopes (Leopold, 1994), these percentages indicate a net scouring of the channel bed and deepening of sections of the stream channel over time. Some distinct variations in the distribution and location of riffles, pools, and runs in many sections of the study reach also were evident (fig. 9). These included the development of runs in the middle and upper sections of the study reach between March 2015 and March 2016, and a distinct lengthening of pooled sections in the study reach between March 2016 and September 2016.

Table 7. Percentage of riffles, pools, and runs in the Tenmile Creek study reach from longitudinal-profile surveys, 2014–16.

[%, percent]

Date of survey	Riffle (%)	Pool (%)	Run (%)
April 24, 2014	56.1	42.5	1.4
March 31, 2015	52.3	46.1	1.6
March 30, 2016	31.2	48.5	20.2
September 14, 2016	32.1	66.1	1.8

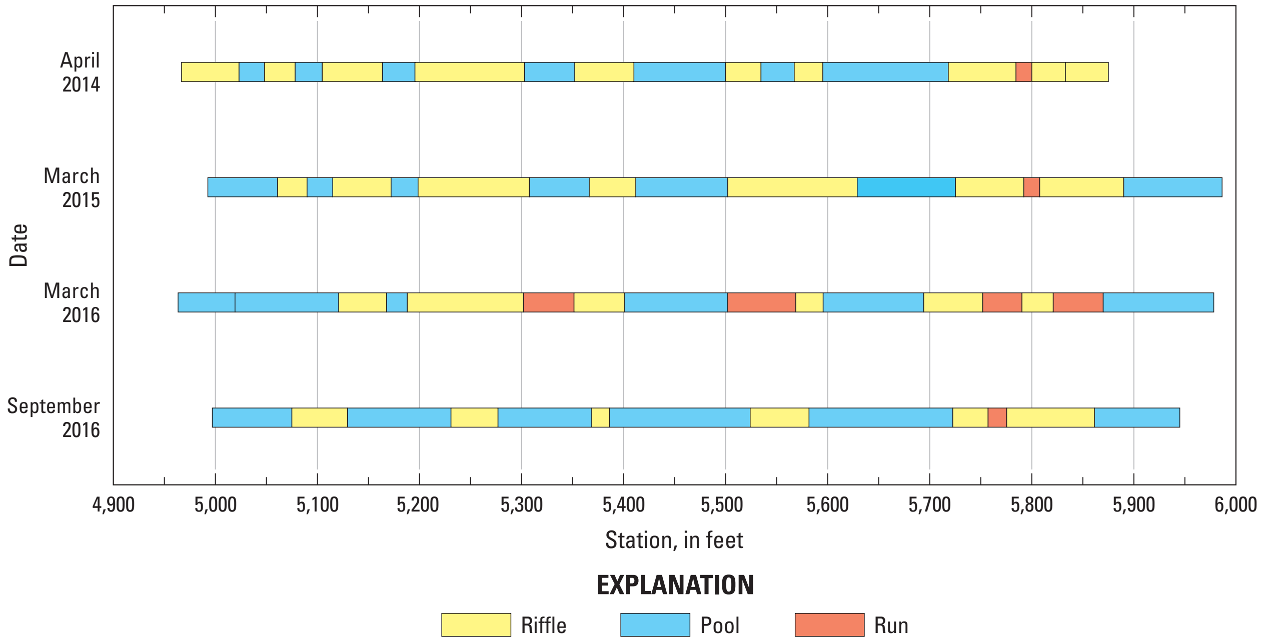


Figure 9. Comparison of riffle, pool, and run distribution in the Tenmile Creek study reach, April 2014 through September 2016.

Cross-Section Geometry

Channel geometry at the seven permanent cross sections in the study reach was investigated on the basis of field surveys conducted in April 2014, March 2015, March 2016, and September 2016. A plot of each cross section for the four surveys was developed to determine changes in bed elevation and channel alignment over time. Plots of the seven permanent cross sections are shown in figures 10–16. Varying degrees of aggradation and degradation of the channel bed are evident over time, as well as lateral erosion in some locations of the study reach.

Cross-section geometry was determined at approximately **bankfull** conditions for the four different surveys at all seven permanent cross-section locations. Hydraulic variables that were determined include cross-sectional area, **wetted perimeter**, **hydraulic radius**, channel width, mean channel depth, maximum channel depth, and **width-to-depth ratio**. These hydraulic variables were compared for each cross section to document changes occurring in the stream channel between field surveys. In order to ensure that a geomorphically feasible bankfull elevation was selected at each cross section, a profile of the selected bankfull elevations for each cross section was plotted for the study reach (fig. 17).

A reasonable profile of bankfull elevation in the Tenmile Creek study reach is shown in figure 17. The bankfull elevation at cross section Cc appeared to be slightly higher than expected compared to other cross sections in the study reach, but was based on a distinct **bankfull indicator** where streamflow begins to break out of the stream channel and into the flood plain. However, cross section Cc is located just downstream from a meander bend, with some cut-bank activity and vertical instability of the channel bed over time. These factors could be contributing to some variability in the bankfull elevation in this section of the stream channel.

A comparison of cross-section geometry for cross-section Dd during the four field surveys conducted between April 2014 and September 2016 is shown in table 8. Comparisons for each of the other six permanent cross sections in the Tenmile Creek study reach are included in Appendix 1.

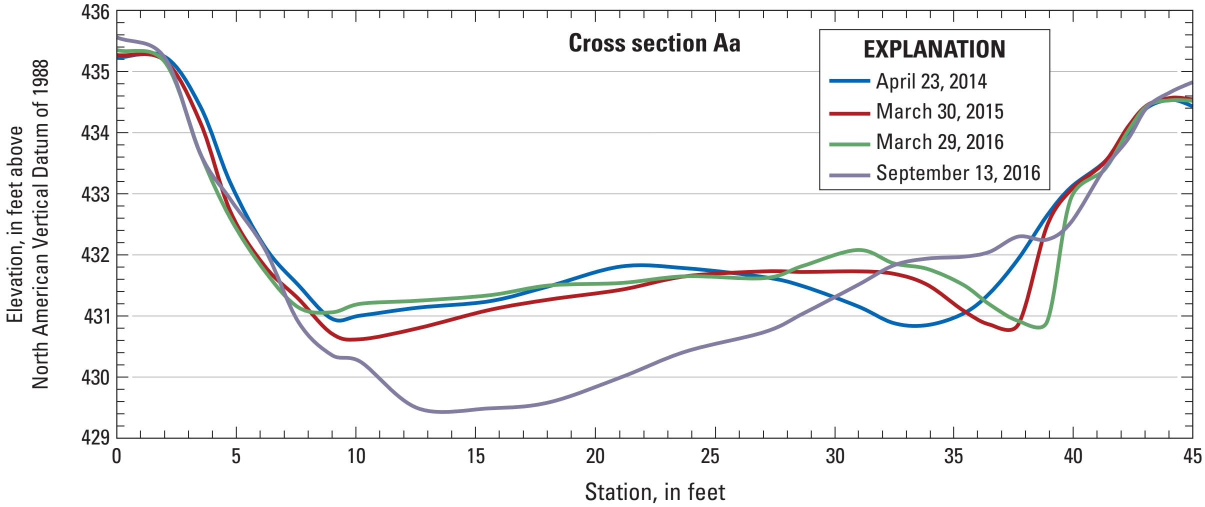


Figure 10. Cross-section geometry at permanent cross section Aa, April 2014 through September 2016.

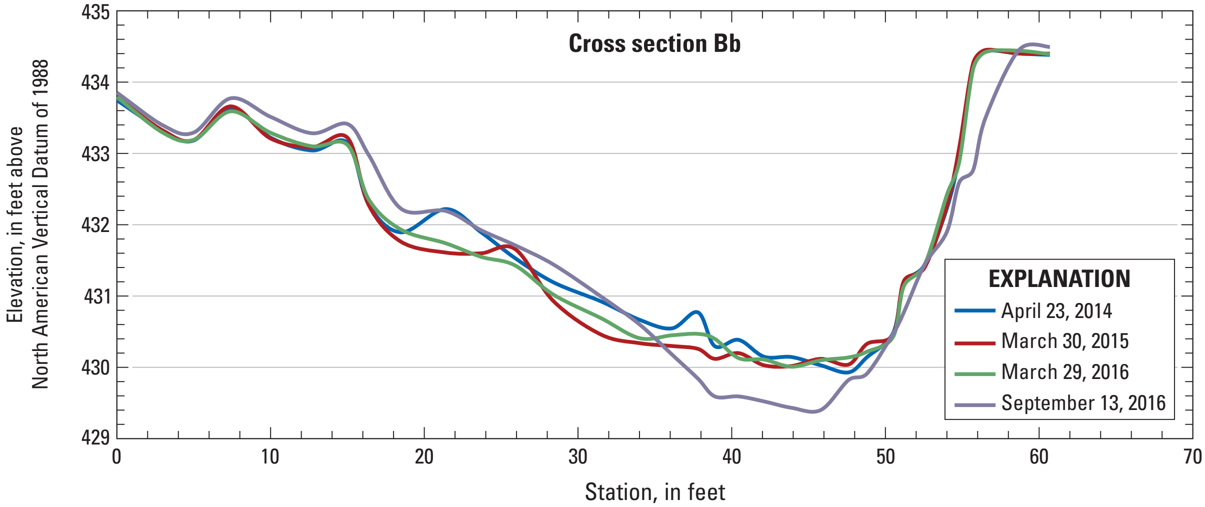


Figure 11. Cross-section geometry at permanent cross section Bb, April 2014 through September 2016.

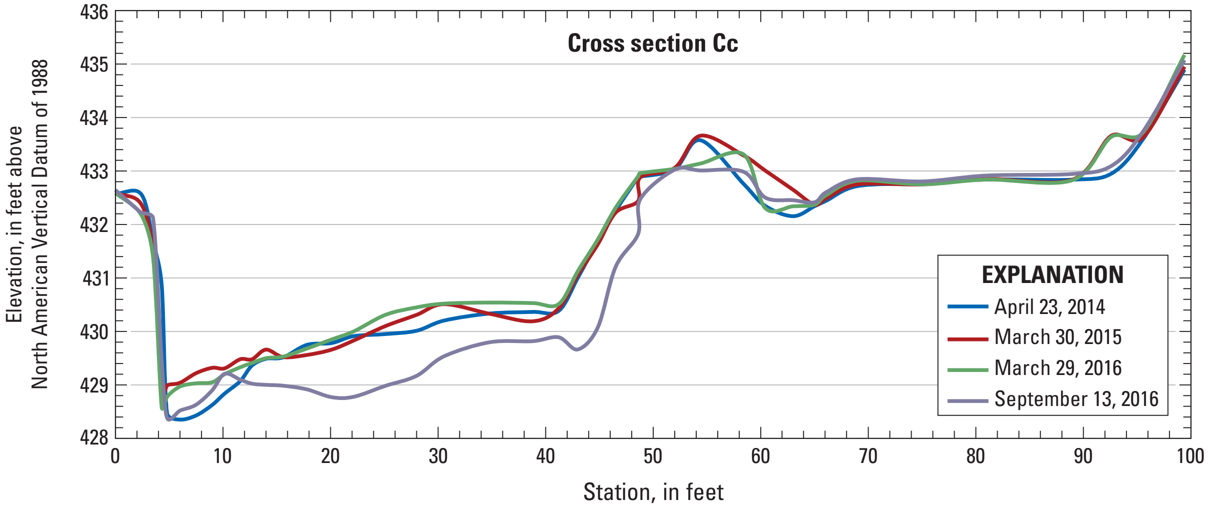


Figure 12. Cross-section geometry at permanent cross section Cc, April 2014 through September 2016.

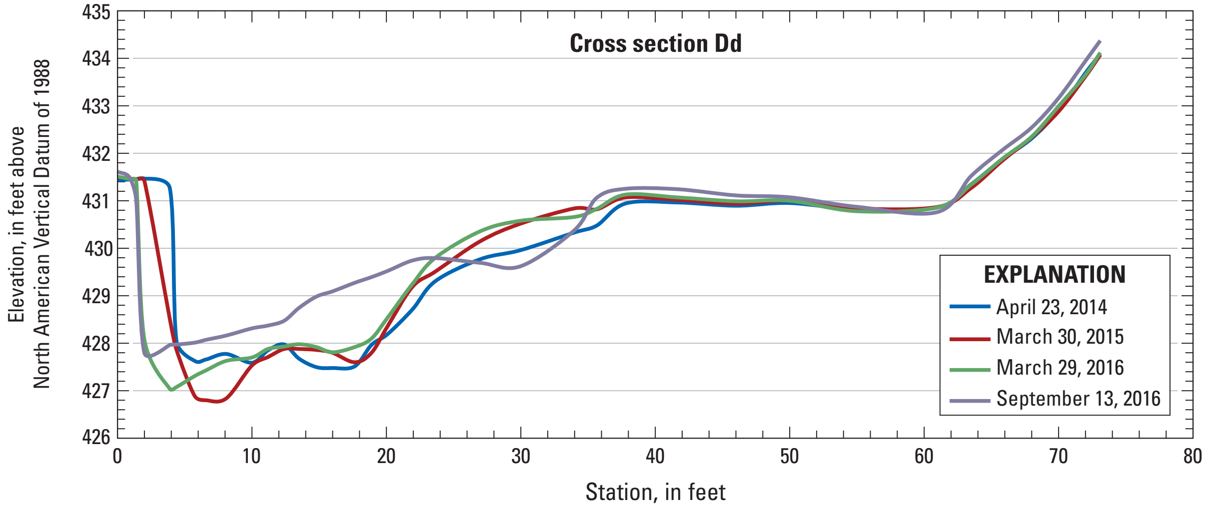


Figure 13. Cross-section geometry at permanent cross section Dd, April 2014 through September 2016.

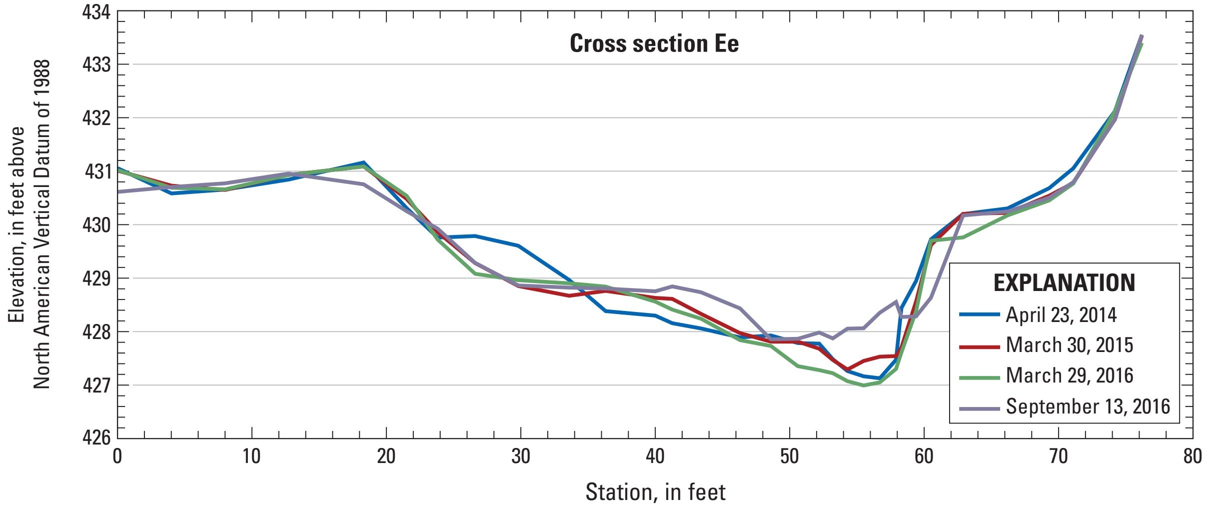


Figure 14. Cross-section geometry at permanent cross section Ee, April 2014 through September 2016.

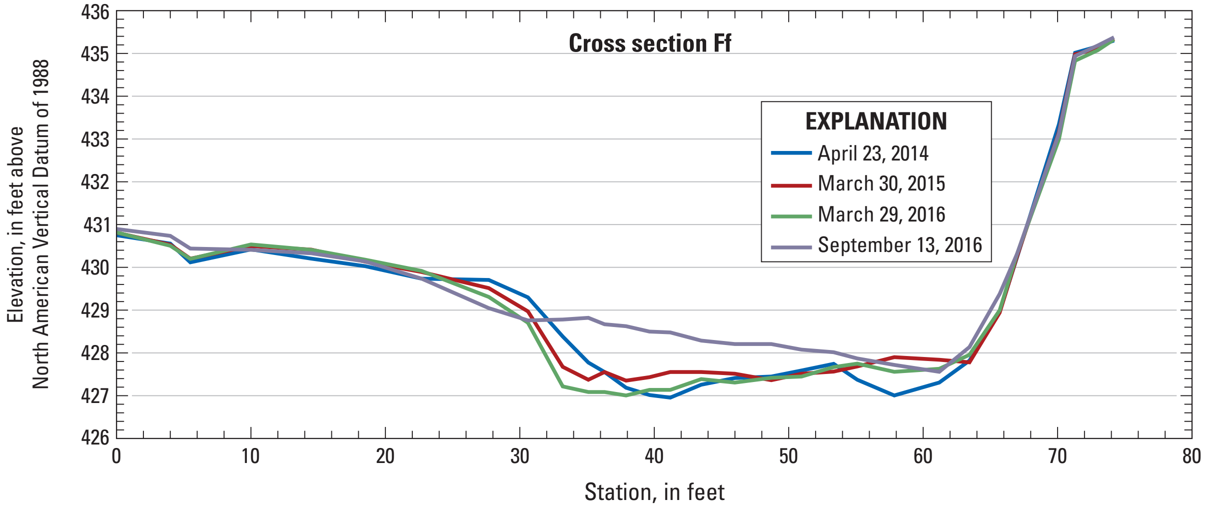


Figure 15. Cross-section geometry at permanent cross section Ff, April 2014 through September 2016.

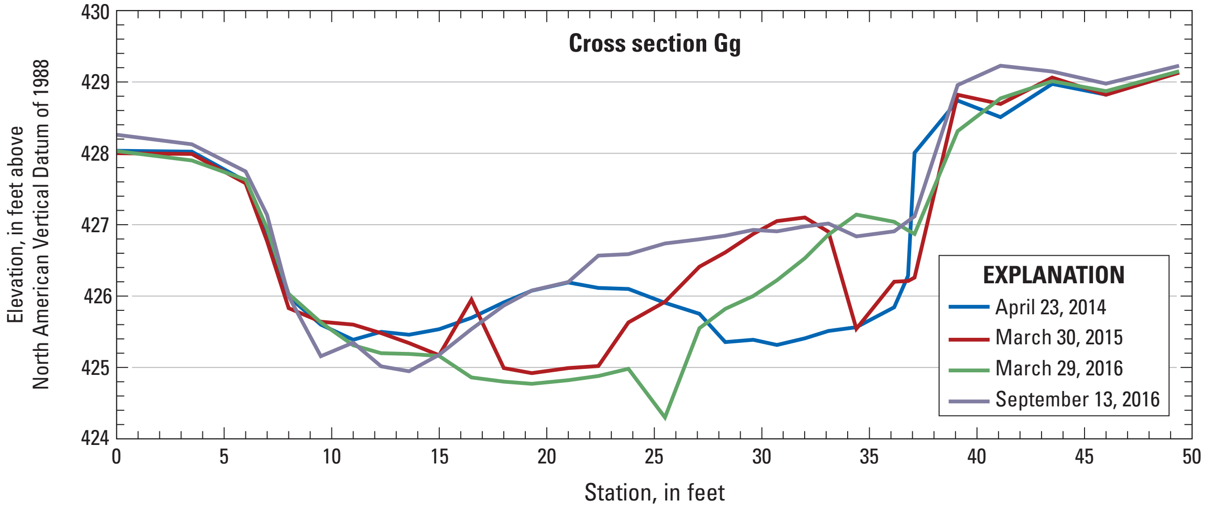


Figure 16. Cross-section geometry at permanent cross section Gg, April 2014 through September 2016.

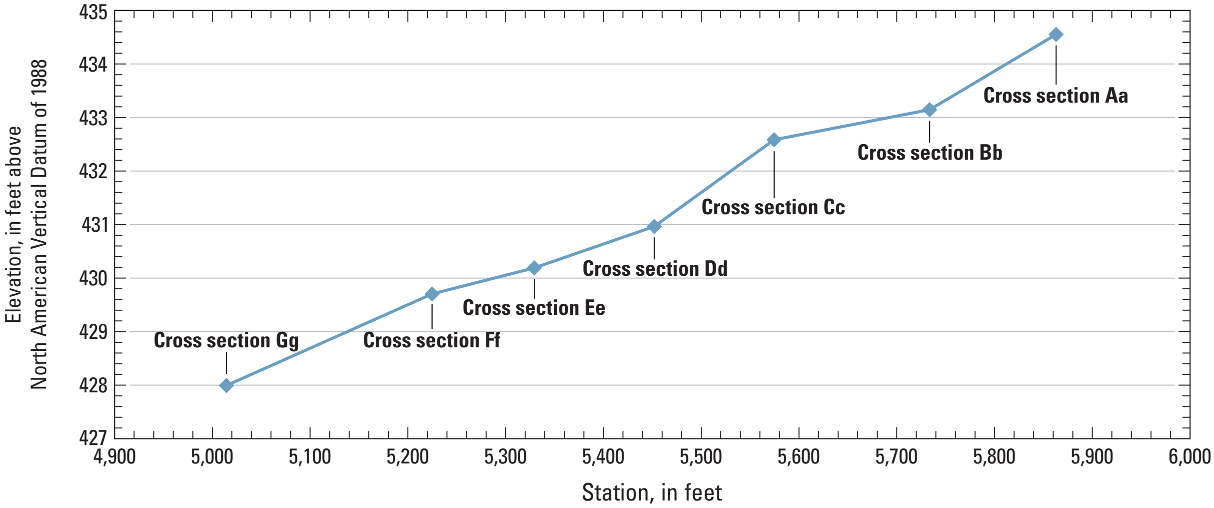


Figure 17. Bankfull water-surface profile, Tenmile Creek study reach, April 2014 through September 2016.

Table 8. Changes in cross-section geometry at permanent cross section Dd for bankfull conditions, Tenmile Creek study reach, April 2014 through September 2016.

[ft, foot; ft^2, square foot; ft/ft, feet per foot]

Cross section Dd (Bankfull water-surface elevation = 430.95 ft)	April 23, 2014	March 30, 2015	March 29, 2016	September 13, 2016
Cross-sectional area (ft^2)	71.9	70.5	71.1	61.1
Channel width (ft)	35.0	34.5	35.0	34.0
Mean depth (ft)	2.05	2.04	2.03	1.80
Maximum depth (ft)	3.47	4.15	3.91	3.15
Wetted perimeter (ft)	38.1	37.0	38.1	36.9
Hydraulic radius (ft)	1.89	1.91	1.87	1.66
Width/depth ratio (ft/ft)	17.1	16.9	17.2	18.9

Table 9. Summary of variability of cross-sectional characteristics in the Tenmile Creek study reach, April 2014 through September 2016.

Cross section	Lateral erosion	Cross-sectional area	Channel width	Mean channel depth	Width to depth ratio	Comments
Aa	Some on left bank	Net increase	Slight decrease	Net increase	Net decrease	Considerable vertical changes in section. Slight channel migration to left side of the valley.
Bb	Some on left bank	Net increase	Slight increase	Slight increase	Net decrease	Considerable vertical changes in section. Very slight channel migration to right side of the valley.
Cc	Little to none	Net increase	Slight increase	Net increase	Net decrease	Considerable vertical changes in section. Some cut bank activity on left side of channel, but little to no bank retreat. Considerable changes to section between March and September 2016.
Dd	Considerable on left bank	Net decrease	Slight decrease	Net decrease	Net increase	Considerable lateral and vertical changes in section. Channel migrating to left side of valley.
Ee	Little to none	Net increase	Net increase	Net decrease	Net increase	Considerable vertical changes in section. Little to no lateral erosion. Considerable changes to section between March and September 2016.
Ff	Little to none	Net decrease	Net increase	Net decrease	Net increase	Considerable vertical changes in section. Little to no lateral erosion. Considerable changes to cross section between March and September 2016.
Gg	Little to none	Net decrease	Net increase	Net decrease	Net increase	Extreme vertical changes in section. Little to no lateral erosion. Considerable changes to cross section documented during all four surveys between April 2014 and September 2016.

A net decrease in cross-sectional area (-15.0 percent), mean depth (-12.2 percent), wetted perimeter (-3.1 percent), and hydraulic radius (-12.2 percent) was evident at cross section Dd, with much of the difference occurring between March 2016 and September 2016 (table 8). The maximum depth in the stream channel showed a 19.6-percent increase between April 2014 and March 2015, then a 5.8-percent decrease in March 2016, and another 19.4-percent decrease in September 2016. Lateral erosion along the left bank in this cross section is the likely cause of some of the variability in maximum depth over time. Channel width showed a net decrease of 2.9 percent over time. The width/depth ratio showed a net increase of 10.5 percent over time, with much of the change occurring between March 2016 and September 2016. Runoff from the storm and flood of July 30, 2016 likely caused the changes in hydraulic variables observed between March 2016 and September 2016.

These analyses were performed for all permanent cross sections in the Tenmile Creek study reach, and were used to develop an overall assessment of the variability of cross-sectional characteristics in the study reach that occurred between April 2014 and September 2016. The results are presented in table 9.

Overall, lateral erosion was not a major factor in most areas of the study reach (table 9). A small amount of lateral erosion was observed at cross sections Aa and Bb. A cut bank was present at the left bank of cross section Cc, but no additional bank retreat was observed during surveys conducted throughout the study period. Cross section Dd was the only location in the study reach where considerable lateral erosion was observed. Little to no lateral erosion was observed at cross sections Ee, Ff, and Gg.

Considerable vertical changes were observed in all cross sections; cross section Gg showed the most extreme changes between surveys. The vertical changes were caused in part by alternating periods of net storage and transport of sand into and out of the lower section of the study reach. The storm and flood of July 30, 2016 was a major factor in some of the vertical changes observed in the channel bed of the study reach cross sections.

A net increase in cross-sectional area (24.0 percent), mean depth (25.2 percent), and hydraulic radius (24.4 percent) was observed at cross section Aa, with much of the difference occurring between March 2016 and September 2016 (table 9). The maximum depth in the stream channel showed alternating increases and decreases over time, with the largest change occurring between March 2016 and September 2016. Channel width and wetted perimeter showed some alternating decreases and increases over time, but only within a small range. The width/depth ratio showed a net decrease of 20.6 percent over time, with much of the change occurring between March 2016 and September 2016, due mainly to a 24.7-percent increase in mean depth in the aftermath of the storm and flood of July 30, 2016.

A net increase of 7.9 percent in cross-sectional area was observed at cross section Bb, with much of the difference occurring between April 2014 and March 2015 (table 9). Smaller increases also were observed over time in channel width, mean depth, wetted perimeter, and hydraulic radius. Maximum depth decreased by 2.5 percent between April 2014 and March 2016, and then increased by 19.6 percent in September 2016. Width/depth ratio showed a net decrease of 6.1 percent over time, with some alternating decreases and increases over time. Other than maximum depth, all other hydraulic variables showed only relatively small changes (plus or minus 2.3 percent or less) in the aftermath of the storm and flood of July 30, 2016.

A net increase in cross-sectional area (14.5 percent), mean depth (13.9 percent), and hydraulic radius (11.7 percent) was observed at cross section Cc, with much of the difference occurring between March 2016 and September 2016 (table 9). The maximum depth in the stream channel showed an 11.1-percent decrease between April 2014 and March 2015, then increases of 6.4 percent in March 2016 and 7.5 percent in September 2016. Channel width and wetted perimeter showed relatively small changes over time. The width/depth ratio showed a 9.5-percent increase between April 2014 and March 2015, a small increase of 1.0 percent between March 2015 and March 2016, and a 20.1-percent decrease between March 2016 and September 2016 caused by runoff from the storm and flood of July 30, 2016.

An increase in cross-sectional area of 29.2 percent was observed in cross section Ee between April 2014 and March 2016, then a decrease of 16.4 percent in September 2016, with an overall net increase of 8.1 percent over time (table 9). Mean depth and hydraulic radius showed respective increases of 5.8 percent and 6.7 percent between April 2014 and March 2016, then respective decreases of 12.2 percent and 11.3 percent in September 2016, with overall net decreases over time of 7.1 percent for mean depth, and 5.3 percent for hydraulic radius. The maximum depth showed some alternating decreases and increases over time, with a 26.9-percent decrease between March 2016 and September 2016 due primarily to runoff from the storm and flood of July 30, 2016. Channel width and wetted perimeter showed increases of 22.3 percent and 21.2 percent, respectively, between April 2014 and March 2016, then decreases of 4.8 percent and 5.8 percent, respectively, between March 2016 and September 2016. The width/depth ratio showed a gradual increase of 25.5 percent over time.

A net decrease in cross-sectional area (-28.2 percent), mean depth (-35.7 percent), and hydraulic radius (-35.1 percent) was observed at cross section Ff, with much of the difference occurring between March 2016 and September 2016 (table 9). The maximum depth in the stream channel showed alternating decreases and increases over time, with a 20.7-percent decrease occurring between March 2016 and September 2016. The channel width and wetted perimeter showed gradual increases of 11.6 percent and 10.1 percent, respectively, over time. The width/depth ratio showed an increase of 18.7 percent between April 2014 and March 2015, a decrease of 6.0 percent between March 2015 and March 2016, and an increase of 55.2 percent between March 2016 and September 2016, mainly caused by runoff from the storm and flood of July 30, 2016.

Respective increases in cross-sectional area of 9.0 percent and 11.5 percent were observed in cross section Gg between April 2014, March 2015, and March 2016. A decrease of 28.2 percent was observed in September 2016, with an overall net decrease of 12.6 percent over time (table 9). Channel width showed a net increase of 6.9 percent with considerable fluctuations over time, but this was caused by large volumes of sand aggrading and degrading in the cross section over time, not by bank erosion and retreat. The mean depth and hydraulic radius in the stream channel showed alternating decreases and increases over time, with net decreases of 18.3 percent and 14.9 percent, respectively. Maximum depth showed a gradual increase of 38.1 percent between April 2014 and March 2016, then a decrease of 17.6 percent between March 2016 and September 2016. Wetted perimeter showed a net increase of 2.7 percent over time, with an increase of 22.4 percent between April 2014 and March 2015, a decrease of 1.7 percent between March 2015 and March 2016, and a decrease of 14.6 percent between March 2016 and September 2016. The width/depth ratio showed a net increase of 31.1 percent over

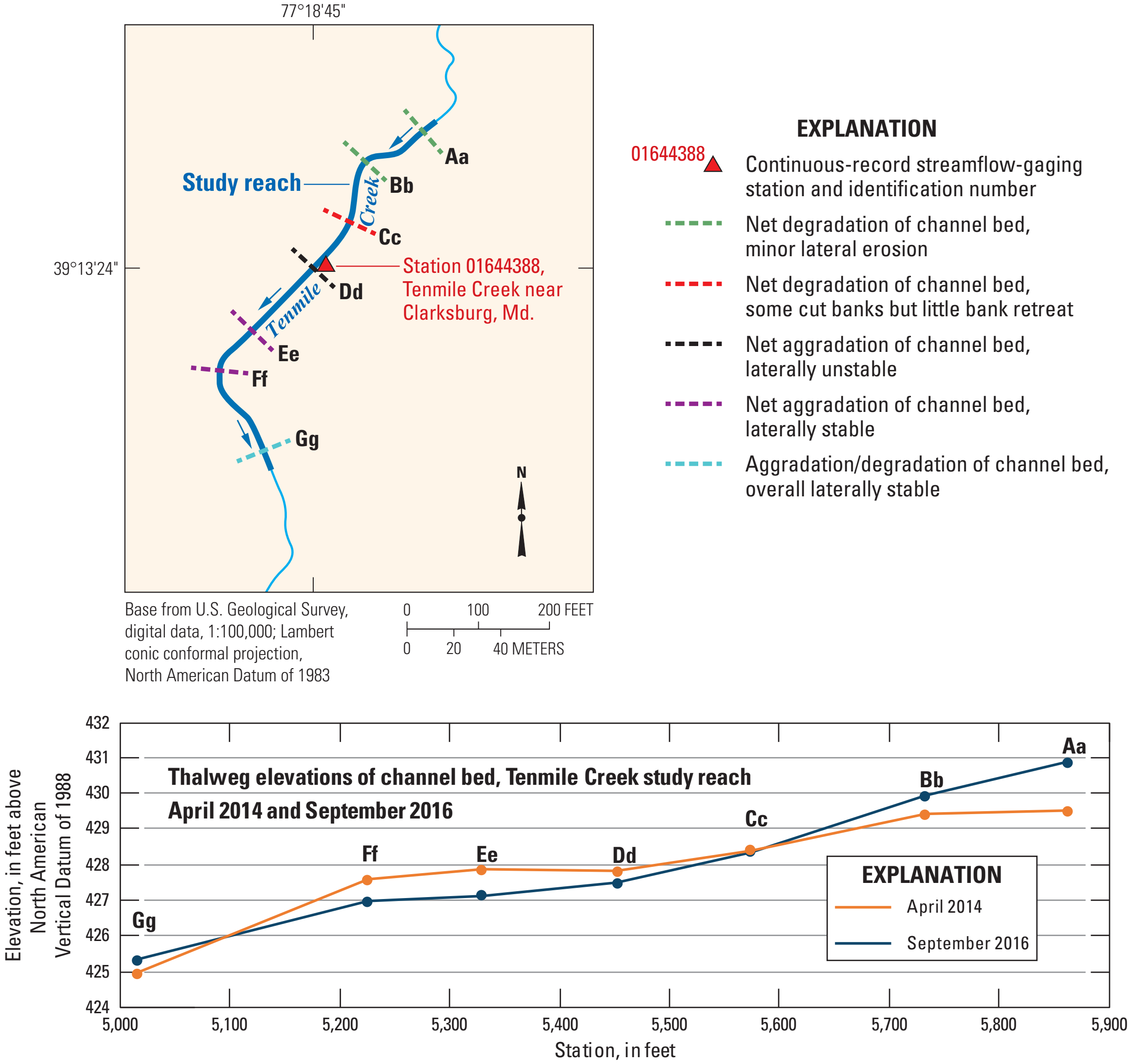


Figure 18. Summary of geomorphic conditions in the Tenmile Creek study reach, April 2014 through September 2016.

time, with an increase of 45.0 percent between April 2014 and March 2015, a decrease of 13.2 percent between March 2015 and March 2016, and an increase of 4.2 percent between March 2016 and September 2016.

A summary of geomorphic conditions interpreted from changes in the cross sections during the monitoring period is shown in figure 18. Cross sections Aa and Bb showed net degradation of the channel bed over time with small amounts of lateral erosion. Cross section Cc also showed net degradation of the channel bed over time with some cut-bank activity on the left bank, but the surveys showed little to no bank retreat during the study period. Cross section Dd showed net aggradation of the channel bed with considerable lateral erosion on the left bank. Cross sections Ee and Ff showed net aggradation of the channel bed with overall lateral stability. Cross section Gg showed alternating periods of more extreme aggradation and degradation and appears to have stored large volumes of sediment for short periods of time, but maintained lateral stability. Based on the location of cut banks and lateral erosion in the study reach, the stream channel was actively adjusting its meander pattern in the straight reach near cross section Dd to increase its sinuosity.

Grain-Size Analysis

Grain-size distributions were determined in the study reach between 2014 and 2016 by use of pebble counts of the surficial channel-bed sediments at each cross section (Wolman, 1954). The distributions were developed for each cross section based on the percentages of measured pebbles that fall within 10 particle-size ranges of sand, gravel, cobbles, and boulders (Wentworth, 1922; Guy, 1969). Pebble counts were conducted at all permanent cross section locations during April 2014, March 2015, March 2016, and September 2016. Cumulative frequency distributions of percent finer were developed for the surficial bed material from all cross sections based on the pebble-count data. The **median particle diameter** (d50) was determined for the pebble counts at each cross section. Grain-size distributions also were combined to develop composite analyses of the surficial bed material for the entire study reach for April 2014, March 2015, March 2016, and September 2016.

The cumulative particle-size distributions for each of the seven permanent cross sections in the study reach between April 2014 and September 2016 is shown in tables 10–13. These analyses also are shown graphically for each cross section in figures 19 through 25. In April 2014, the largest percentage of sand (18 percent) was present in cross section Dd. During the April 2014 survey, all other cross sections had sand percentages of 6 percent or less (table 10). The distribution of grain sizes in April 2014 indicated a channel composed of predominantly medium-to-coarse gravel in all cross sections. In March 2015, the largest percentages of sand were in cross section Gg at 30 percent (table 11). This indicates that sand transported through the study reach between April 2014 and March 2015 was being deposited in larger volumes in the lower section of the study reach. Cross section Aa also indicated an increase in sand percentages from 5 percent in April 2014 to 18 percent in March 2015 (tables 10–11). Because cross section Aa is located at the upstream end of the study reach, the increase in sand percentages is indicative of larger volumes of sand entering the study reach between April 2014 and March 2015. Cross section Dd showed a slight decrease in the percentage of sand from 18 percent in April 2014 (table 10) to 16 percent in March 2015 (table 11). The distribution of grain sizes in March 2015 indicated a channel composed of predominantly medium-to-very-coarse gravel (table 11). In March 2016, the largest percentages of sand were still in cross section Gg, but had increased from 30 percent to 51 percent (table 12). Compared to the March 2015 survey, the percentages of sand also were larger in cross sections Ee and Ff in March 2016, which indicates continued deposition of sand in the lower sections of the study reach between March 2015 and March 2016. The distribution of grain sizes in March 2016 indicated a channel composed predominantly of medium-to-very-coarse gravel, except for cross section Gg, which was predominantly sand as a result of the considerable deposition occurring over the preceding 2 years (tables 10–12).

In September 2016, all cross sections in the study reach had sand percentages of 7 percent or less (table 13). Cross section Gg decreased in sand percentage from 51 percent to 5 percent between March 2016 and September 2016. This indicates that runoff from the storm and flood of July 30, 2016 transported much of the stored sediment from the study reach farther downstream in the watershed, while depositing considerably smaller volumes of sediment originating from upstream of the study reach on the recession of the storm. The distribution of grain sizes in September 2016 indicated a channel composed predominantly of medium-to-coarse gravel in all cross sections.

All cross sections showed an alternating pattern of changes in channel-bed roughness based on analysis of the pebble counts. Cross sections Aa, Bb, Cc, and Ee indicated a general pattern of coarsening, then fining over time (figs. 19–21, 23). Cross sections Dd and Gg indicated a general pattern of fining, then coarsening over time (figs. 22, 25). Cross section Ff indicated a pattern of fining, coarsening, and then fining over time (fig. 24). The largest difference in these patterns was observed in cross section Gg, where considerable deposition of sand was observed between April 2014 and March 2016. Much of the sand in this cross section was gone in September 2016, after the storm and flood of July 30, 2016. The patterns observed in all cross sections are the likely result of periodic high flows from storms that transport sand and small gravel into, out of, and through the study reach. The large variation in sand percentages (previously shown in tables 10–13) contributes to the observed changes in grain-size distribution at the cross sections.

Table 10. Cumulative distribution of grain sizes, in percent finer, for surficial bed material at permanent cross-section locations in the Tenmile Creek study reach, April 23, 2014.

[Values represent the percentage of total particles that are finer than the particle size indicated in the second column of each row of values; mm, millimeter; %, percent]

Particle description	Particle size limit (mm)	Cross section						
		Aa (%)	Bb (%)	Cc (%)	Dd (%)	Ee (%)	Ff (%)	Gg (%)
Silt	0.062	0	0	0	0	0	0	0
Sand	2	5.0	0	5.0	18.0	2.0	5.0	6.0
Very fine gravel	4	10.0	3.0	7.0	23.0	6.0	12.0	7.0
Fine gravel	8	21.0	10.0	18.0	38.0	20.0	21.0	20.0
Medium gravel	16	54.0	20.0	42.0	63.0	41.0	31.0	43.0
Coarse gravel	32	78.0	50.0	69.0	84.0	68.0	50.0	65.0
Very coarse gravel	64	90.0	83.0	90.0	97.0	93.0	78.0	85.0
Small cobbles	128	99.0	97.0	100.0	100.0	100.0	96.0	98.0
Large cobbles	256	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Small boulders	512	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 11. Cumulative distribution of grain sizes, in percent finer, for surficial bed material at permanent cross-section locations in the Tenmile Creek study reach, March 30, 2015.

[Values represent the percentage of total particles that are finer than the particle size indicated in the second column of each row of values; mm, millimeter; %, percent]

Particle description	Particle size limit (mm)	Cross section						
		Aa (%)	Bb (%)	Cc (%)	Dd (%)	Ee (%)	Ff (%)	Gg (%)
Silt	0.062	0	0	0	0	0	0	0
Sand	2	18.0	3.0	6.0	16.0	5.0	8.0	30.0
Very fine gravel	4	24.0	3.0	7.0	30.0	5.0	9.0	34.0
Fine gravel	8	33.0	5.0	9.0	42.0	7.0	14.0	43.0
Medium gravel	16	49.0	10.0	15.0	59.0	18.0	24.0	62.0
Coarse gravel	32	81.0	29.0	37.0	84.0	43.0	59.0	85.0
Very coarse gravel	64	94.0	74.0	78.0	94.0	78.0	93.0	99.0
Small cobbles	128	96.0	93.0	99.0	99.0	99.0	99.0	100.0
Large cobbles	256	100.0	99.0	100.0	100.0	100.0	100.0	100.0
Small boulders	512	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 12. Cumulative distribution of grain sizes, in percent finer, for surficial bed material at permanent cross-section locations in the Tenmile Creek study reach, March 29, 2016.

[Values represent the percentage of total particles that are finer than the particle size indicated in the second column of each row of values; mm, millimeter; %, percent]

Particle description	Particle size limit (mm)	Cross section						
		Aa (%)	Bb (%)	Cc (%)	Dd (%)	Ee (%)	Ff (%)	Gg (%)
Silt	0.062	0	0	0	0	0	0	0
Sand	2	6.0	9.8	3.0	14.0	18.1	13.5	51.0
Very fine gravel	4	8.0	10.8	4.0	24.0	20.0	14.4	59.0
Fine gravel	8	13.0	13.7	5.9	36.0	29.5	19.2	71.0
Medium gravel	16	25.0	25.5	17.8	64.0	42.9	27.9	82.0
Coarse gravel	32	60.0	49.0	46.5	86.0	66.7	50.0	88.0
Very coarse gravel	64	88.0	80.4	82.2	97.0	84.8	82.7	98.0
Small cobbles	128	100.0	97.1	97.0	100.0	98.1	95.2	99.0
Large cobbles	256	100.0	100.0	100.0	100.0	100.0	99.0	100.0
Small boulders	512	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 13. Cumulative distribution of grain sizes, in percent finer, for surficial bed material at permanent cross-section locations in the Tenmile Creek study reach, September 14, 2016.

[Values represent the percentage of total particles that are finer than the particle size indicated in the second column of each row of values; mm, millimeter; %, percent]

Particle description	Particle size limit (mm)	Cross section						
		Aa (%)	Bb (%)	Cc (%)	Dd (%)	Ee (%)	Ff (%)	Gg (%)
Silt	0.062	0	0	0	0	0	0	0
Sand	2	2.0	1.0	7.0	5.0	3.0	1.0	5.0
Very fine gravel	4	5.0	3.0	14.0	10.0	16.0	5.0	11.0
Fine gravel	8	13.0	13.0	32.0	25.0	38.0	18.0	24.0
Medium gravel	16	46.0	25.0	55.0	43.0	77.0	48.0	63.0
Coarse gravel	32	79.0	64.0	82.0	77.0	95.0	78.0	90.0
Very coarse gravel	64	94.0	91.0	94.0	91.0	100.0	92.0	97.0
Small cobbles	128	99.0	97.0	99.0	98.0	100.0	100.0	100.0
Large cobbles	256	100.0	99.0	100.0	100.0	100.0	100.0	100.0
Small boulders	512	100.0	100.0	100.0	100.0	100.0	100.0	100.0

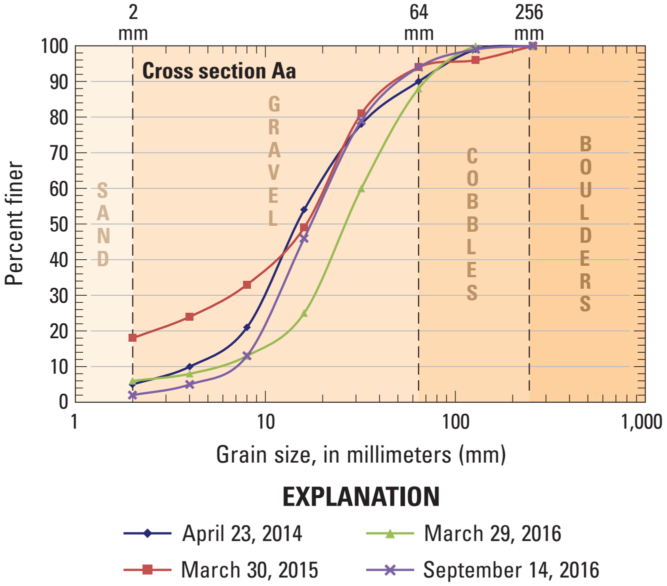


Figure 19. Comparison of grain-size distributions at cross section Aa, April 2014 through September 2016.

Note: Grain-size classes were defined by Wentworth (1922).

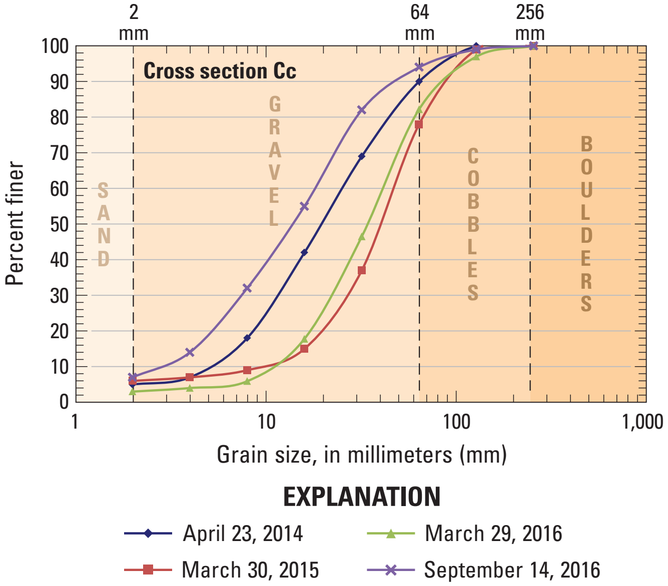


Figure 21. Comparison of grain-size distributions at cross section Cc, April 2014 through September 2016.

Note: Grain-size classes were defined by Wentworth (1922).

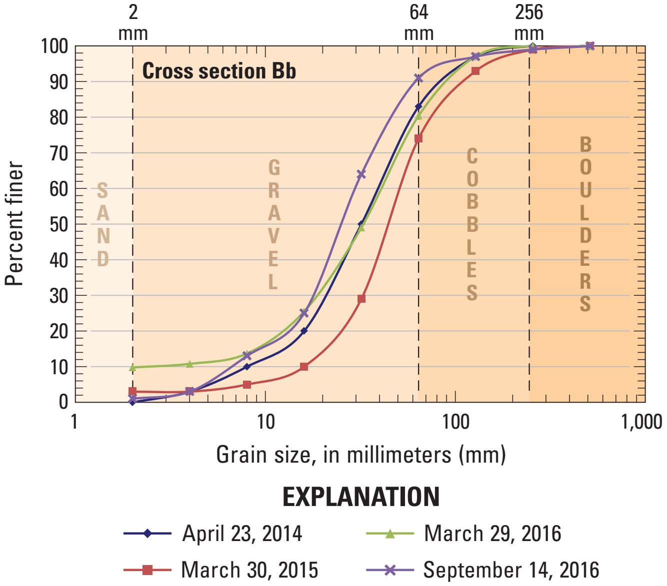


Figure 20. Comparison of grain-size distributions at cross section Bb, April 2014 through September 2016.

Note: Grain-size classes were defined by Wentworth (1922).

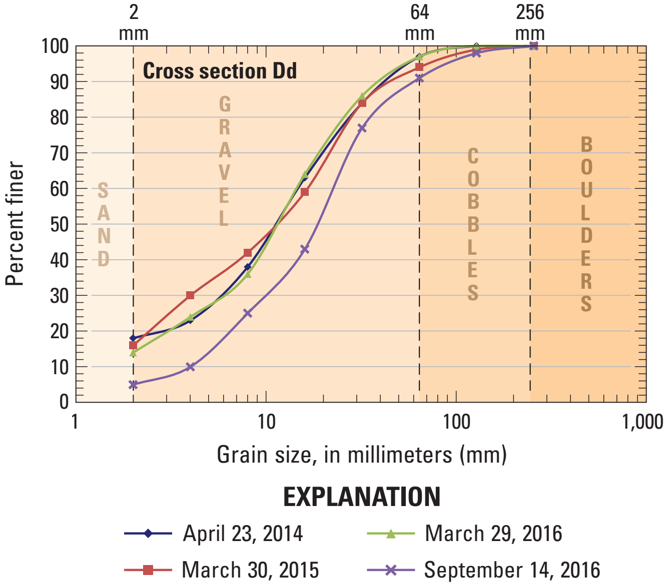


Figure 22. Comparison of grain-size distributions at cross section Dd, April 2014 through September 2016.

Note: Grain-size classes were defined by Wentworth (1922).

Data from the pebble counts at each of the seven cross sections also were combined to develop a composite grain-size distribution of the surficial bed material for the entire study reach. The distribution was developed using a sample of 700 or more pebbles that were collected in the cross sections in April 2014, March 2015, March 2016, and September 2016. The grain-size distributions and computations of percent finer for the composite pebble counts are shown in table 14 and figure 26.

The data in table 14 and figure 26 show that most of the particle sizes in the Tenmile Creek study reach were between fine gravel and very coarse gravel. The analysis also indicated increasing percentages of sand in the study reach, from 5.9 percent in April 2014 to 16.4 percent in March 2016. In September 2016, the composite pebble count only indicated 3.4 percent of the particles being sand in the study reach. This indicated that the stormflows from the storm and flood of

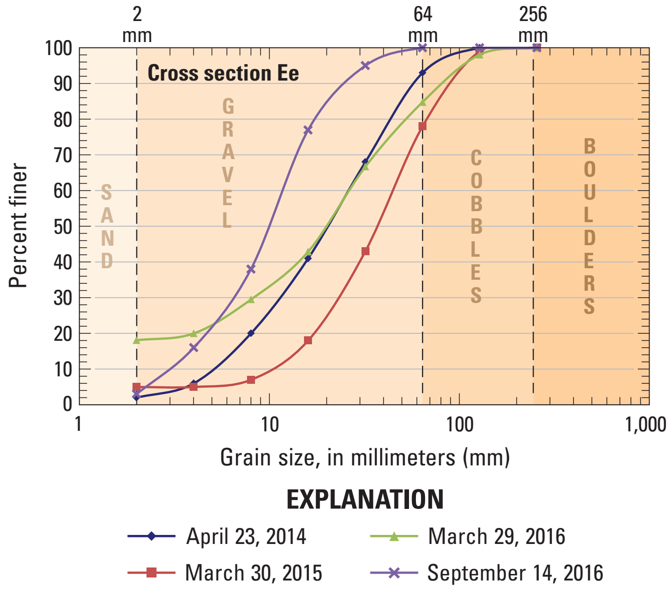


Figure 23. Comparison of grain-size distributions at cross section Ee, April 2014 through September 2016.

Note: Grain-size classes were defined by Wentworth (1922).

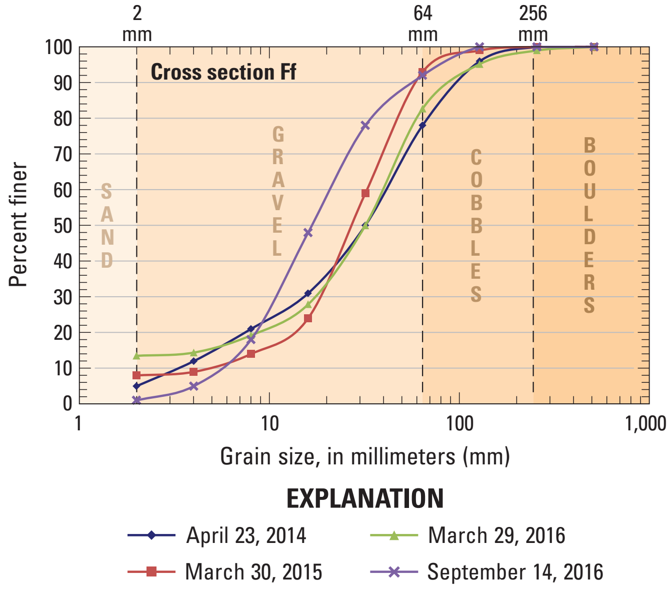


Figure 24. Comparison of grain-size distributions at cross section Ff, April 2014 through September 2016.

Note: Grain-size classes were defined by Wentworth (1922).

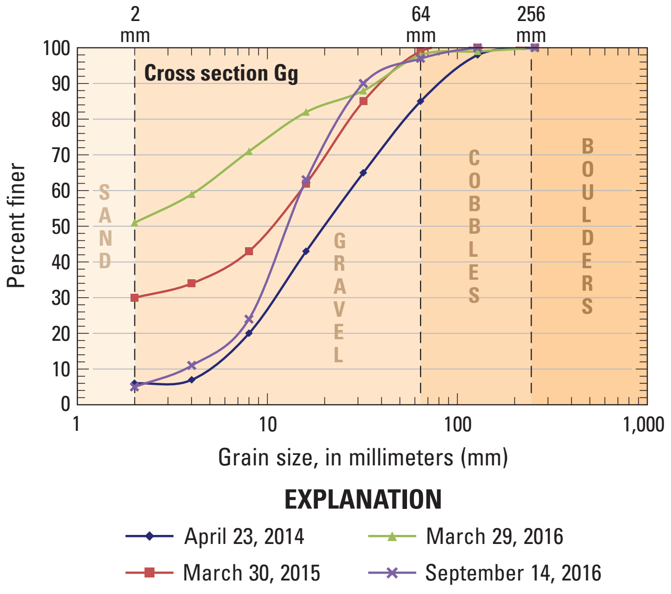


Figure 25. Comparison of grain-size distributions at cross section Gg, April 2014 through September 2016.

Note: Grain-size classes were defined by Wentworth (1922).

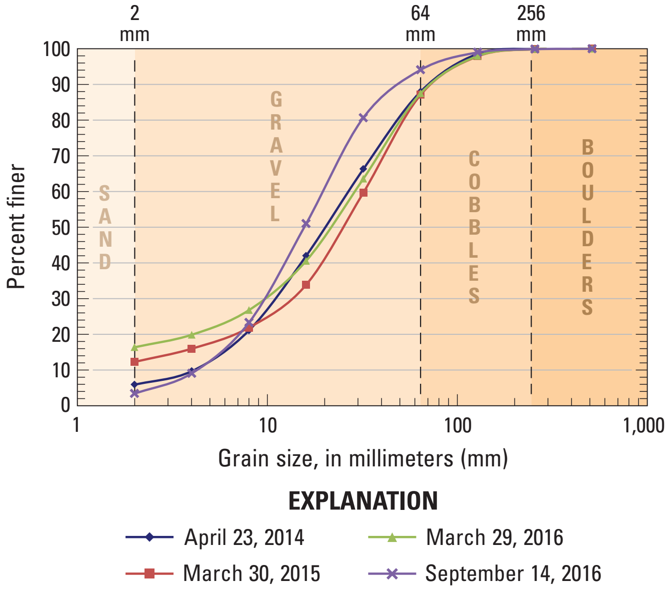


Figure 26. Comparison of composite pebble counts for Tenmile Creek study reach, April 2014 through September 2016.

Note: Grain-size classes were defined by Wentworth (1922).

Table 14. Grain-size distributions and computation of percent finer from composite pebble counts at all permanent cross sections, Tenmile Creek study reach, April 2014 through September 2016.

[Values represent the percentage of total particles that are finer than the particle size indicated in the second column of each row of values; mm, millimeter; %, percent]

Particle description	Particle size limit (mm)	April 23, 2014 (%)	March 30, 2015 (%)	March 29, 2016 (%)	September 14, 2016 (%)
Silt	0.062	0	0	0	0
Sand	2	5.9	12.3	16.4	3.4
Very fine gravel	4	9.7	16.0	19.9	9.1
Fine gravel	8	21.1	21.9	26.8	23.3
Medium gravel	16	42.0	33.9	40.6	51.0
Coarse gravel	32	66.3	59.7	63.6	80.7
Very coarse gravel	64	88.0	87.1	87.5	94.1
Small cobbles	128	98.6	97.9	98.0	99.0
Large cobbles	256	100.0	99.9	99.9	99.9
Small boulders	512	100.0	100.0	100.0	100.0

July 30, 2016 transported considerably more sand out of the study reach than the amount that was deposited.

Median particle diameters (d50) for all pebble counts conducted in the study reach between April 2014 and September 2016 were determined. This included each of the seven permanent cross sections, and a study reach composite, which integrated the pebble counts from all seven cross sections. The results are presented in table 15.

Based on the analyses of d50 for the cross sections, the channel bed ranged from medium-to-very-coarse gravel in cross sections Aa through Ff, and from coarse sand to coarse gravel in cross section Gg. The d50 values ranged from 10.5 millimeters (mm) to 32.0 mm in April 2014, 10.0 mm to 43.5 mm in March 2015, 1.9 mm to 35.0 mm in March 2016, and 9.7 mm to 25.0 mm in September 2016. These ranges indicated some coarsening of the channel bed between April 2014 and March 2015, slight fining of the channel bed between March 2015 and March 2016, and more fining of the channel bed between March 2016 and September 2016.

Based on the study reach composite of d50 shown in table 15, the channel bed can be characterized as medium-to-coarse gravel. Between April 2014 and March 2015, the change in composite d50 from 20.0 mm to 23.1 mm indicated coarsening of the channel bed. Between March 2015 and March 2016, the change in composite d50 from 23.1 mm to 22.0 mm indicated only slight fining of the channel bed. Between March 2016 and September 2016, the change in composite d50 from 22 mm to 15.5 mm indicated considerable fining of the channel bed, caused in large part by the storm and flood of July 30, 2016, and despite the fact that much of the sand that had been stored in the study reach was transported downstream by that storm.

Table 15. Median particle diameters, in millimeters, for each permanent cross-section location and study reach composite, Tenmile Creek study reach, April 2014 through September 2016.

Cross section	April 23, 2014	March 30, 2015	March 29, 2016	September 14, 2016
Aa	13.7	16.5	26.0	17.0
Bb	32.0	43.5	33.0	25.0
Cc	19.0	40.5	35.0	14.0
Dd	10.5	10.5	11.0	17.5
Ee	20.0	36.0	20.0	9.7
Ff	32.0	25.8	32.0	17.0
Gg	19.0	10.0	1.9	12.0
Study reach composite	20.0	23.1	22.0	15.5

Stream-Channel Classification

Rosgen (1994) developed a classification system for natural rivers that groups different types of rivers and streams according to quantitative measurements of dimension, pattern, profile, and composition of the bankfull channel. Stream channels are grouped according to single-thread or multiple-thread channels, and then divided into stream types according to their degree of entrenchment, bankfull width/depth ratio, sinuosity, water-surface slope, and type of channel materials (Rosgen, 1994, 1996). The Rosgen system can be used to describe landforms and channel dimensions within a river valley, and is widely used as a tool for investigations of sediment supply, stream sensitivity to disturbance, recovery potential of natural channels, channel response to change in flow regime, fish habitat potential, and river-restoration designs (Rosgen, 1994, 1996; Anderson and others, 2002; Doheny and others, 2007).

The stream channel in the Tenmile Creek study reach was classified according to Level II of the Rosgen stream-classification system, which is used to determine a morphological description of a given natural stream reach (fig. 27). Data from cross-sectional and longitudinal-profile surveys collected in the study reach in April 2014 were used to determine entrenchment, width/depth ratio, and water-surface slope. Sinuosity was calculated on the basis of the stream length that was determined from the longitudinal-profile survey, and valley length that was measured from a topographic map as the straight line distance between the upper and lower ends of the study reach (U.S. Geological Survey, 2012). Pebble-count data collected during April 2014 were used to classify the channel materials in the study reach.

The reach containing cross section Dd was selected for classification for several reasons. This reach of stream was straight and bankfull indicators were visible and fairly easy to identify. This cross section also was the closest one to the continuous-record streamflow-gaging station and as a result, bankfull indicators were easily related to the gage height at the station and associated with a discharge from the stage-discharge rating that is representative of bankfull conditions. The data variables that describe the bankfull channel at cross section Dd in April 2014 are summarized in table 16.

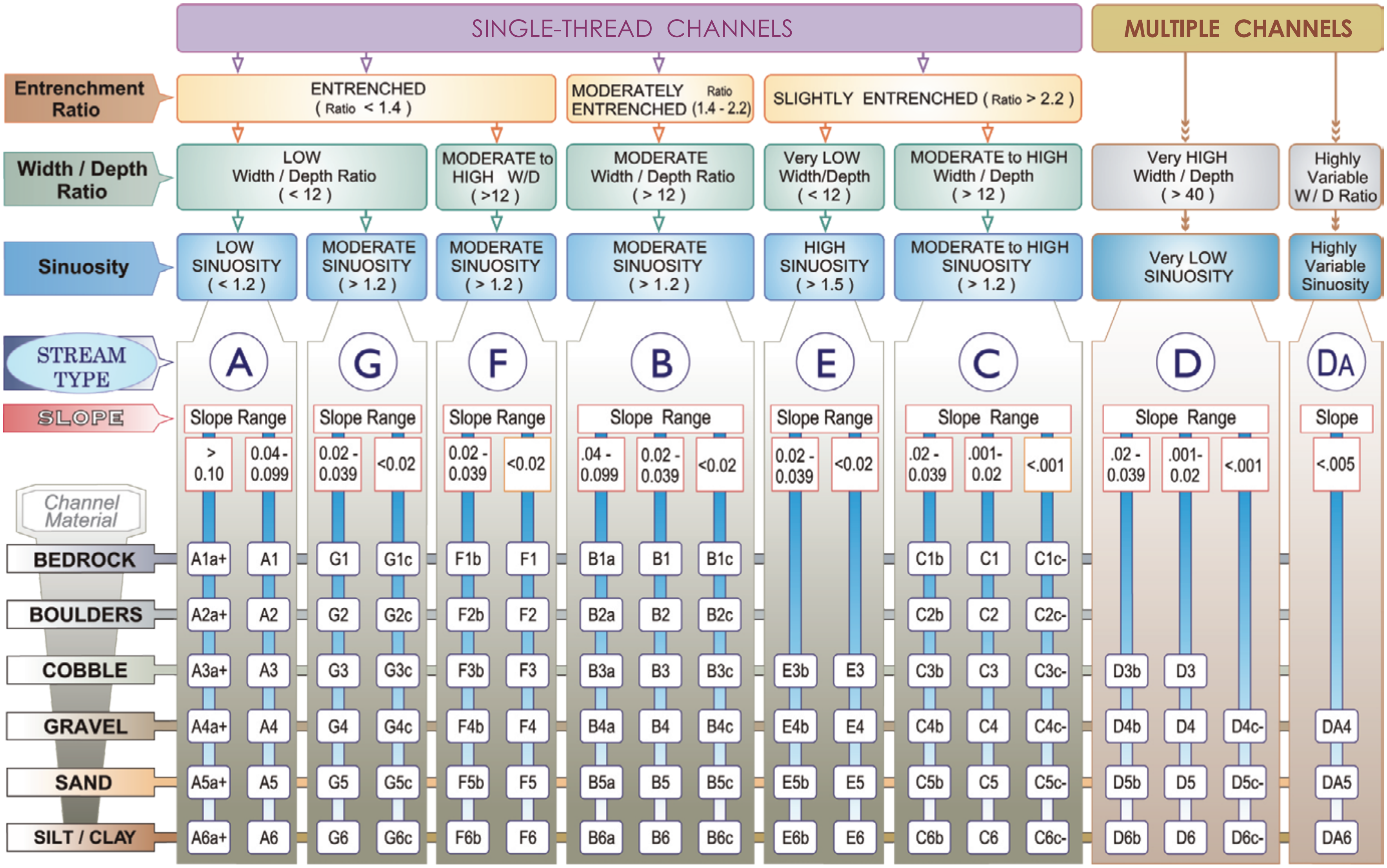
On the basis of the data variables shown in table 16, the Tenmile Creek stream channel was classified as a C stream type, indicating slight entrenchment, a moderate-to-high width/depth ratio, and moderate-to-high sinuosity. Since the water-surface slope was considerably less than 2 percent in the study reach, and the composite pebble count for the reach indicated a d50 of 20 mm (coarse gravel), the stream channel was classified as a C4 channel based on the Level II Rosgen morphological descriptions (fig. 27).

The bankfull indicators near the streamflow-gaging station and cross section Dd correspond to the profile of the top of a terrace feature that was visible along the right side of the stream channel that was surveyed in several locations during the longitudinal profile survey in April 2014. When using this feature as bankfull, the stage-discharge rating at USGS station 01644388 indicated a bankfull discharge of approximately 349 cubic feet per second (ft^3/s). Leopold (1994) suggested that for many streams, the bankfull discharge is the flow that occurs at an average recurrence interval of approximately 1.5 years, or an annual exceedance probability (AEP) of 0.6667. Because of the short record length at USGS station 01644388, a recurrence interval for this streamflow could not be directly assigned during this study. However, a discharge of 349 ft^3/s for a Piedmont watershed with this station's basin characteristics (drainage area of 3.37 mi^2, forest cover of 43.3 percent, no underlying carbonate rock, and 6.0 percent impervious area) falls within the standard error ranges of an event between 1.5 and 2.0 years, by use of peak-flow, fixed-region regression equations for non-urban watersheds in the Piedmont and Blue Ridge regions of Md. (Thomas and Moglen, 2016).

Table 16. Data variables describing the bankfull channel at cross section Dd that were used for Rosgen classification of the Tenmile Creek stream channel, April 2014.

[ft, foot; NAVD 88, North American Vertical Datum of 1988; ft^2, square foot; ft/ft, feet per foot]

Data variable	April 2014
Bankfull elevation (ft above NAVD 88)	430.96
Cross-sectional area (ft^2)	72.2
Wetted perimeter (ft)	40.0
Hydraulic radius (ft)	1.81
Mean depth (ft)	1.95
Maximum depth (ft)	3.48
Top width (ft)	37.0
Entrenchment width (in ft, at twice the maximum bankfull depth)	284.0
Entrenchment ratio (ft/ft)	7.7
Width/depth ratio (ft/ft)	18.9
Sinuosity	1.13
Water-surface slope (ft/ft)	0.0065



KEY to the ROSGEN CLASSIFICATION of NATURAL RIVERS. As a function of the "*continuum of physical variables*" within stream reaches, values of ***Entrenchment*** and ***Sinuosity*** ratios can vary by +/– 0.2 units; while values for ***Width / Depth*** ratios can vary by +/– 2.0 units.

Figure 27. Key to the Rosgen classification of natural rivers (modified from Rosgen, 1996).

(<, less than; >, greater than; +/–, plus or minus)

Shear-Stress Analysis

Boundary shear stress, in relation to streamflow and natural channels, is the force in pounds per square foot (lb/ft^2) that flowing water imposes on the channel bed and banks of the stream (Doheny and others, 2007; Doheny and others, 2012). Shear stress was first described by Shields (1936) as follows:

$$T = URS \tag{1}$$

where

T = boundary shear stress (lb/ft^2),
U = unit weight of water (pound per cubic foot, or lb/ft^3),
R = hydraulic radius (ft),
S = water-surface slope (feet per foot, or ft/ft).

Boundary shear stresses were computed for 12 stormflows at Tenmile Creek, based on five storm events. These storm events were April 30, 2014; May 16, 2014; June 27, 2015; October 28, 2015; and July 30, 2016. For the first four storms, boundary shear stress was computed for the peak discharge only, because the water-surface slope was based only on high-water marks from the crest-stage gages that were installed in the study reach. For the storm of July 30, 2016, water-surface slope was determined for a series of eight points over the storm hydrograph using data from HOBO loggers, which produced continuous stage data for the storm at the crest-stage gage locations and allowed the water-surface slope to be computed on a continuous basis. Hydraulic radius was determined by use of the geometry characteristics surveyed at cross section Dd. The unit weight of water was considered to be a constant value of 62.4 lb/ft^3. Corresponding mean velocities also were computed for each stormflow using the computed discharge from USGS station 01644388 and the corresponding cross-sectional area at cross section Dd. The results are summarized in table 17.

The computed boundary shear stress values were plotted against the associated discharge for each stormflow (fig. 28). Simple linear regression was used to determine logarithmic relations for boundary shear stress and discharge. The following equation was developed based on the data from the Tenmile Creek study reach:

$$Q = 1{,}927.1(SS)^{2.477} \tag{2}$$

where

Q = discharge (ft^3/s), and
SS = boundary shear stress (lb/ft^2).

The equation for boundary shear stress in relation to discharge indicated a **coefficient of determination** (R^2) of 0.68. The **residual standard error** (RSE) was 0.240 log units, or approximately 36.8 percent.

The relation of boundary shear stress and discharge at Tenmile Creek also was compared to relations developed by Doheny and others (2007) and Doheny and others (2012) for pre- and post-restoration conditions at Minebank Run, a small urban watershed in the eastern section of the Piedmont Physiographic Province in Baltimore County, Md. (figs. 29–30).

Table 17. Data variables and boundary shear stress computations for five storm runoff events in the Tenmile Creek study reach, April 2014 through July 2016.

[EST, Eastern Standard Time; ft^3/s, cubic foot per second; ft^2, square foot; ft/s, foot per second; ft, foot; ft/ft, feet per foot; lb/ft^2, pound per square foot]

Date of storm event	Time[1] (EST)	Discharge (ft^3/s)	Cross-sectional area (ft^2)	Mean velocity (ft/s)	Hydraulic radius (ft)	Water-surface slope (ft/ft)	Boundary shear stress (lb/ft^2)
4/30/2014	1945	610	129.2	4.72	1.87	0.00443	0.52
5/16/2014	0445	730	164.3	4.44	2.10	0.00456	0.60
6/27/2015	1440	685	150.8	4.54	1.99	0.00518	0.64
10/28/2015	2010	499	105.5	4.73	1.56	0.00475	0.46
7/30/2016	1915	2,860	662.0	4.32	2.36	0.00803	1.18
7/30/2016	1950	1,120	308.0	3.64	1.22	0.00701	0.53
7/30/2016	1955	872	162.8	5.36	1.32	0.00839	0.69
7/30/2016	2000	659	138.7	4.75	1.59	0.00796	0.79
7/30/2016	2015	356	65.5	5.44	1.36	0.00701	0.60
7/30/2016	2030	267	50.1	5.33	1.40	0.00664	0.58
7/30/2016	2100	167	35.5	4.70	1.06	0.00664	0.44
7/30/2016	2200	79	21.9	3.61	0.85	0.00664	0.35

[1] Time is presented in 24-hour notation referenced to EST.

The study reach that was used between 2002 and 2008 for pre- and post-restoration monitoring of geomorphology at Minebank Run drains 2.06 mi^2 and is 39.9 percent impervious (U.S. Geological Survey, 2012). Relief ranged from about 100 to 300 ft in most areas of the watershed (Doheny and others, 2006; Doheny and others, 2007). The stream channel had moderate-to-high entrenchment (Rosgen, 1994, 1996; Doheny and others 2007). Water-surface slopes computed for the geomorphic investigation at Minebank Run ranged from 0.0054 to 0.0112 ft/ft during the pre-restoration period (2002 to 2004), and 0.0065 to 0.0119 ft/ft during the post-restoration period (2005 to 2008) (Doheny and others, 2007; Doheny and others, 2012). For purposes of evaluating differences in boundary shear stresses, a comparison of selected basin characteristics and hydraulic channel variables for the Tenmile Creek and Minebank Run study reaches is shown in table 18.

For equivalent storm discharges, boundary shear stresses were predominantly larger in the Minebank Run study reach in comparison to the Tenmile Creek study reach (figs. 29–30).

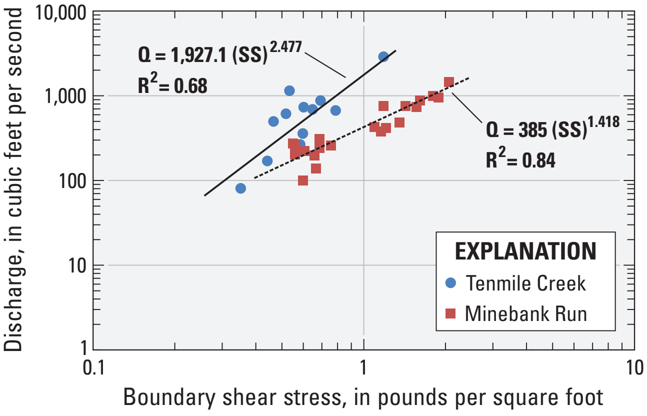


Figure 29. Comparison of boundary shear stress and discharge relations, Tenmile Creek study reach and Minebank Run study reach, prior to stream-channel restoration.

(Q, discharge estimated by least-squares regression; SS, boundary shear stress; R^2, coefficient of determination)

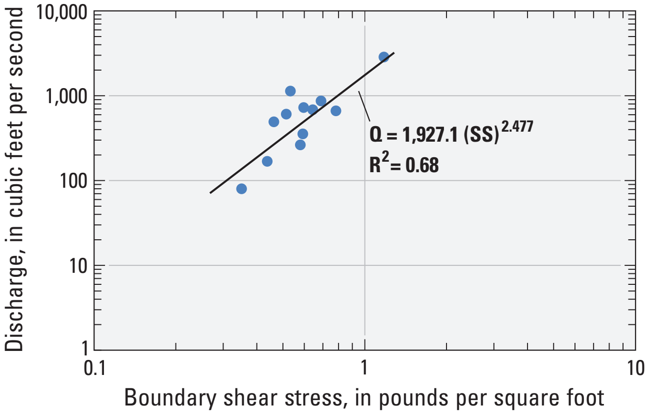


Figure 28. Boundary shear stress and discharge relations in the Tenmile Creek study reach, April 2014 through July 2016.

(Q, discharge estimated by least-squares regression; SS, boundary shear stress; R^2, coefficient of determination)

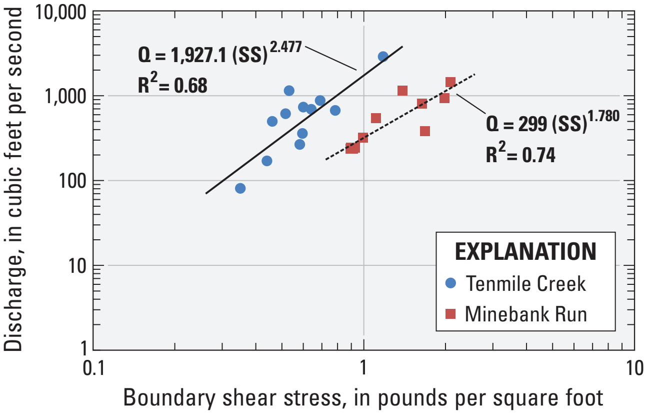


Figure 30. Comparison of boundary shear stress and discharge relations, Tenmile Creek study reach and Minebank Run study reach, after stream-channel restoration.

(Q, discharge estimated by least-squares regression; SS, boundary shear stress; R^2, coefficient of determination)

Table 18. Comparison of selected basin characteristics and hydraulic channel variables between the Tenmile Creek and Minebank Run study reaches in Maryland.

[mi^2, square mile; ft, foot; %, percent; ft^3/s, cubic foot per second; ft/s, foot per second; ft/ft, feet per foot; lb/ft^2, pound per square foot]

Basin characteristic or channel variable	U.S. Geological Survey station 01644388, Tenmile Creek near Clarksburg, Maryland	U.S. Geological Survey station 0158397967, Minebank Run near Glen Arm, Maryland
Drainage area (mi^2)	3.37	2.06
Range of watershed relief (ft)	30 to 140	100 to 300
Impervious area (%)	6.0	39.9
Channel entrenchment	slight	moderate to high
Range of monitored storm discharges (ft^3/s)	79 to 2,860	95 to 1,400
Range of computed mean channel velocity (ft/s)	3.61 to 5.44	2.79 to 9.29
Range of computed water-surface slope (ft/ft)	0.0044 to 0.0084	0.0054 to 0.0119
Range of computed boundary shear stresses (lb/ft^2)	0.35 to 1.18	0.55 to 2.12

The slopes of the regression lines in figs. 29 and 30 are also considerably flatter for Minebank Run in both its unrestored and restored conditions. This indicates that for the Minebank Run study reach, smaller changes in discharge resulted in larger changes in boundary shear stress when compared to the Tenmile Creek study reach. The erosive power in the urban watershed of Minebank Run is much more sensitive to discharge magnitude than the non-urban watershed of Tenmile Creek. Rapid increases in boundary shear stress indicate rapidly increasing forces that the flowing water imposes on the channel bed and banks of the stream channel, and thus a greater ability for the stream to transport sediment (Doheny and others, 2007).

Computed boundary shear stresses at Tenmile Creek ranged from 0.35 to 1.18 lb/ft^2 (table 18), whereas the previously published values for Minebank Run ranged from 0.55 to 2.12 lb/ft^2 (Doheny and others, 2007; Doheny and others, 2012). In general, steeper water-surface slopes contribute directly to the larger boundary shear stresses that were computed at Minebank Run. Although the largest monitored storm discharge at Tenmile Creek was more than twice as large as that at Minebank Run, the largest computed boundary shear stress at Tenmile Creek was nearly half that at Minebank Run. Differences in impervious area, channel entrenchment, and flood-plain characteristics also likely contributed to the difference in boundary shear stress between the two study reaches. In comparison to the Tenmile Creek watershed, the Minebank Run watershed had considerably more impervious area and a more-entrenched channel (table 18). A broad flood plain on the left side of the Tenmile Creek stream channel allows a large amount of extreme storm discharge to spill out into the overbank area, thus directing less shearing force at the bed and banks of the stream channel. Differences in channel entrenchment also likely explain the considerable differences in the range of computed mean channel velocity between the two study reaches.

Data Limitations

The geomorphic data collected during this study are representative of approximately 2.5 years in the long-term geomorphic evolution of the Tenmile Creek stream channel. Data collection over longer periods could provide a longer-term perspective on the geomorphic form and processes of the stream channel (Doheny and others, 2007).

Although permanent monuments were used to identify and re-survey cross sections, there is a degree of difficulty in maintaining the same stations from survey to survey. Because of geomorphic changes in the stream channel over time, there also is a small degree of error in maintaining exact longitudinal stationing from survey to survey, especially in locations where the channel meanders (Doheny and others, 2007).

Pebble-count data represent a random sampling of particle sizes from the channel bed. As a result, small differences in particle-size distribution may in some cases be explained by random variability of the samples taken from the channel bed (Doheny and others, 2007).

Summary

In February 2014, the U.S. Geological Survey (USGS), the U.S. Environmental Protection Agency (EPA), and the Montgomery County Department of Environmental Protection (DEP) began a study to enhance hydrologic monitoring in the Tenmile Creek watershed, and to document geomorphic characteristics of the stream channel in a selected reach of Tenmile Creek near Clarksburg, Maryland, prior to any additional development of the watershed. This report describes the methods used to collect geomorphic data in the Tenmile Creek study reach from April 2014 through September 2016. Data collected included surveyed elevations of the channel bed, water surface, and bank features; surveyed cross sections; pebble counts of the channel bed for determining grain-size analyses; and high-water mark elevations and supplemental stage data along the study reach from storm runoff events in the watershed. Streamflow data and precipitation data also were collected in the watershed during the study period to provide perspective on the geomorphic changes observed in the study reach.

These data were used to assess geomorphic characteristics over time in the Tenmile Creek study reach. Longitudinal profiles of the channel bed, water surface, and bank features were developed from field surveys. Changes in cross-section geometry were documented. Grain-size distributions were developed from pebble counts on the channel bed. The stream channel was classified according to morphological descriptions, using measurements of water-surface slope, entrenchment ratio, width-to-depth ratio, sinuosity, and median particle diameter of the channel materials. Boundary shear stress was analyzed near USGS streamflow-gaging station 01644388, Tenmile Creek near Clarksburg, Md., by use of hydraulic variables that were computed from the cross-section surveys, and slope measurements that were made by use of crest-stage gages and temporary stage sensors that were installed in the study reach.

Comparison of the longitudinal profiles showed relatively small changes in the percentage and distribution of riffles, pools, and runs in the study reach between April 2014 and March 2015, and more significant changes between surveys conducted in March 2015, March 2016, and September 2016. The channel-bed slope showed a net reduction over time from 0.0072 to 0.0040 feet per foot (ft/ft). The water-surface slope also showed a net reduction over time from 0.0065 to 0.0045 ft/ft. The storm and flood of July 30, 2016 was a major factor in the observed changes of the longitudinal profiles between the March 2016 and September 2016 surveys.

The cross-section surveys indicated that lateral erosion was not a major factor in most areas of the study reach. Cross section Dd was the only location where considerable lateral erosion was documented during the study period. Considerable vertical changes were observed in all cross sections, with cross section Gg showing the most changes between surveys. The vertical changes were caused in part by alternating periods of net storage and transport of sand into and out of the lower section of the study reach. The storm and flood of July 30, 2016 was a major factor in some of the vertical changes observed in the channel bed of the study reach cross sections.

Particle-size analyses of the channel bed from pebble counts indicated median particle diameters ranging from 15.5 millimeters (mm) to 23.1 mm, which can be characterized as medium-to-coarse gravel. Sand percentages ranged from 3.4 percent to 16.4 percent of the total counts over time, and indicated net increases in the storage of fine sediment in the study reach between April 2014 and March 2016, and a considerable reduction between March 2016 and September 2016.

The Tenmile Creek stream channel was classified as a C4 channel on the basis of morphological descriptions in the Rosgen stream-classification system. The C4 classification describes a single-thread channel with a slight entrenchment ratio; a moderate-to-high width-to-depth ratio; moderate-to-high sinuosity; a water-surface slope of less than 2 percent; and a median particle diameter in the gravel range (from 2 to 64 mm).

The analysis of boundary shear stress indicated a range of 0.35 to 1.18 pounds per square foot for instantaneous streamflow ranging from 79 to 2,860 cubic feet per second during the study period. The relation between discharge and boundary shear stress for Tenmile Creek was compared to similar relations that were previously developed for Minebank Run, a small, urban watershed in the eastern section of the Piedmont Physiographic Province in Baltimore County, Md. that was physically restored during 2004–05. The comparison indicated a much flatter slope in the relation for Minebank Run in both its unrestored and restored conditions. This difference in the relation indicates that the erosive power in the urban watershed of Minebank Run is much more sensitive to increases in discharge magnitude than in the non-urban watershed of Tenmile Creek.

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Glossary

Bankfull (stage or discharge) Bankfull stage refers to the water-surface elevation at the level of the active flood plain in the stream channel. Bankfull discharge refers to the stream discharge at the level of the active flood plain. It is also the discharge that, over time, transports the largest volumes of sediment, and forms and maintains the morphological features in the stream channel.

Bankfull indicator(s) Geomorphic features in a stream channel that define the elevation of the active flood plain. These features might include the top of point bar surfaces and depositional features, breaks or changes in bank vegetation, breaks or changes in bank slope, changes in channel-material sizes or distribution on the channel banks, the upper extent of bank undercuts, and stain lines on rocks.

Boundary shear stress The force, in pounds per square foot, that flowing water applies to the channel bed and banks of a stream.

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

Continuous-record streamflow-gaging station Location where a water-stage recorder is used to collect continuous time-series stage data that are related to systematic discharge measurements at the station in order to interpret a continuous record of streamflow at the station.

Crest-stage gage(s) A device that will register the peak stage of the stream occurring between inspections of the gage. Crest-stage gages are typically used as a supplement to a water-stage recorder since the peak stage of a storm can occur in between recorded stage values. Crest-stage gages can be used to obtain high-water marks at a given location during a flood, or to determine water-surface slopes at different stream stages if placed in multiple locations along a reach of stream. A stage-discharge relation for the location of a crest-stage gage can be developed using discharge data obtained from indirect measurements of peak flow, or direct measurement of a range of discharges by use of a current meter or acoustic Doppler current profiler.

Cut bank(s) A channel bank with a nearly vertical slope, which is formed by erosion from flowing water. Cut banks often form on the outside of a meander in the channel, where the flowing water causes erosion on an ongoing basis.

Daily mean discharge(s) Discharge that is computed as the arithmetic mean of the instantaneous discharge values for a given day of the water year.

Hydraulic radius The cross-sectional area of a channel divided by the wetted perimeter.

Left bank The left channel bank when facing in a downstream direction. For the Tenmile Creek stream valley, the left bank is also the east bank.

Maximum precipitation intensity Precipitation intensity is presented in inches per hour, and is computed as the largest precipitation rate that was recorded by the continuous-record precipitation gages during any 15-minute period in a specific water year. For example, if the largest amount of precipitation that fell during any 15-minute period in the 2016 water year was 0.98 inches, the maximum precipitation intensity would be computed as 0.98 inches divided by 0.25 hours, or 3.92 inches per hour.

Median particle diameter (d50) The particle diameter associated with 50 percent of the bed material being finer, and 50 percent of the bed material being coarser.

Metagraywacke A type of sandstone that is characterized by its hardness, dark color, and poorly sorted angular grains of quartz, feldspar, and small rock fragments that are set in a clay-fine matrix. Graywackes are mostly grey, brown, yellow, or black in color, and can occur in thick or thin beds with shales and limestones.

Percent finer A cumulative percentage, associated with a particular particle size or diameter that represents how much of the material that composes the channel bed or banks is smaller, or finer, than that particle diameter.

Point bar (or point-bar surface) A depositional feature, composed of alluvium in a meandering stream or river, that accumulates on the inside of a meander bend, or downstream from an area of significant debris accumulation.

Pool(s) A longitudinal section of stream channel with fine bed materials in deeper, slower-moving water, with a light slope and very smooth water surface.

Relief The variation between the highest and lowest elevations at any location in a watershed, using a common elevation datum. For this report, relief was estimated for the Tenmile Creek watershed based on elevations from a topographic map.

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

Riffle(s) A longitudinal section of stream channel with coarse bed materials, shallow depths, steep slope, swift velocities, and a turbulent water surface.

Right Bank The right channel bank when facing in a downstream direction. For the Tenmile Creek stream valley, the right bank is also the west bank.

Run(s) A longitudinal section of stream channel that has a moderate current, moderate depth, and a relatively smooth water surface.

Sinuosity The ratio of stream length to valley length. The minimum value of sinuosity is 1.0 for a straight channel, and increases depending on the amount of meandering in the reach of interest.

Stage-discharge rating A logarithmic relation of stream stage (or gage height) and stream discharge that is developed from a series of discharge measurements made in a particular location. A stage-discharge rating can be presented as a curve, or as a table that is prepared from the curve.

Terrace(s) An abandoned flood plain in a river or stream channel. A flood plain may become abandoned when a stream channel degrades and forms new channel features that are indicative of the active flood plain.

Thalweg The lowest elevation along a cross section in a stream channel.

Water Year(s) Water year is defined as the 12-month period beginning October 1 and ending September 30. The water year is designated by the calendar year in which it ends and includes 9 of the 12 months. For example, the year beginning October 1, 2015 and ending September 30, 2016 is called “water year 2016.”

Wetted Perimeter The length along the cross-sectional boundary of a channel that is contacted by water. In an open channel, such as a stream or river, the cross-sectional boundary is the channel bed and banks.

Width-to-Depth Ratio The channel width divided by the mean channel depth at a specified water-surface elevation in a stream channel.

Appendix 1. Changes in Cross-Section Geometry at Permanent Cross Sections for Bankfull Conditions, Tenmile Creek Study Reach, April 2014 through September 2016

Appendix 1. Changes in cross-section geometry at permanent cross section Aa for bankfull conditions, Tenmile Creek study reach, April 2014 through September 2016.

[ft, foot; ft^2, square foot; ft/ft, feet per foot]

Cross section Aa (Bankfull water-surface elevation = 434.52 ft)	April 23, 2014	March 30, 2015	March 29, 2016	September 13, 2016
Cross-sectional area (ft^2)	109.7	113.6	110.4	136.0
Channel width (ft)	41.2	40.2	41.4	40.8
Mean depth (ft)	2.66	2.83	2.67	3.33
Maximum depth (ft)	3.67	3.90	3.62	5.03
Wetted perimeter (ft)	43.2	42.7	44.2	43.1
Hydraulic radius (ft)	2.54	2.66	2.50	3.16
Width/depth ratio (ft/ft)	15.5	14.2	15.5	12.3

Appendix 1. Changes in cross-section geometry at permanent cross section Bb for bankfull conditions, Tenmile Creek study reach, April 2014 through September 2016.—Continued

[ft, foot; ft^2, square foot; ft/ft, feet per foot]

Cross section Bb (Bankfull water-surface elevation = 433.12 ft)	April 23, 2014	March 30, 2015	March 29, 2016	September 13, 2016
Cross-sectional area (ft^2)	80.8	87.4	85.2	87.2
Channel width (ft)	39.9	39.7	40.0	40.2
Mean depth (ft)	2.03	2.20	2.13	2.17
Maximum depth (ft)	3.19	3.10	3.11	3.72
Wetted perimeter (ft)	41.3	41.2	41.2	41.4
Hydraulic radius (ft)	1.96	2.12	2.07	2.11
Width/depth ratio (ft/ft)	19.7	18.0	18.8	18.5

Appendix 1. Changes in cross-section geometry at permanent cross section Cc for bankfull conditions, Tenmile Creek study reach, April 2014 through September 2016.—Continued

[ft, foot; ft^2, square foot; ft/ft, feet per foot]

Cross section Cc (Bankfull water-surface elevation = 432.57 ft)	April 23, 2014	March 30, 2015	March 29, 2016	September 13, 2016
Cross-sectional area (ft^2)	113.4	109.4	106.8	129.8
Channel width (ft)	46.2	47.5	47.3	46.5
Mean depth (ft)	2.45	2.30	2.26	2.79
Maximum depth (ft)	4.22	3.75	3.99	4.29
Wetted perimeter (ft)	49.3	50.3	50.2	50.5
Hydraulic radius (ft)	2.30	2.17	2.13	2.57
Width/depth ratio (ft/ft)	18.9	20.7	20.9	16.7

Appendix 1. Changes in cross-section geometry at permanent cross section Ee for bankfull conditions, Tenmile Creek study reach, April 2014 through September 2016.—Continued

[ft, foot; ft^2, square foot; ft/ft, feet per foot]

Cross section Ee (Bankfull water-surface elevation = 430.19 ft)	April 23, 2014	March 30, 2015	March 29, 2016	September 13, 2016
Cross-sectional area (ft^2)	55.8	66.7	72.1	60.3
Channel width (ft)	35.9	40.3	43.9	41.8
Mean depth (ft)	1.55	1.66	1.64	1.44
Maximum depth (ft)	3.06	2.90	3.20	2.34
Wetted perimeter (ft)	37.3	41.3	45.2	42.6
Hydraulic radius (ft)	1.50	1.62	1.60	1.42
Width/depth ratio (ft/ft)	23.1	24.3	26.8	29.0

Appendix 1. Changes in cross-section geometry at permanent cross section Ff for bankfull conditions, Tenmile Creek study reach, April 2014 through September 2016.—Continued

[ft, foot; ft^2, square foot; ft/ft, feet per foot]

Cross section Ff (Bankfull water-surface elevation = 429.70 ft)	April 23, 2014	March 30, 2015	March 29, 2016	September 13, 2016
Cross-sectional area (ft^2)	75.9	72.4	79.6	54.5
Channel width (ft)	38.7	41.2	41.9	43.2
Mean depth (ft)	1.96	1.76	1.90	1.26
Maximum depth (ft)	2.74	2.35	2.70	2.14
Wetted perimeter (ft)	39.8	42.3	43.0	43.8
Hydraulic radius (ft)	1.91	1.71	1.85	1.24
Width/depth ratio (ft/ft)	19.8	23.5	22.1	34.3

Appendix 1. Changes in cross-section geometry at permanent cross section Gg for bankfull conditions, Tenmile Creek study reach, April 2014 through September 2016.—Continued

[ft, foot; ft^2, square foot; ft/ft, feet per foot]

Cross section Gg (Bankfull water-surface elevation = 428.00 ft)	April 23, 2014	March 30, 2015	March 29, 2016	September 13, 2016
Cross-sectional area (ft^2)	61.9	67.5	75.3	54.1
Channel width (ft)	30.6	38.5	37.9	32.7
Mean depth (ft)	2.02	1.75	1.99	1.65
Maximum depth (ft)	2.68	3.08	3.70	3.05
Wetted perimeter (ft)	33.0	40.4	39.7	33.9
Hydraulic radius (ft)	1.88	1.67	1.90	1.60
Width/depth ratio (ft/ft)	15.1	21.9	19.0	19.8

For additional information, contact:
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or visit our website at:
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