The Self-Recovery of Stream Channel Stability in Urban Watersheds due to BMP Implementation

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Prepared by the Center for Watershed Protection, Inc.

Prepared for the Carroll County Bureau of Resource Management

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List of Acronyms

ANCOVA	Analysis of Covariance
BANCS	Bank Assessment for Non-point Source Consequences of Sediment
BEHI	Bank Erosion Hazard Index
BMP	Best Management Practice
C	Control Site
CBP	Chesapeake Bay Program
Cpv	Channel Protection Volume
EIA	Effective Impervious Area
ESD	Environmental Site Design
MDE	Maryland Department of Environment
MEP	Maximum Extent Practicable
MS4	Municipal Separate Storm Sewer System
NBS	Near Bank Stress
PT	Pressure Transducer
RCN	Runoff Curve Number
T	Treatment Site
TMDL	Total Maximum Daily Load
TSS	Total Suspended Solids
USDA	United States Department of Agriculture
USFWS	United States Fish and Wildlife Service

Introduction

Decades of research have improved the scientific understanding of urban hydrology and stream processes, including hydraulics, that have informed the way stormwater is regulated and managed. This scientific-based understanding of stormwater runoff, its quality, quantity, and downstream impacts, has advanced the innovative design of best management practices (BMPs) to better protect water resources. To comply with the requirements of the Clean Water Act (CWA), Title 4, Subtitle 2 of the Environment Article of Annotated Code of Maryland states that "the management of stormwater runoff is necessary to reduce stream channel erosion, pollution, siltation and sedimentation, and local flooding, all of which have adverse impacts on the water and land resources of Maryland." However, the capacity of upland BMPs to affect stream energy dynamics that reduce erosive flows causing channel instability remains a needed area of research.

It is well-documented that altered hydrology within the drainage area due to urbanization is a major cause of stream erosion leading to degraded stream water quality and biology (e.g., Paul & Meyer, 2001; Schueler et al., 2009, Hawley, et al. 2019). The specific causes of degradation may be attributed to site- or watershed-specific characteristics that alter the timing, magnitude, and rate of streamflow. For example, the changes in stream energy from higher magnitude and frequency flows result in increased rates of channel erosion and sediment yield in urbanizing streams as documented by many researchers (Trimble, 1997; Booth & Henshaw, 2001; Langland & Cronin, 2003; Allmendinger et al., 2007; Fraley et al., 2009). Downcutting or channel incision is a common feature of urban stream channels due to high volume scouring flows and lateral constraints to channel migration (Wolman, 1967; Henshaw & Booth, 2000). Sediment correlation studies indicate that upland erosion and channel enlargement are significant components of the sediment budget (Allmendinger et al., 2007), and erosion and deposition values are higher in unstable reaches (Bergmann & Clauser, 2011). Fraley et al. (2009) found that bank erosion contributed an estimated 43% of the suspended sediment load in an urbanizing Pennsylvania tributary. Similarly, for an urban stream in southern California, Trimble (1997) found that channel erosion contributed about two-thirds of the total sediment yield. A study of streams in Maryland and Pennsylvania found sediment loading rates attributed to stream channel erosion in the range of 300 to 1,500 lb/ft/yr (Landstudies, 2005).

Given the requirements to meet stormwater performance standards as part of CWA National Pollutant Discharge Elimination (NPDES), Municipal Separate Storm Sewer System (MS4) program to improve the quality of streams, it is expected that practice designs that mimic a more natural hydrologic regime will reduce impacts to receiving streams and as such enhance the potential for restoration to be successful. To date, research typically evaluates the hydrologic benefits (i.e., reduction of peak discharge, volume reduction) of BMPs at the site or watershed scale but research is limited at evaluating the effect of BMP implementation on the stream channel itself. Aulenbach et al. (2017) found that for every 1% increase in watershed effective impervious area (EIA), about 1.5% to 2.6% increases in EIA treated by BMPs would be required to counteract the effects of EIA added to the watersheds to adequately address peak streamflow, stormwater yield, and storm streamflow runoff. Paired watershed studies by Barr Engineering (2006) and Claussen (2007) find that runoff reduction practices effectively reduce runoff volumes by up to 97%. Pennino et al. (2016) demonstrated through a regional study of green infrastructure impacts at the small watershed scale in Baltimore and Montgomery Counties in Maryland that small watersheds with more than 10% of their total area treated by green infrastructure had less flashy hydrology, with 44% lower peak runoff, 26% less frequent runoff events, and 26% less variable runoff compared to watersheds without green infrastructure. Sand filters and infiltration trenches were found to be the most prevalent practices in the watershed, most likely accounting for these reductions. Research to evaluate the hydrogeomorphic response attributed to BMPs is less studied regarding the degree that BMPs may mitigate flows that contribute to excessive stream bed and bank erosion.

The full recovery of a stream due to BMP implementation is a complex process. Despite expected water quality improvement at the site-scale, the long-term and full restoration of stream health may be hampered by lag effects (Lyerly et al., 2014), extent, and type of practice implemented, as well as incomplete identification or inadequate treatment of the causes of degradation (Palmer et al., 2014; Chesapeake Bay Program, 2015). A study of stormwater basins by Burns et al. (2011) found that conventional approaches to stormwater management (e.g., focusing on peak storm rate control) fail because they do not address the full spectrum of changes to the flow regime caused by upstream development and subsequent stormwater drainage designs. Hawley and Vietz (2016) found that the optimum design criteria for maintaining stream stability is a threshold-based approach in which a critical discharge (Q_c) target is established based on hydrogeomorphic data from the stream to maintain/restore a more natural sediment transport regime similar to that of equilibrium channels of undeveloped watersheds. His recommendations focus on controlling stormwater during relatively large events (two-year and larger) in such a way as to minimize frequencies and durations of discharges greater than the Q_c design target for a broader spectrum of storm frequencies, relative to the predevelopment regime.

Structural BMPs have traditionally been designed in Maryland to reduce the discharge from the two-year post-development peak flow rate to predevelopment levels (MDE, 2010). However, channel instability may result despite reduced post-development peak-flow magnitude and increased storage duration. In some cases, controlling the two-year storm may accelerate streambank erosion because it exposes the channel to a longer duration of erosive flows than it would have otherwise received. This was demonstrated in a modeling study of a small catchment in Colorado by Bledsoe (2002) that found a 2-year stormwater peak control detention facility would need its storage volume increased by 61% to adequately protect the stream channel. Fennesy et al. (2001) evaluated the effectiveness of 5 different stormwater management ordinances using simulation studies and found that although all of the ordinances required post-development runoff rates from the site be less than or equal to the predevelopment runoff rates for each return period (e.g., 100 yr – 1 yr, 10 yr -2 yr), none of the ordinances were effective at controlling the 1 and 2 year (or more frequent) storm events that are associated with nuisance flooding and stream bank erosion.

Increasingly, MS4 jurisdictions are adopting storm water management design standards that use runoff reduction practices or “green infrastructure” to mimic a more natural hydrologic regime (Schueler & Lane, 2015). Implementing Hawley and Vietz recommendations would be difficult because of the wide range of bed material and different hydrologic regimes across the state of Maryland. Instead, the current approach adopted by the Maryland Department of Environment (MDE) is towards smaller distributed systems and environmental site design (ESD) to mimic a site’s pre-development hydrology and reduce negative impacts on receiving stream channels. These distributed systems seek to promote infiltration to increase groundwater flows with the intent to restore baseflow to urban streams. Maryland’s performance standard is to implement ESD BMPs to the maximum extent practicable (MEP) to replicate runoff characteristics for a 1-year, 24-hour storm similar to “woods in good condition”

(MDE, 2010). When the targeted rainfall is not met, any remaining channel protection volume (Cpv) requirements shall be treated using structural practices.

Recent findings suggest unstable streambanks in headwater streams can recover channel stability due to the implementation of upstream BMPs. Hawley et al. (2019) found in studying 61 suburban streams over a ten-year period that suburban streams become unstable due to increases in impervious cover and follow Schumm's' channel evolution progressing toward dynamic equilibrium with the post-development hydrologic regime. However, after 10 years only one stream channel approached potential geomorphic recovery, attributable to an upstream stormwater retrofit. Hawley et al. (2017) found that this retrofit reduced the cumulative sediment transport capacity of the pre-retrofit condition by greater than 40% and contributed to reduced flashiness and prolonged baseflows in the receiving streams. Using an iterative modeling approach showed that existing basins can be retrofit to reduce the peak discharge of design storms such as the three-month, six-month, and one-year events to rates below Q_c, while maintaining adequate levels of service for flood flows such as the 100-year discharge. Further, Hawley found that retrofit designs do not have to be complicated and can involve restrictions of the low-flow orifice and a bypass for larger than the two-year storm (Hawley et al. 2017).

Covington (2015) found that stream channel stability can be recovered due to implementation of BMPs that treat nearly 100% of the drainage area. For more than 10 years, Carroll County has experimented with the retrofit of existing stormwater ponds originally designed for peak flow control using enhanced sand filter and wet pond designs. Modeling results indicate that these retrofit designs reduce the two-year storm peak flow below that of the "forest in good condition" performance standard which reduces or ceases bank retreat and causes revegetation of riparian areas to occur downstream (Covington, 2015). The reduction in post-development discharge of these designs is much greater than those from "conventional" two-year peak post-development to two-year post-redevelopment design criteria. The County observed that the highly eroded streambanks downstream of the retrofits stopped retreating and began to re-vegetate over months or years after the construction of the retrofits. Two pond retrofits in Carroll County were selected for analysis as part of this study, including Shannon Run and Central MD SVC. A description of the retrofits and their performance is provided in the Methods section below.

This study was undertaken to examine the downstream effects of Carroll County's enhanced sand filter and wet pond retrofit designs utilizing two treatment and two control sites. With the limited sample size and timing it takes for geomorphic changes to occur, results from studies of this nature can take longer than the study period allows. However, based on the anecdotal evidence from the retrofit designs by Carroll County, observation of hydrologic changes were expected, as well as initial geomorphic changes to the downstream channel. The goals of this study were to:

i. Determine the effectiveness of BMPs retrofitted to meet Carroll County's sand filter design standard (and related design factors) on stream channel stability based on standard geomorphic measurement methods.
ii. Evaluate the extent that this type of retrofit practice can affect downstream impacts such as stream channel erosion.
iii. Evaluate the extent that the retrofit can mitigate the effects of downstream uncontrolled runoff from the same reach.

iv. Provide recommendations to credit flow controlling BMPs as a hydrogeomorphic stream stabilization technique for inclusion as part of the nutrient and sediment credits for the Bay Total Maximum Daily Load (TMDL).

The specific hypotheses this research seeks to address include:

H1: The implementation of BMPs retrofitted to meet Carroll County's sand filter design standard will modify the runoff response from the watershed (hydrograph) resulting in a reduction of the magnitude, duration and frequency of erosive flow rates that meet and or exceed MDE performance standards for stream channel protection.

H2: The implementation of these BMPs will create hydraulic conditions that lead to self-recovery of channel stability.

a. The bank erosion rate in treatment reaches will be lower than the control reaches due to reduction in magnitude, duration and frequency in flows that contribute to bank erosion.
b. The treatment reaches will be aggrading due to reductions in stream power. These reductions will reduce the sediment transport capacity resulting in sediment deposition on the streambed, which results in aggradation.
c. The longitudinal extent of reduced stream bank erosion downstream of the BMP implementation sites will be a function of the total watershed area treated (e.g., x linear ft of stream for every y-acre impervious area treated in the watershed).

H3: The implementation of these BMPs will decrease sediment loadings downstream as a result of reduced bank erosion rates.

Methods and Data

Study Design Overview

A modified version of the paired watershed study design approach described by Claussen & Spooner (1993) and before after control impact (BACI) study described by Osenberg et al. (2006) was used to evaluate the effectiveness of stormwater retrofits on the hydrogeomorphic changes in downstream stream channels and subsequent reductions in nutrient and sediments. Multiple treatment and control sites were used, following the modified BACI design approach described by Downes et al. (2002).

Following the paired watershed design, a set of control and treatment watersheds were selected to generate precipitation, hydrologic, hydraulic, geomorphic, and riparian vegetation data during the calibration (pre-treatment) and post-treatment periods. A total of 4 study sites, 2 treatment sites, and 2 control sites were used in this study (Table 1). A third treatment site (Blue Ridge) was originally included in the study but was removed because the sand filter retrofit did not function as designed during the study period. Establishment of vegetation on the surface of the sand filter retrofit is an important aspect to the continued functionality of the BMP, as the root system of the grass keeps the surface of the media from binding. A good stand of vegetation generally takes two growing seasons to establish. Unfortunately, Blue Ridge was completed just prior to record precipitation in 2018. The continued inundation of the facility prevented any vegetation from getting established and the weight of the water and leaf detritus compressed the filter media. The media was tilled and re-seeded it in the Fall of 2019. The facility is now functioning as designed, but the interruption of functionality removed it from this study. Although not included as part of the analysis for this study, post-treatment data continues to be collected at this site for use in future analyses. A detailed description of the methods is provided in the Monitoring Plan and Quality Assurance Project Plan (Appendix A).

The total project period is four years and 9 months (July 1, 2016 – March 31, 2021) with the key activities that occurred during the pretreatment and post-treatment monitoring periods presented in Figure 1.

Table 1. Study site characteristics.

Study Site	Treatment or Control	Drainage Area (ac)	Impervious Cover (%)	Study Reach Length (ft)	Existing BMP Type	Retrofit Type
Blue Ridge[1,2]	Treatment	33.6	26.9%	145	Retention	Sand Filter
Central MD SVC[1]	Treatment	91.7	31.3%	325	Detention	Sand Filter
Robert's Field[1]	Control	28.8	37.4%	157	Extended Detention	N/A
Shannon Run	Treatment	209	20%	366	Retention	Wet Pond
Piney Ridge	Control	91.1	36.1%	559	Retention	N/A

[1] Rain gauge located at site.
[2] Site removed from analysis due to retrofit failure.

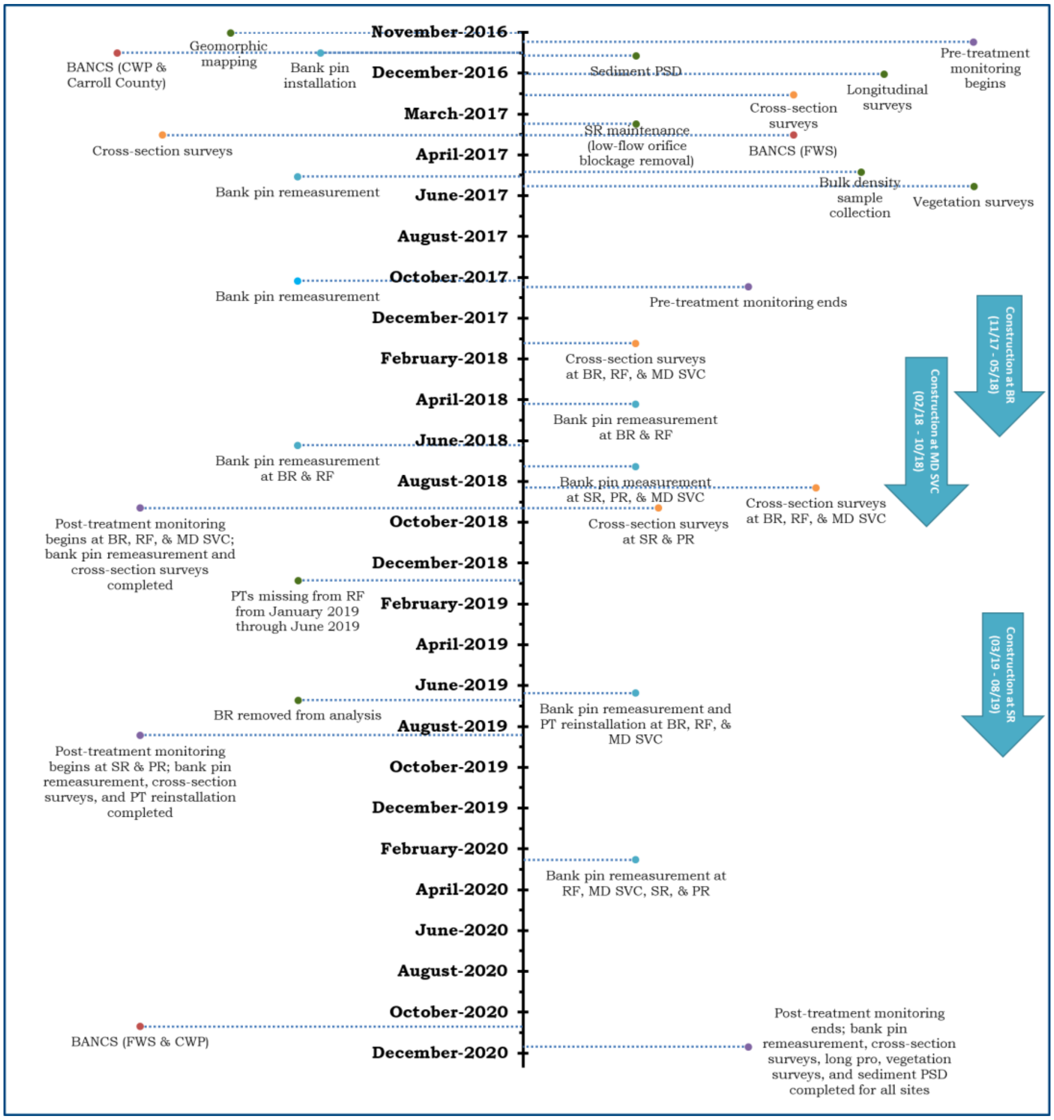

Figure 1. Timeline of key activities.

Abbreviation definitions for Figure 1: BANCS (Bank Assessment for Non-point Source Consequences of Sediment); BR (Blue Ridge); CWP (Center for Watershed Protection, Inc.); FWS (U.S. Fish & Wildlife Service); MD SVC (Central MD SVC); PR (Piney Ridge); PSD (Particle Size Distribution); PT (Pressure Transducer); RF (Robert's Field); SR (Shannon Run).

Study Site Description

The study area is located in Carroll County, MD in the Piedmont physiographic region (Figure 2). Five, first-order tributaries and their drainage areas were selected based on the following criteria:

- Treatment and Control sites have existing stormwater water management structure in drainage area designed to manage 2-year and 10-year storm events.
- Treatment sites were selected based on planned implementation of stormwater retrofits by Carroll County, MD to address channel protection volume (Cpv).
- The BMPs in the drainage area treat most of the runoff from the upstream impervious cover, leaving minimal uncontrolled runoff entering the stream channel.
- Channels have similar channel type, stream stability condition and evolutionary trend (e.g., Rosgen classification).
- Drainage areas are similar in size, location, and land cover characteristics.

All the selected study sites were classified as “F” stream types according to the Rosgen stream classification system and characterized as entrenched meandering riffle/pool channels on low gradients with high width/depth ratios. “F” stream channels can develop very high bank erosion rates, accelerated lateral migration, significant bar deposition and accelerated channel aggradation and/or degradation while providing for very high sediment supply and storage capacities. They are often observed to be working towards re-establishment of a functional floodplain inside the confines of a channel that is consistently increasing its width within the valley (Rosgen 1994, 1996). Images of the stream study reaches are provided in Figure 3.

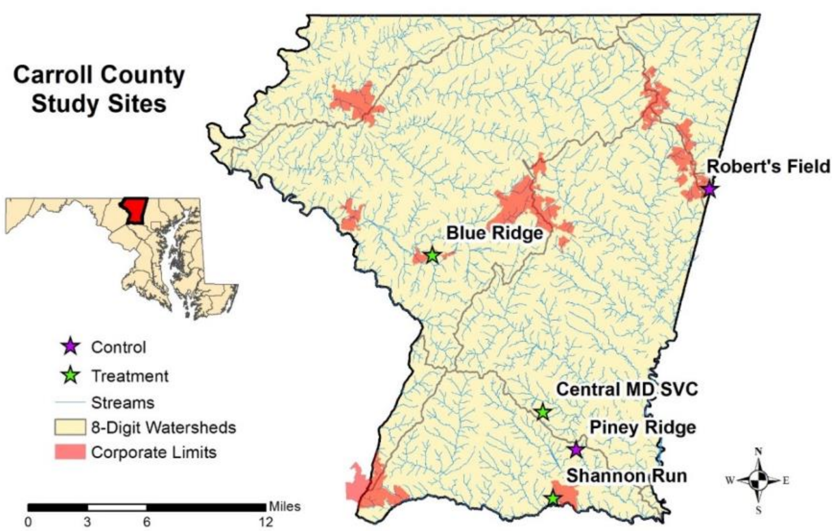

Figure 2. Map of stream monitoring sites in Carroll County, MD. Blue Ridge was removed as a study site due to failure of the sand filter retrofit.

Shannon Run (T)

Piney Ridge (C)

Central MD SVC (T)

Roberts Field (C)

Figure 3. Study site stream reaches (T = Treatment; C = Control).

Carroll County implemented stormwater retrofits at the treatment sites to provide channel protection volume. Table 2 provides the hydraulic discharge summary for the pre- and post-treatment conditions at the Shannon Run and Central MD SVC treatment sites. Central Maryland SVC is located at an industrial and commercial development that was constructed in the 1980's and was designed as a detention basin that does not provide any water quality treatment for the contributing runoff. The treatment consisted of a surface sand filter retrofit designed to provide water quality treatment up to 2.5" of runoff from the contributing impervious area. The existing dam was raised to provide adequate freeboard from the 100-year water surface elevation. The retrofit provides quantity management for up to the 25-year storm and safe conveyance of the 100-year storm (CLSI, 2019).

Shannon Run is in a residential subdivision and was designed as a wet pond that was constructed in the 1990's. The treatment consisted of a retrofit design that maintained the existing riser and barrel assembly and emergency spillway at their existing elevations. A new low-flow orifice was installed into the existing riser and the existing opening bulkheaded to meet the hydraulic requirements of the retrofit design included in Table 2 (CLSI, 2016).

Table 2. Treatment site hydraulic discharge summary								
	Central MD SVC				Shannon Run			
	Pretreatment Detention Basin		Post-Treatment Surface Sand Filter Retrofit		Pretreatment Wet Pond		Post-Treatment Wet Pond Retrofit	
	WSE[1]	cfs[2]	WSE[1]	cfs[2]	WSE[1]	cfs[2]	WSE[1]	cfs[2]
1-Year	672.42	7.3	673.48	1.3	453.95	41.40	453.28	4.1
2-Year	672.83	18.5	673.76	6.5	454.23	78.20	453.88	14.3
5-Year	673.34	52.4	674.08	32.4	-	-	-	-
10-Year	673.68	80.9	674.36	65.5	454.97	207.30	455.01	154.00
25-Year	674.13	126.1	674.71	122.5	455.58	343.00	455.78	329.60
50-Year	674.39	164.3	674.95	171.3	-	-	-	-
100-Year	674.49	227.3	675.12	213.4	456.64	527.70	457.02	528.80
[1]WSEL = water surface elevation (ft) *[2]cfs = discharge (cubic feet per second)*								

Hydrology and Hydraulics Data Collection and Methods

Continuous stage and discharge data were used to evaluate the runoff response and discharge in the stream channel because of BMP implementation. Measurement methods to quantify these parameters included precipitation, channel stage and ambient air pressure, and discharge. HOBOware Pro version 3.7.13 software was used to process the data obtained from the rain gauges and pressure transducers.

Stage

Three Onset HOBO pressure transducers (PTs) were installed in November 2016 at each of the three cross-sections of the study reaches to obtain a continuous record of stage during the pre- and post-treatment monitoring periods. Central MD SVC had four cross-sections, with PTs installed in three of the four cross-sections. The PTs were secured in a PVC housing mounted along one of the banks in each cross-section and extending down to the toe of the bank. Additional pressure transducers to monitor ambient air pressure were installed at the Blue Ridge study site (November 2016), with another one installed at Shannon Run to measure ambient air temperature in March 2017. This allowed for corrections in barometric pressure due to differences in altitude and temperature (CSGNetwork, 2017).

During the pretreatment period, manual adjustments to the PT water depth measurements were made at Blue Ridge and Piney Ridge due to scour below the PT or sediment deposition from bank slumping. This resulted in erroneous water depth measurements from the PT as scour sites showed near-zero depths, while an increase in water depths were measured relative to previous depths for similar flows for sites with sediment deposition. During the post-treatment period, the PTs were discovered missing from Robert's Field and Piney Ridge and are estimated to have been stolen sometime between January and March 2019. To replace the lost PTs and avoid additional loss, the PTs were reinstalled at all sites using a modified approach that involved securing a smaller PVC housing secured directly to the channel bed. This set-up was less visible compared to the initial setup with the PVC housing mounted along the streambank and was assumed would discourage theft. The PTs were reinstalled at Blue Ridge, Robert's Field, and Central MD SVC in June 2019 and at Piney Ridge and Shannon Run in August 2019. Similar to the pretreatment period, manual adjustments were made to the PT water depths to align stage before and after the PT reinstallation occurred. Appendix B provides the dates, locations, and adjustments.

Discharge

Stream discharge was estimated based on discrete flow measurements in the stream channel using a Flowtracker ADV. Flow rating curves for each of the treatment and control study sites were developed based on the stage and discharge data for the most stable cross-section at each study site that produced the best fit of a trendline through the data. The flow rating curves were then used to extrapolate discharge to the continuous record of stage measurements recorded by the PTs.

The discharge measured at all the cross-sections at each study site were compiled into the one representative cross-section for each site to compensate for the small number of storm events. The cross-sections included Robert's Field XS2 Central MD SVC XS1, Piney Ridge XS1, and Shannon Run XS1. The discharge and start time of measurements at the other cross-sections were incorporated into the plot of the representative cross-section, where the start time of measurement was used to adjust the corresponding stage based on the representative cross-section.

The discharge from Shannon Run was impacted due to a blockage at the low flow orifice during part of the pretreatment period. Consequently, discharge data for this site was supplemented with calculated estimates of discharge using the stage located on the pond riser and pond hydraulics. Stage at the pond riser was obtained by relocating the PT originally installed at cross-section 2 to the pond riser. The pretreatment data used for this site and its control (Piney Ridge) was split into two separate relationships: one before the blockage (11/13/2016 - 3/4/2017) and one after the blockage (6/11/2017 - 10/2/2017). The relationship after the blockage was used for the pre-treatment period and compared with the post-treatment period results.

Rainfall

Local rainfall was monitored at three of the study site locations using HOBO Onset rain gauge and data loggers (Blue Ridge, MD Central SVC, and Robert's Field). The Central MD SVC gage is proximate to Shannon Run and Piney Ridge and considered representative for all three of these study sites. The rain gauges recorded every 0.01 inch of rainfall and the associated time. During the study period, there were some gaps where the gages malfunctioned and did not collect data. Daily rainfall from Westminster, MD was used as supplemental information to fill in the data gaps to create a continuous period of record.

Storm Event Metrics

Analyses was also completed to evaluate change in stream hydraulics using selected storm metrics (e.g., changes in total volume, peak flows rates and stream energy) (Andrade and Estévez-Pérez, 2014). Low and high flow variability metrics were calculated from the average daily discharge (m^3/s) to characterize and compare stream hydraulics across the paired study sites (Dingman 1993). Low flow variability was calculated by determining the flow exceedance ratio of the 50% and 90% flows (Q_{50}/Q_{90}). High flow variability (flashiness) was calculated by determining the flow exceedance ratio of the 10% and 50% flows (Q_{10}/Q_{50}). Low and high-flow variability metrics that are closer to 1 infer less variability. Pretreatment storm event metrics were calculated for Central MD SVC and Robert's Field for the period 11/13/2016 – 10/19/2017. Pretreatment storm event metrics were calculated for Shannon Run and Piney Ridge for the period after the weir blockage was removed at Shannon Run (6/11/2017 – 10/19/2017). During the post-treatment period, storm event metrics were calculated for Central MD SVC and Robert's Field for the period 10/31/2018 – 12/3/2020. Post-treatment storm event metrics were calculated for Shannon Run and Piney Ridge for the period 8/31/2019 – 12/3/2020.

Runoff Response Relationship

The effect of treatment on the runoff response from the watershed was evaluated based on the change in slope of the regression for the pre-and post-treatment runoff response and change in runoff curve numbers (RCN). Runoff is expressed as a depth and is standardized for each study site by dividing the discharge by the catchment area. While the runoff response reflects how the control and treatment watersheds respond across a wide range of paired storm events, the runoff curve number reflects how the watershed responds to relatively large storm events.

To compare the runoff response between treatment and control sites, daily rainfall and runoff data for each site were aggregated into multi-day events, using the following set of rules: 1) an event may span multiple days, 2) any day with rainfall greater than 0.1 inches is part of a rainfall event and 3) since the runoff response may be delayed, the total runoff response includes the sum of all days where rainfall exceeded 0.1 inches, plus the following day. The rainfall for these paired events for treatment and control sites were then plotted to compare the relationship between the control and treatment sites during the pre-treatment and post-treatment periods for two metrics: the runoff depth (cm) and the peak discharge (m^3/s).

The relationships of runoff depths and peak discharges between treatment and control watersheds was developed using least squares regression. For both the pre- and post-treatment periods, the regression was ensured to be statistically significant by evaluating the regression's p-value and ensuring that the regression met the basic assumptions of a linear model. An analysis of covariance (ANCOVA) was used to compare line slopes between pre-treatment and post-treatment periods.

Change in the RCN was also used to evaluate the effect of the treatment on the runoff response from the watershed. The curve number method is a simple, widely used method for determining the approximate amount of runoff from a rainfall event. Although the method is designed for a single storm event, it can be scaled to find average annual runoff values. Baseflow separation of the total discharge at each site was required to calculate the storm flow for this calculation, where the total discharge minus baseflow was considered storm flow. Baseflow was defined as the 5-day minimum antecedent flow using a method described by Jordan et al. (1997). Computation of the curve number is based on the following equation.

$$CN = \frac{2540}{5\left[P + 2Q - \sqrt{Q(4Q + 5P)}\right] + 25.4}$$

Where CN is curve number, P is precipitation (cm), Q is runoff (cm), and initial abstraction was assumed to be 0.2 times potential retention, which is a common assumption (Christianson et al., 2016), although research is finding this value should be much smaller (Woodword et al., 2003) especially for urban watersheds (Krajewski et al., 2020).

Curve number values were adjusted for initial soil moisture based on 5-day antecedent rainfall criteria referenced in Chow et al. (1988). That is, a higher RCN is calculated when antecedent soil moisture is higher, or wet; compared to drier conditions[1].

$$CNII = \frac{10\ CN1}{4.2 + 0.058CNI}$$

$$CNII = \frac{10CNIII}{23 - 0.13CNIII}$$

Where CNII represents normal moisture conditions, CNI is dry, and CNIII is wet. Conversion back to normal conditions allows comparison of CN values regardless of soil moisture at the time of a storm.

Curve numbers were calculated for each site for rain events greater than 1-inch (2.5cm). It has been noted in research that estimating curve number values from smaller storms is generally not accurate (Suresh Babu & Mishra, 2012; Christianson et al., 2016). In addition, only rainfall data from the installed gauges were used. Rainfall data from the Westminster Airport station used to fill in the missing gaps in gauge data was excluded because it may not accurately represent rainfall at a given site, which would misrepresent the relationship between rainfall and runoff. Storm events greater than or equal to 1-inch were identified based on the rainfall record of the three rain gauges. The cumulative rainfall for an individual event was based on start and end times for a rainfall event. This may occur within an hour or span 2 days of continuous rainfall.

Channel Stability

To evaluate channel stability, the frequency of bankfull flow exceedance was compared both before and after treatment at both control and treatment sites. Rate of flow at bankfull was estimated using Manning's Equation[2]:

$$Q = \frac{1.49 \times A \times R^{2/3} \times S^{1/2}}{n}$$

Where:

Q	=	Flow (cfs)
A	=	Channel Area (sf)
R	=	Hydraulic Radius (ft)
S	=	Slope
n	=	Manning's n

Bankfull depth was estimated in the field for the pre-developed condition using field indicators, and RiverMorph software was used to calculate stream geometry at bankfull, including the Hydraulic Radius (R) and the Channel Area (A) at reaches where flow was estimated from pressure transducer data

[1]http://www.utdallas.edu/~brikowi/Teaching/Applied_Modeling/SurfaceWater/LectureNotes/Travel_Time/Antecedent_Rainfall_Limits.html#f-antecedent

[2] Manning's equation is presented in SI Units. In practice, data were a combination of SI and Metric units, and flow was calculated in cubic meters.

(Reach 1 for Central MD SVC, Shannon Run and Piney Ridge, and Reach 2 for Robert's Field). The field-measured bankfull channel dimensions (i.e., width, depth, and cross-sectional area) were compared to the U.S Fish and Wildlife Service (USFWS) Piedmont Regional Curve (USFWS, 2002) to ensure the appropriate bankfull feature was identified. Bankfull indicators were assumed to be the same during the post-construction period. Further, site-specific channel slope (S) was estimated at these locations using estimated channel surface elevations from RiverMorph. Manning's n was estimated using the methods described in Arcement and Schneider (1989). In this method, the "base" n value is calculated using the Limerinos equation:

$$n = \frac{0.0926 \times R^{1/6}}{1.16 + 2.0 \times \left(\frac{R}{d_{84}}\right)}$$

Where:

D_{84} = The 84th percentile diameter particle in ft.

Further adjustments were made to this initial n value to account for Channel irregularity and Channel Obstructions, using guidance in Arcement and Schneider (1989).

Geomorphological Data Collection and Methods

The stream channel is defined as the path for water and sediment flowing within the streambanks up to the top of banks. For the purposes of this study, stability is operationally defined by measuring channel adjustments through data collected by changes in cross-sections and longitudinal profiles in response to changes in flow.

Data to support an assessment of the stream geomorphic functions included: channel evolution, lateral stability, floodplain connectivity, riparian vegetation, and bed material characterization (Harman et al., 2012). Measurement methods to quantify these functions included: cross-sections, longitudinal profiles, bank pin surveys, streambed particle size distributions, and riparian vegetation assessment. Data generated was used to evaluate the lateral rate of channel migration. In addition to these measurements, a geomorphic map created in November 2016 of each of the study reaches (Appendix C) provides qualitative data documenting the stream and riparian conditions that may influence results from the other monitoring procedures described below.

Bulk Density

Bulk density samples were collected on June 26, 2017. A total of three samples were taken at each cross-section location representing the lower (below bankfull), middle (just above bankfull), and upper extents of the banks. Samples were taken only from one bank at each cross-section, either left bank or right bank, and only the sides where erosion was evident. For example, samples were collected on the outer meander bend as opposed to the inside bend where deposition was occurring. Samples were collected from alternating left and right banks at each study site. The samples were analyzed by Waypoint Analytical in Richmond, Virginia using Methods of Soil Analysis, Part 3, Chemical Methods, 2nd ed. Rev. Soil Science of America.

Bed Sediment Particle Size Distribution

Pebble counts were used to generate bed sediment particle size distributions following the methodology of Wolman (1954). At each cross-section 150 individual pebbles were obtained from the streambed by walking heel to toe across the bankfull channel width and selecting the particle at the toe of the boot. The particles were measured using a gravelometer to classify them into half phi unit size classes. Although measurement with a gravelometer may not accurately account for particles that have one axis much larger than the other two, it provided an expedited method for collecting the data and helped to reduce operator error in the measurements. Pebble counts were conducted in December 2016 during the pretreatment period.

Cross-Section Surveys

Three rebar-monumented cross-sections were installed at each study site except for Central MD SVC, which has four cross-sections. The cross-sections were installed in representative areas of each study site based on the geomorphic mapping and included riffles, pool, runs, and glides. Cross-sections were completed at each study site at the beginning and end of both the pretreatment and post-treatment periods (Table 3).

Table 3. Cross-sectional surveys of study sites.

Study Site	Pretreatment Start Survey	Pretreatment End Survey	Construction Period	Post-Treatment Start Survey	Post-Treatment End Survey
Shannon Run (T)	Feb/Apr 2017	Oct 2018[1]	Phase 1: pond dredging July 2017 Phase 2: March 2019 – August 2019	Sept 2019	Dec 2020
Piney Ridge (C)	Feb/Apr 2017	Oct 2018[1]	N/A – Control Site	Sept 2019	Dec 2020
Blue Ridge (T)	Feb/Apr 2017	Feb 2018	Nov 2017- May 2018	N/A – removed from analysis	N/A – removed from analysis
Robert's Field (C)	Feb/Apr 2017	Feb 2018	N/A - Control Site	Oct 2018	Dec 2020
Central MD SVC (T)	Feb/Apr 2017	Feb 2018	Feb 2018-Oct 2018	Oct 2018	Dec 2020

The initial baseline cross-sections (start of pretreatment) were done with a rod and transit level and all subsequent surveys were done with a total station. Shannon Run cross-sections were first surveyed December 2016, with the remainder of the sites surveyed in February 2017.

WinXSPRO Version 3.0 from the United States Department of Agriculture (USDA) Forest Service was used to measure the changes in channel dimension, including the area of erosion, deposition, and net channel area change for the left bank, right bank, and channel bottom. Bank changes represent the area of change between the top of bank and toe of slope, where the toe was determined based on visual observation of the plotted cross-section, as well as notes recorded during the cross-section surveys. Average bank erosion rates were calculated by dividing the eroded bank area by the bank height for each cross-section. Figure 4 shows an example of the division between the left bank, right bank, and channel change areas.

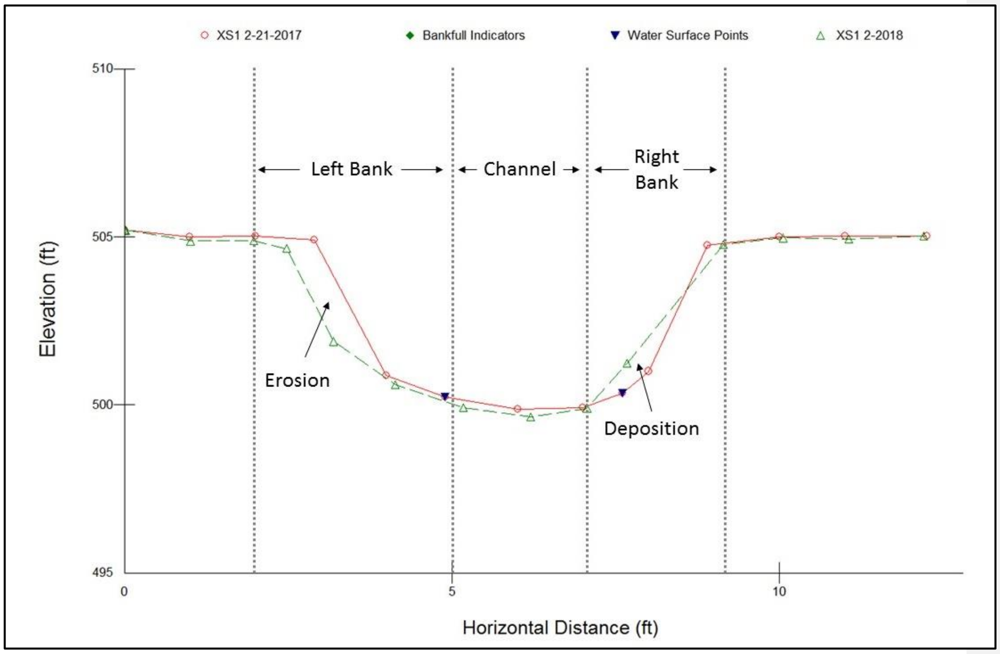

Figure 4. Cross-section change division between the left bank, right bank, and channel change areas.

Changes in cross-section area were calculated for both bankfull depth and total channel area extending to the top of bank. Area was calculated using RiverMorph and estimates of bankfull depths were obtained from the BANCS assessments. Bankfull field indicators were difficult to determine in the study reaches. As such, bankfull was approximated as 1 foot above the toe of slope for Central MD SVC, Shannon Run, and Piney Ridge. Bankfull depth was approximated as 0.8 feet above the toe of slope for Robert's Field. These bankfull depths were based on the USFWS Piedmont Regional Curve (USFWS, 2002) to ensure the approximate depths were appropriate. The same bankfull elevations at each cross-section were used for both the pre and post-treatment cross-section area calculations. The area of change was divided by the monitoring period length (in years) for the pre- and post-treatment periods to normalize the percentage of change that occurred on a per-year basis.

Longitudinal Profile Surveys

Longitudinal profile surveys were conducted using a total station during the pre- and post-treatment periods for each study site. Pretreatment surveys were completed in January and February 2017 and post-treatment surveys were conducted December 2020 – February 2021. During the pretreatment monitoring period, the wet pond at Shannon Run was dewatered from March 24 – March 31, 2017 to conduct maintenance for the low flow orifice blockage. A limited resurvey of the Shannon Run longitudinal profile was conducted in October 2017 that included the thalweg and water surface that was used as the pretreatment condition instead of the previous survey.

The longitudinal profile survey extents were monumented with a pair of rebar monuments (1 each side of the stream) installed at the upstream and downstream end of the study sites to replicate the measurements. The data from the two time periods were compared to determine changes in water surface slope and qualitatively identify system-wide changes, including degradation and aggradation of the channel bed.

Bank Pins

Bank pin installation and measurement followed the protocol for bank profile measurements in Rosgen (2014). Pins were installed at 4 locations in Blue Ridge, 5 in Central MD SVC, 3 in Robert's Field, and 6 in Shannon Run and Piney Ridge in December 2016. The timeline for pre- and post-treatment bank pin measurements is provided in Table 4. Locations were chosen to represent a range of Bank Erosion Hazard Index/Near Bank Stress (BEHI/NBS) scores from the BANCS assessment and were installed in locations other than the monumented cross-sections. The bank pins were installed horizontally into the streambank at 3 positions along the bank profile: below bankfull depth, just above bankfull depth, and mid to top of bank. Average bank erosion rates were calculated in RiverMorph (Stantec, 2013), which generates bank profiles from the bank pin data. Subsequent bank profiles are overlain to calculate the area of bank erosion and average bank erosion rate.

Table 4. Bank pin surveys of study sites.

Study Site	Pretreatment Pin Installation	End of Pretreatment Bank Pin Measurement	Construction Period	Start of Post-Treatment Bank Pin Measurement	End of Post-Treatment Bank Pin Measurement
Shannon Run (T)	Dec 2016	Nov 2017	Phase 1: pond dredging July 2017 Phase 2: March 2019 – August 2019	Aug 2019	Dec 2020
Piney Ridge (C)	Dec 2016	Nov 2017	N/A – Control Site	Aug 2019	Dec 2020
Blue Ridge (T)	Dec 2016	Nov 2017	Nov 2017- May 2018	N/A – removed from analysis	N/A – removed from analysis
Robert's Field (C)	Dec 2016	Nov 2017	N/A - Control Site	Oct 2018	Dec 2020
Central MD SVC (T)	Dec 2016	Nov 2017	Feb 2018-Oct 2018	Oct 2018	Dec 2020

BANCS Assessment

The "Bank Assessment for Non-point Source Consequences of Sediment" or BANCS method (Rosgen, 2001; Doll et al., 2003) was used to estimate the total erosion potential from the study reaches. These estimated rates of erosion are compared to rates of erosion derived from field measurements using bank pins and cross section surveys.

Riparian Vegetation

Riparian vegetation was assessed in June 2017 and November 2020 at the end of the pretreatment and post-treatment periods, respectively, to characterize the function of buffers to support stream geomorphic function. The United States Fish and Wildlife Service (USFWS) Riparian Buffer Vegetation Evaluation Methods from the USFWS Chesapeake Bay Field Office were used (USFWS, 2013). This assessment included:

- Canopy coverage
- Stand density
- Regeneration
- Species composition
- Vegetative distance from stream

Sediment Loading Estimation

Total suspended solids (TSS) load estimates were calculated based on the results of the BANCS assessment and the TMDL Credit Reduction Workbook for Protocol 1 of the Recommendations of the Expert Panel to Define Removal Rates for Individual Stream Restoration Projects (Schueler & Stack, 2014; USFWS CBP Office & EPR, 2017; Wood, 2020). The average measured bulk density at each site was used. A sediment delivery factor and restoration efficiency were not applied in order to calculate the total edge-of-stream load as opposed to an estimated credit from stream restoration. The estimated sediment loads attributed to stream erosion based on the TMDL Credit Workbook were then compared to measured rates of erosion.

Monitored rates of erosion from bank pins and cross-sections were estimated from the bank height at the monitoring site, estimate of the reach length represented by the monitoring location, and the average measured bulk density of the study site. Reach length represented by the monitoring location was approximated based on the location of the monitoring locations in relation to the BANCS delineated reaches. When a monitoring location was located within a BANCS assessed reach, it was assumed that the monitoring location was representative of conditions that along the length of that BANCS reach.

Results

The results are presented based on the research hypotheses with complete data records provided in the report appendices.

Hydrologic and Hydraulic Assessment

The following results relate to Hypothesis 1: *"The implementation of BMPs retrofitted to meet Carroll County's sand filter design standard will modify the runoff response from the watershed (hydrograph) resulting in a reduction of the magnitude, duration and frequency of erosive flow rates that meet and or exceed MDE performance standards for stream channel protection."*

The total annual rainfall during the pretreatment period was similar to, but slightly lower when compared to the 30-year climate normal average annual rainfall (Table 5). The post-treatment period average annual rainfall was higher than the long-term average. Because of the limited pretreatment period (12 months), there were greater opportunities to collect data during the post-treatment period (26 months at Central MD SVC and Robert's Field; 16 months at Shannon Run and Piney Ridge). Discrete flow measurements for three storm events were measured during the pretreatment period, with an additional four-six baseflow measurements (Table 6). Eleven additional storm event discharge measurements for Shannon Run were calculated based on pond hydraulics between May 25 and August 15, 2017 based on the stage recorded with the pressure transducer located on the pond riser. During the post-treatment period, 7 additional discrete storm events were measured at Shannon Run and Piney Ridge, as well as 10 storm events at Central MD SVC and 13 storm events at Robert's Field. Each of four study sites were very responsive to rainfall events as shown by the change in stage and discharge measurements. An example of the continuous stage and rainfall with discharge measurements is shown in Figure 5 for the Central MD SVC site. Appendix D provides similar plots for all study sites with the date and number of discharge measurements taken during pretreatment and post-treatment periods provided in Table 6.

Table 5. Average annual precipitation[1] during pretreatment monitoring period (November 2016 – November 2017), post-treatment monitoring period (August 2019 – December 2020 Shannon Run and Piney Ridge; October 2018 – December 2020 Central MD SVC and Robert's Field), compared to the long-term average.

Average Annual Precipitation (in)		
Pretreatment Period	**Post-Treatment Period**	**1981-2010 Climate Normal**
39.46	49.98 (Central MD SVC, Robert's Field) 49.67 (Shannon Run, Piney Ridge)	41.9

[1]Annual precipitation data retrieved from: https://www.weather.gov/media/lwx/climate/bwiprecip.pdf.

Table 6. Summary of discharge measurements at each study site (T = treatment site; C = control site).

Study Site	**Number of Discharge Measurements**	**Period of Record**
Pre-Treatment Period		
Central MD SVC (T)	4 Baseflow, 3 Storm	1/18/2017 - 10/9/2017
Shannon Run (T)[1]	6 Baseflow, 3 Storm	1/19/2017 – 7/21/2017
Robert's Field (C)	4 Baseflow, 3 Storm	1/18/2017 - 10/9/2017
Piney Ridge (C)	6 Baseflow, 3 Storm	1/19/2017 – 7/21/2017
Post-Treatment		
Central MD SVC (T)	10 Storm	12/15/2018 – 10/29/2020
Shannon Run (T)	7 Storm	12/10/2019 – 11/12/2020
Robert's Field (C)	13 Storm	5/18/2018 – 10/29/2020
Piney Ridge (C)	7 Storm	12/10/2019 – 11/12/2020

[1]Discharge data for this site was supplemented with calculated estimates of 11 additional discharge measurements using the stage located on the pond riser.

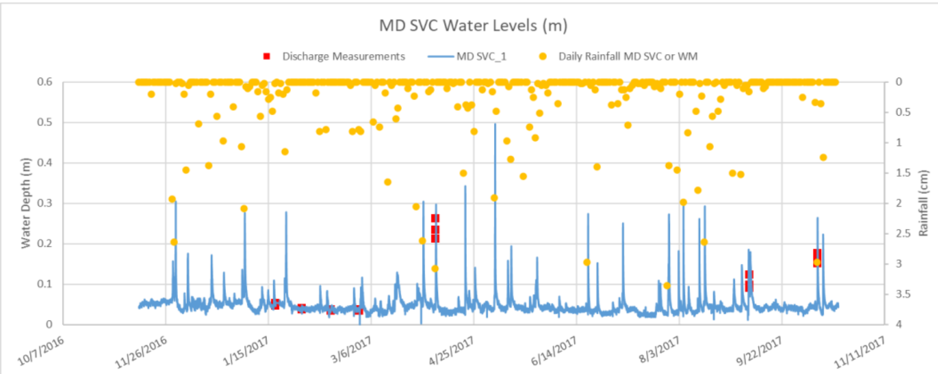

Figure 5. Central Maryland SVC stage, rainfall, and discharge measurements during the pretreatment period.

A statistically significant regression of measured stage and discharge was used to generate flow rating curves for each site. A linear relationship was used to represent stage-discharge at all sites except for Central MD SVC. While a non-linear relationship is more typical, a linear relationship was chosen because the rainfall and corresponding discharge and stage measurements were not representative of high-flow or large storm events. Figure 6 provides an example of a flow rating curve linear relationship for Piney Ridge and Figure 7 provides the flow rating curve with power function relationship for Central MD SVC. The flow rating curves for all the sites are provided in Appendix E.

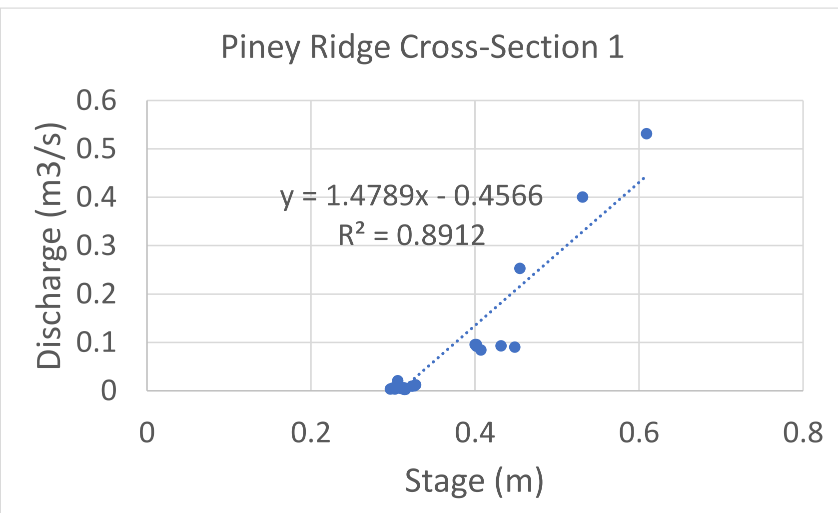

Figure 6. Piney Ridge cross-section 1 flow rating curve linear relationship.

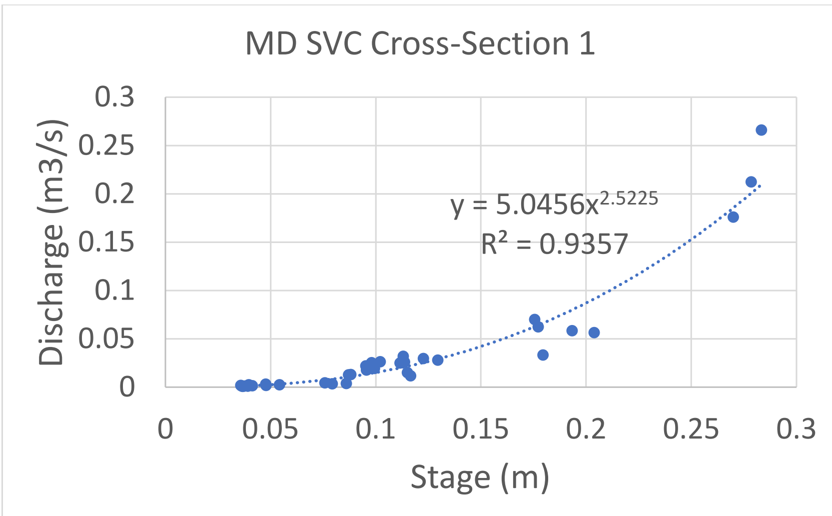

Figure 7. Central Maryland SVC cross-section 1 flow rating curve power function relationship.

The flow rating curves were used to translate the continuous record of stage at each site into a continuous record of discharge. The flow rating curve for Piney Ridge generated negative discharges for some of the lower recorded stages due to negative intercepts for the stage-discharge linear regression. The negative discharges were corrected by assigning a minimum discharge because the site is perennial and had continuous flow. The minimum discharge was calculated as the average discharge measured during baseflow conditions (0.005 m^3/s) to account for the slight variability in discharge measurements during these lower recorded stages.

Storm event metrics were estimated using the monitoring data at the control and treatment sites. The metrics evaluate total volume, peak flows rates, and stream energy (e.g., flashiness index; Table 7). The average daily peak flow rate decreased during the post-treatment period at the treatment sites and increased at the control sites. Average daily total flow increased at all the sites except for Shannon Run. The treatment sites had an increase in low flow variability, while the control sites had a decrease. All the sites had an increase in high flow variability. Note the increase in post-treatment daily total flow in both for Central MD SVC, Piney Run, and Robert's Field are due to a much wetter period (39.5 inch average annual rainfall during the pretreatment period compared to 50 inches during the post-treatment period) according to regional rainfall data collected at BWI airport (Table 5).

Table 7. Storm event metrics.								
Study Site	**Average Daily Peak Flow Rate (m^3/s)**		**Average Daily Total Flow (m^3/day)**		**Low Flow Variability**		**High Flow Variability (Flashiness)**	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
Piney Run[1] (C)	0.0276	0.0365	965	1,467	1.06	1.01	5.23	9.31
Shannon Run[1] (T)	0.0256	0.0154	1,101	746	1.15	1.24	1.22	1.35
Robert's Field (C)	0.0117	0.0170	404	740	1.51	1.15	1.56	5.41
Central MD SVC (T)	0.0182	0.0142	348	486	2.00	3.06	4.13	6.32

[1]Pretreatment storm event metrics are for the period after the blockage was removed at Shannon Run (6/11/2017 – 10/19/2017).

Runoff Response Relationship

The effect of treatment on the runoff response from the watershed was evaluated based on the change in slope of the regression for the pre-and post-treatment runoff relationships and change in runoff curve numbers (RCN). The runoff relationships reflect how the control and treatment watersheds respond across a wide range of paired storm events. Results of pre-and post-treatment regressions for all paired treatment and control watersheds (Figure 8) suggest that the slope decreased (i.e., the treatment watershed did not have as much runoff) after the pond retrofits were installed. This graph does not include the full range of data recorded, however, because the post-treatment period included events with larger runoff volumes, and some influential outlier points. Consequently, the data were limited so that the pre- and post-treatment periods included the same range of runoff depths in the control watersheds during both periods. Appendix F includes plots of the full dataset, as well as a description of how the data were limited.

The ANCOVA results for this limited data set confirm that the slopes are significantly lower at the lower than 5% significance (Table 8; see model output in Appendix F). The results of the same analysis for the peak discharge are summarized in Figure 9 and Table 8, with details of the analysis described in Appendix F. Overall, the results were similar except for the pairing between Robert's Field and Shannon Run, where both the pre- and post-treatment relationships were not as strong, and the change in slope was barely significant at the 5% level (p-value of 0.043).

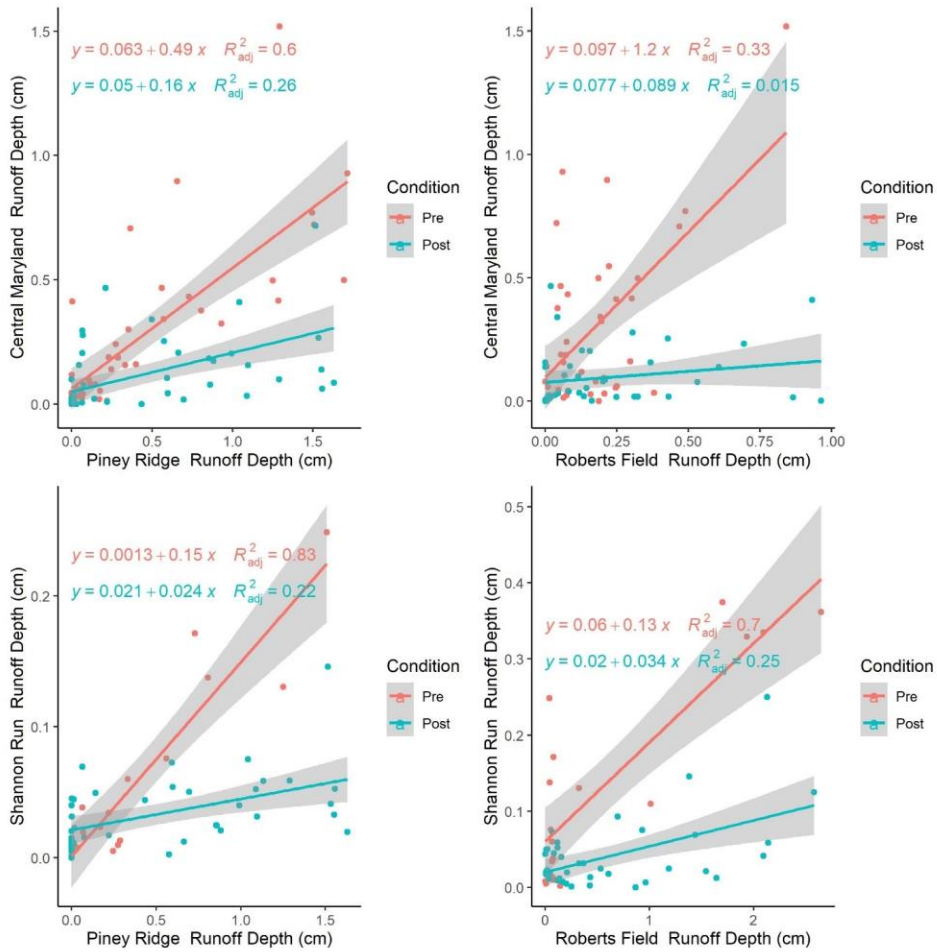

Figure 8. Pre-versus post-treatment runoff relationships between control (x-axis) and treatment (y-axis) watersheds.

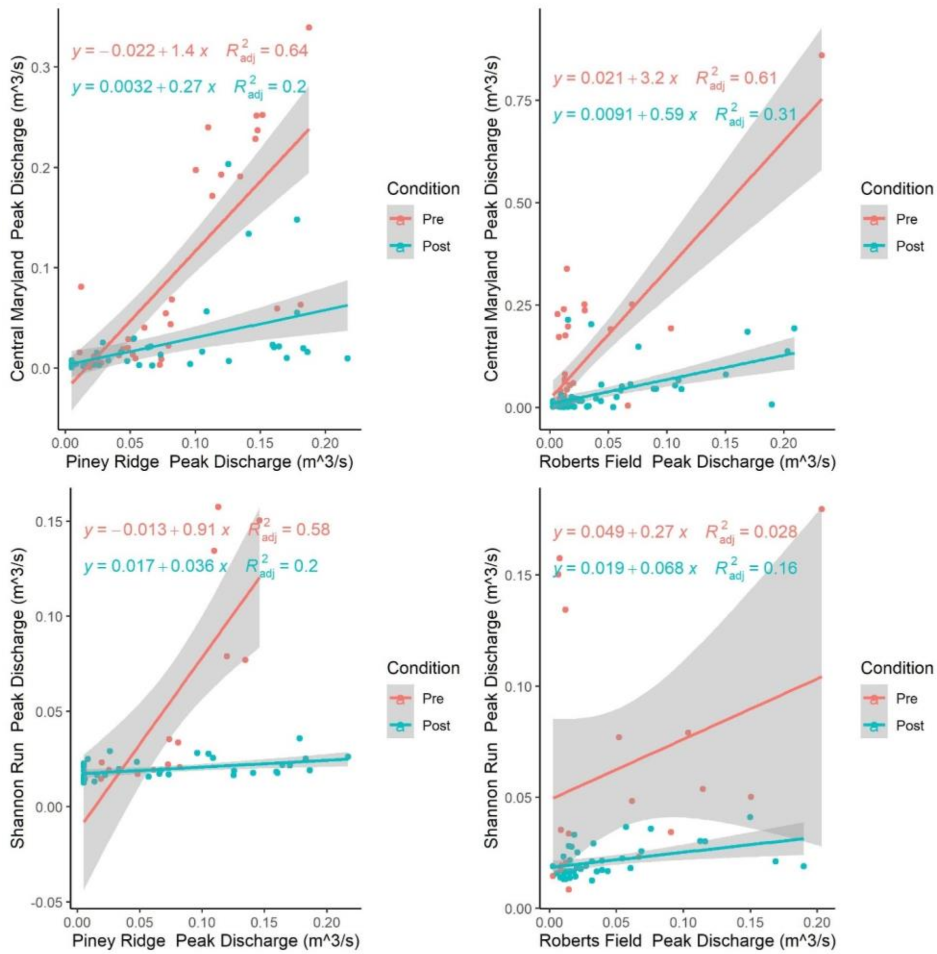

Figure 9. Pre-versus post-treatment peak discharge relationships between control (x-axis) and treatment (y-axis) watersheds.

Table 8. Comparison of regression slopes between pre-and post-treatment conditions.[1]				
Paired Project Sites	**Pre-treatment Slope**	**Post-Treatment Slope**	**Change**	**Significance of Change (p-Value)**
Runoff Depth (cm)				
Central MD SVC (T) – Robert's Field (C)	1.2	0.089	-1.09	<0.001
Shannon Run (T) – Robert's Field (C)	0.13	0.034	-0.10	<0.001
Central MD SVC (T) – Piney Ridge (C)	0.49	0.16	-0.33	<0.001
Shannon Run (T) – Piney Ridge (C)	0.15	0.024	-0.13	<0.001
Peak Discharge (m^3/s)				
Central MD SVC (T) – Robert's Field (C)	3.2	0.59	-2.56	<0.001
Shannon Run (T) – Robert's Field (C)	0.27	0.068	-0.20	0.043
Central MD SVC (T) – Piney Ridge (C)	1.4	0.27	-1.11	<0.001
Shannon Run (T) – Piney Ridge (C)	0.91	0.036	-0.87	<0.001

[1]Uses a limited set of data (See Appendix F for Model Results and data limitations).

Change in the RCN was also used to evaluate the effect of the treatment on the runoff response from the watershed. The number of storm events greater than 1 inch (2.5 cm) used in the RCN analysis varied at each study site from three at Shannon Run during the pretreatment period to 24 at Robert's Field during the post-treatment period. The storm events and corresponding RCN calculations for all sites are included in Appendix G and depicted in Figure 10. The average RCNs for each study site are provided in Table 9.

Table 9. Measured curve number comparison to the theoretical predevelopment, post development, and retrofit design curve numbers.

Study Site	**Calculated "Woods in Good Condition" RCN[1]**	**Calculated Pre-development RCN[1]**	**Calculated Post development RCN (Pre-treatment BMP)[2]**	**Measured Pre-treatment Average Calculated RCN (# Storms)[3]**	**Calculated Retrofit Design: 1-yr RCN Reduction[4]**	**Calculated Retrofit Design: 2-yr RCN Reduction[4]**	**Measured Post-Treatment Average Calculated RCN (# Storms)[5]**
Central MD SVC (T)	68	69	84	89.0 (5 storms)	44	54	65.5 (17 storms)
Robert's Field (C)	N/A	60	75	74.6 (6 storms)	N/A	N/A	81.6 (24 storms)
Shannon Run (T)	58	60	72	84.83 (3 storms)			65.58 (5 storms)
Piney Ridge (C)	N/A	60	75	87.31 (4 storms)	N/A	N/A	91.01 (8 storms)

[1]Calculated based on the hydrologic soil group and drainage areas provided in CLSI (2019) and CLSI (2016) and the "woods in good condition" RCNs from the MD Stormwater Design Manual (MDE, 2010).
[1] Predevelopment condition indicates woods and meadows. Predevelopment RCNs were obtained from Carroll County.
[2]Post-development RCN (pretreatment BMP) indicates the RCN for the existing ponds during the pretreatment period. RCNs were obtained from the County. The Shannon Run and Central MD SVC post-development RCNs are weighted averages based on a subarea curve number analysis from CLSI (2019) and CLSI (2016).
[3]Pretreatment average RCN was calculated based on storms ≥ 1-inch during the pretreatment period.
[4]Retrofit design RCN was obtained from Carroll County.
[5]Post-treatment average RCN was calculated based on storms ≥ 1-inch during the post-treatment period.

Commented [LFM1]: Retrofit design 1-yr and 2-yr RCNs for Shannon Run to be inserted here.

The data suggest that the control watersheds (Robert's Field and Piney Ridge) both show an increasing RCN, and the treatment watersheds (Central MD SVC and Shannon Run) show a substantial decrease in RCN. A visual inspection of the data (Figure 10) suggest a similar pattern. The post-treatment calculated average RCN for Central MD SVC is slightly lower and Shannon Run is slightly higher than the "woods in good condition" performance standard from MDE (2010). It is not possible to draw a conclusion from these data with confidence, however, due to two confounding variables. The first is that the number and range of events was different between the pre- and post-treatment periods, and the data suggest that lower curve numbers are predicted for higher runoff volumes (e.g., between at Robert's Field and Shannon Run for runoff depths over 6 cm). Another potential confounding variable is the antecedent moisture condition (AMC), which is calculated based on the rainfall in the days preceding a rainfall event. Using the calculation methods described to back-calculate the curve number, events with low antecedent moisture (AMC1) appear to have the highest calculated curve numbers (Figure 10), with values decreasing as the AMC value increases. This effect, combined with an unequal distribution of AMC conditions in the predevelopment condition, result in very few points with which to directly compare the curve number results.

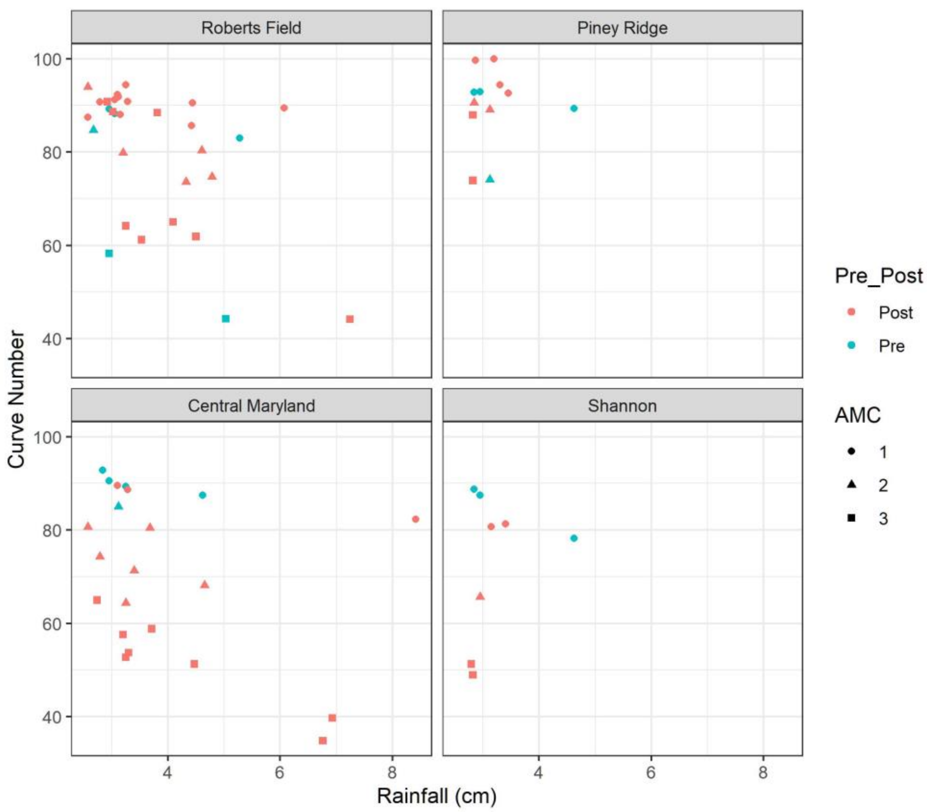

Figure 10. Storm event calculated curve numbers.

Channel Stability

The Shannon Run and Central Maryland SVC retrofits substantially reduced the pre-retrofit discharges over a range of flow rates. The exceedances of the critical velocity across these storms as shown in Hawley et al. (2017) and Hawley et al. (2019) could not be done without additional pebble count and storm flow data. To evaluate channel stability, the number of peak discharges observed above the bankfull rate of discharge were compared between the pre- and post-treatment monitoring periods. Using Manning's equation, the bankfull rate of discharge was computed for each cross-section where the peak discharge was measured. Next, the number of events where bankfull flow was exceeded in each condition was summarized using paired peak discharge data. The results (Table 10) indicate that the bankfull discharge was not exceeded at any site during the pre-treatment period, but there were a few exceedances in the post-treatment period, with most of the exceedances at Piney Ridge, and none at Shannon Run. These few data points may anecdotally point to a decreased rate of bankfull discharge and accompanying shear stress in treatment watersheds, but insufficient data are available to draw conclusions with confidence.

Table 10. Bankfull discharge calculations and number of exceedances.								
	Channel Characteristics from RiverMorph			Field Data	Calculated Data		Number of Events Exceeding Discharge	
	Channel Area (sf)	Hydraulic Radius (ft)	Channel Slope	D_{84} Particle size (mm)[2]	Estimated Manning's n[1]	Calculated Bankfull Discharge (m^3/s)	Pre-treatment	Post-Treatment
Robert's Field (C)	4.7	0.54	0.03961	92.01	0.062	0.42	0	1
Piney Ridge (C)	6.4	0.72	0.00701	77.12	0.051	0.35	0	3
Shannon Run (T)	23.5	1.09	0.02255	109.8	0.053	2.97	0	0
Central MD SVC (T)	8.1	0.89	0.01778	62.78	0.046	0.91	0	1

[1]The estimated value is calculated based on Hydraulic Radius and particle size and includes an adjustment factor of 0.008 for channel irregularity at all sites, 0.002 for obstructions at all sites except Robert's Field, which had an adjustment factor of 0.005 for obstructions.

[2]To avoid influence of the bimodal particle size distribution related to fine sediment, the D_{84} particle size was calculated excluding particles <2mm measured during the pebble counts.

Geomorphological Assessment

The following results relate to Hypothesis 2: "*The implementation of BMPs as retrofits will create hydraulic conditions that lead to self-recovery of channel stability*."

Bulk Density

A total of 39 bulk density samples were taken for stream banks from all study sites with values ranging from 44.95 to 72.42lb/ft^3 with an average bulk density value of 56.3 lb/ft^3. A summary of the bulk density values for each of the sites is provided in Table 11. These measured bulk densities are comparable to bulk density measurements from other projects across Virginia, Maryland, and Pennsylvania.

Table 11. Average measured bulk density for each site.				
Study Site	**Number of Samples**	**Average Bulk Density (lb/ft^3)**	**Minimum**	**Maximum**
Shannon Run (T)	9	62.29	51.19	68.67
Piney Ridge (C)	7	61.09	54.94	72.42
Central MD SVC (T)	7	53.78	44.95	63.05
Blue Ridge (T)	8	52.91	46.20	58.06
Robert's Field (C)	8	51.27	48.07	56.81
Total:	**39**	**56.27**	**44.95**	**72.42**

Bed Sediment Particle Size Distribution

The D_{35}, D_{50}, and D_{84} for each of the study sites is provided in Table 12. It should be noted that all sites exhibited a bimodal particle-size distribution due to the presence of a high percentage of fine particles (≤2mm) during the pebble count measurements. Figure 11 provides an example cumulative particle size distribution and histogram for Central MD SVC.

Table 12. Particle size distributions measured at each cross-section location during the pretreatment period.

Study Site	D_{35} (mm)	D_{50} (mm)	D_{85} (mm)
Central MD SVC (T)			
XS 1 (pool)	10.37	17.41	55.80
XS 2 (riffle)	16.13	27.79	103.30
XS 4 (riffle)	13.41	22.12	62.48
Reach Average	**13.07**	**22.36**	**73.58**
Shannon Run (T)			
XS 1 (riffle)	8.86	20.67	97.98
XS 2 (pool)	11.43	27.97	89.6
XS 3 (riffle)	18.29	30.74	89.56
Reach Average	**12.66**	**27.30**	**92.96**
Robert's Field (C)			
XS 1 (glide)	4.38	10.06	51.84
XS 2 (riffle)	9.38	16.51	77.00
XS 3 (run)	1.88	7.81	57.26
Reach Average	**4.64**	**12.60**	**62.45**
Piney Ridge Village (C)			
XS 1 (pool)	10.09	18.38	71.67
XS 2 (riffle)	3.86	10.02	38.06
XS 3 (glide)	3.10	7.16	29.58
Reach Average	**5.11**	**10.81**	**42.87**

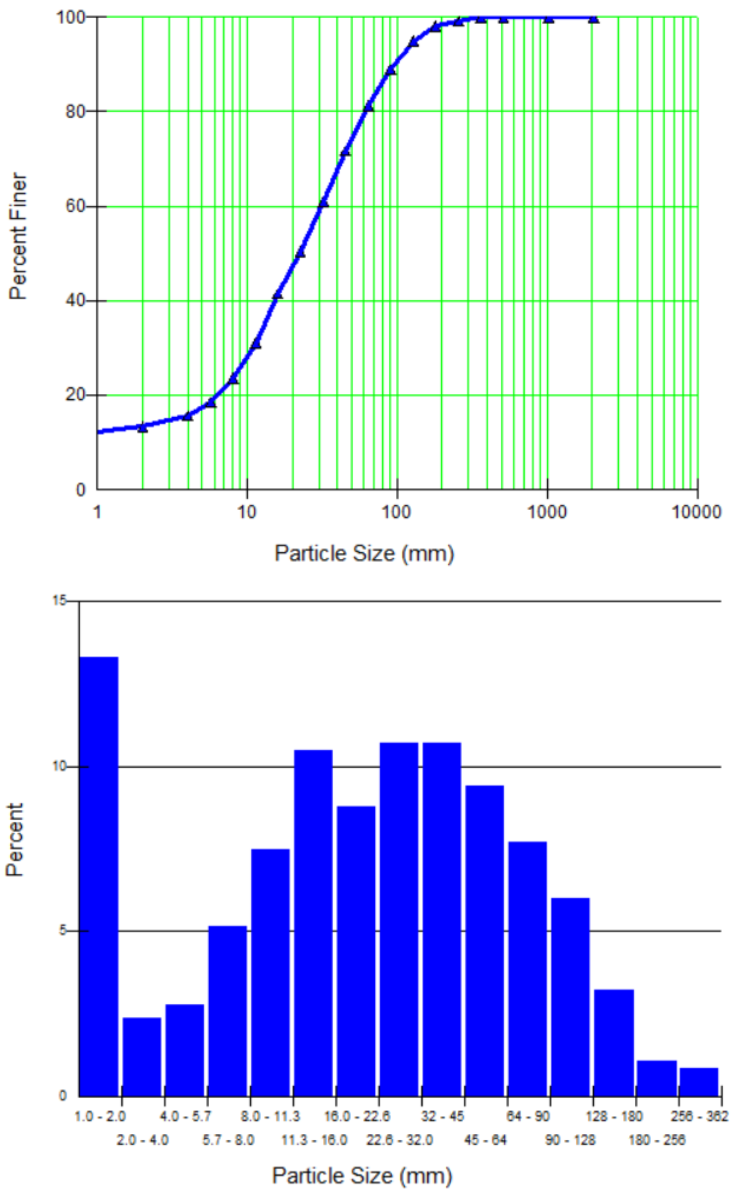

Figure 11. Cumulative particle size distribution (top) and histogram (bottom) for Central MD SVC.

Cross-Section Surveys

Example cross-sectional profiles are shown in Figure 12 – Figure 15 illustrating the erosion that occurred during the pre- and post-treatment periods. Shannon Run and Piney Ridge both exhibited undercutting and bank retreat, with Shannon Run showing the greatest degree of undercutting. Cross-section changes at these two sites are the more pronounced of all the study sites, but also had the longest pretreatment time period, extending from April 2017 to October 2018. The pretreatment period at the other study sites ended February 2018.

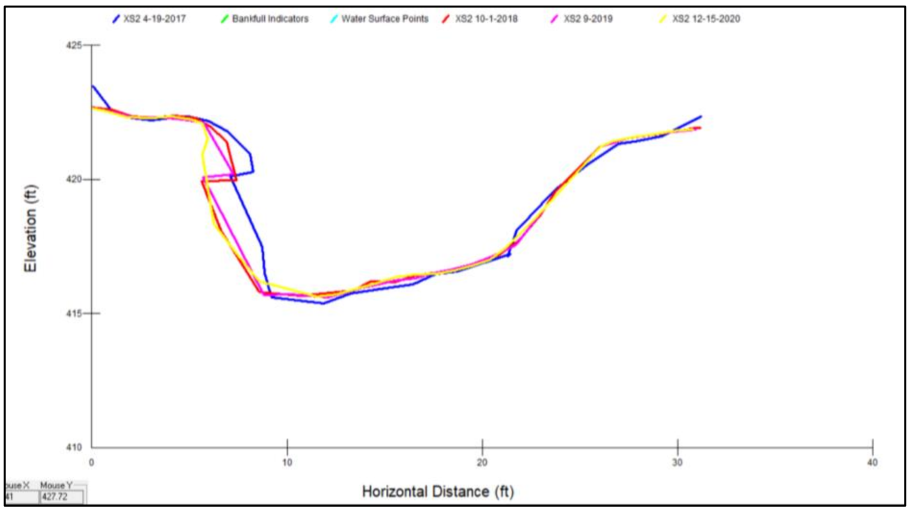

Figure 12. Shannon Run cross-section 2 showing an undercut and retreating left bank.

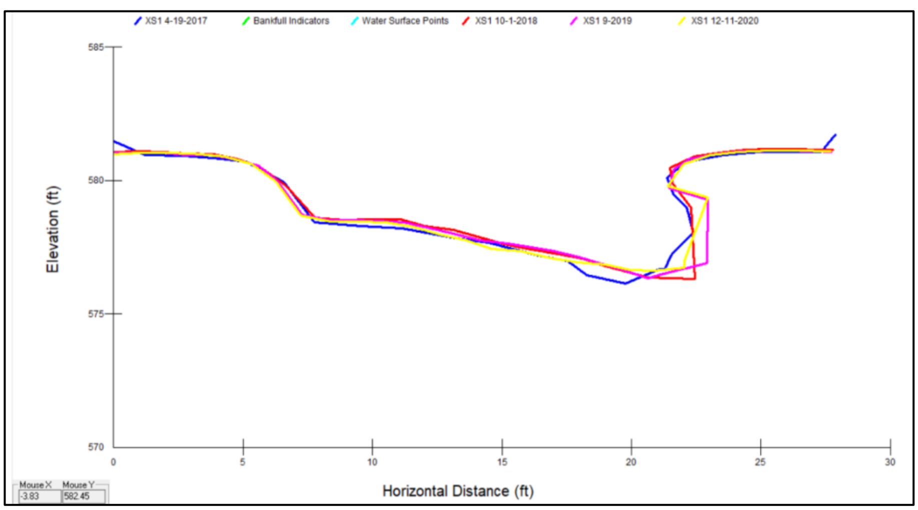

Figure 13. Piney Ridge cross-section 1 showing an undercut and retreating right bank.

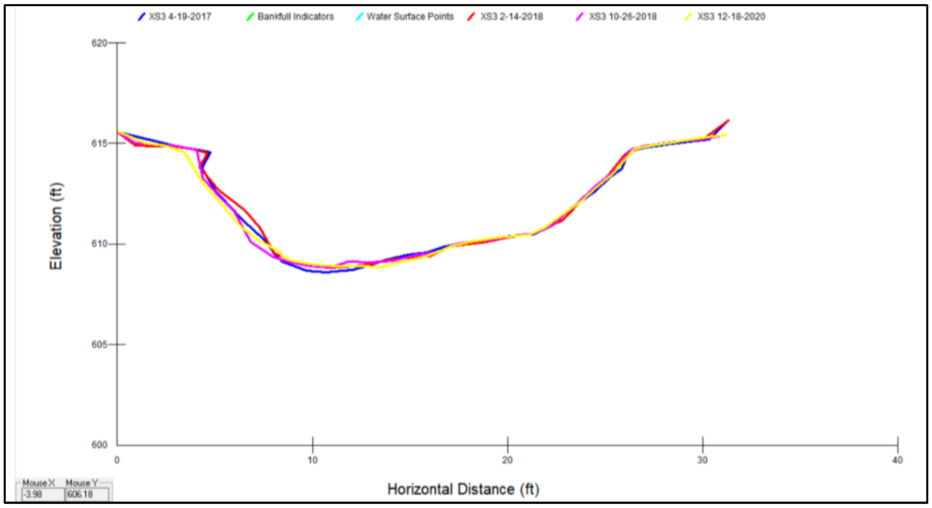

Figure 14. Central Maryland SVC cross-section 3 showing left bank erosion.

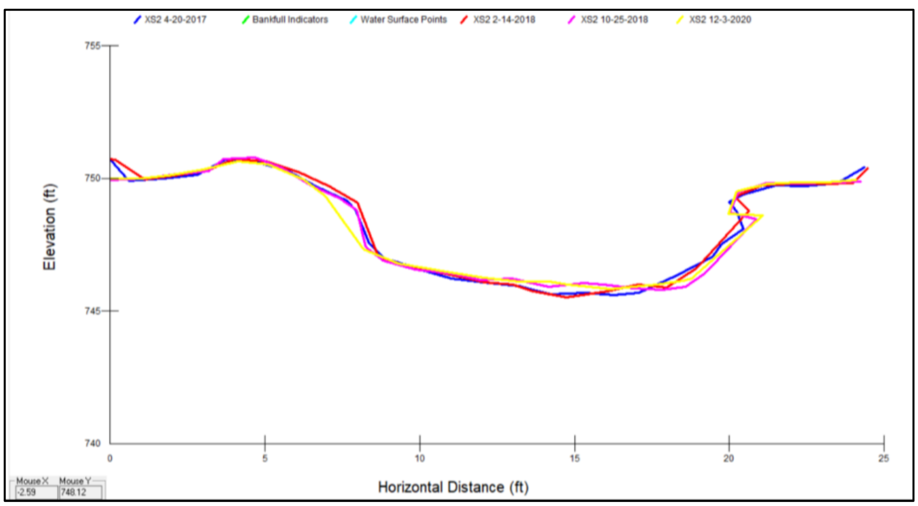

Figure 15. Robert's Field cross-section 2 showing an undercut right bank and left bank that eroded during the end of the post-treatment period.

A summary of the streambank changes observed from the cross-section surveys is provided in Figure 16 and Figure 17. The complete cross-section change analysis results are included in Appendix H. The cross-section pretreatment bank erosion rate (sum of both left and right bank erosion rate) ranged from 0.00 to 0.69 ft/yr at treatment sites and 0.13 to 0.28 ft/yr at control sites. The cross-section post-treatment bank erosion rate ranged from 0.09 to 0.51 ft/yr at treatment sites and 0.09 to 0.25 ft/yr at control sites. Bank erosion at all cross-sections decreased between the pre- and post-treatment period, except for the cross-sections at Central MD SVC that all increased in erosion rates during the post-treatment period. Deposition along the banks was variable between the sites and the pre- and post-treatment periods and no discernable patterns were observed.

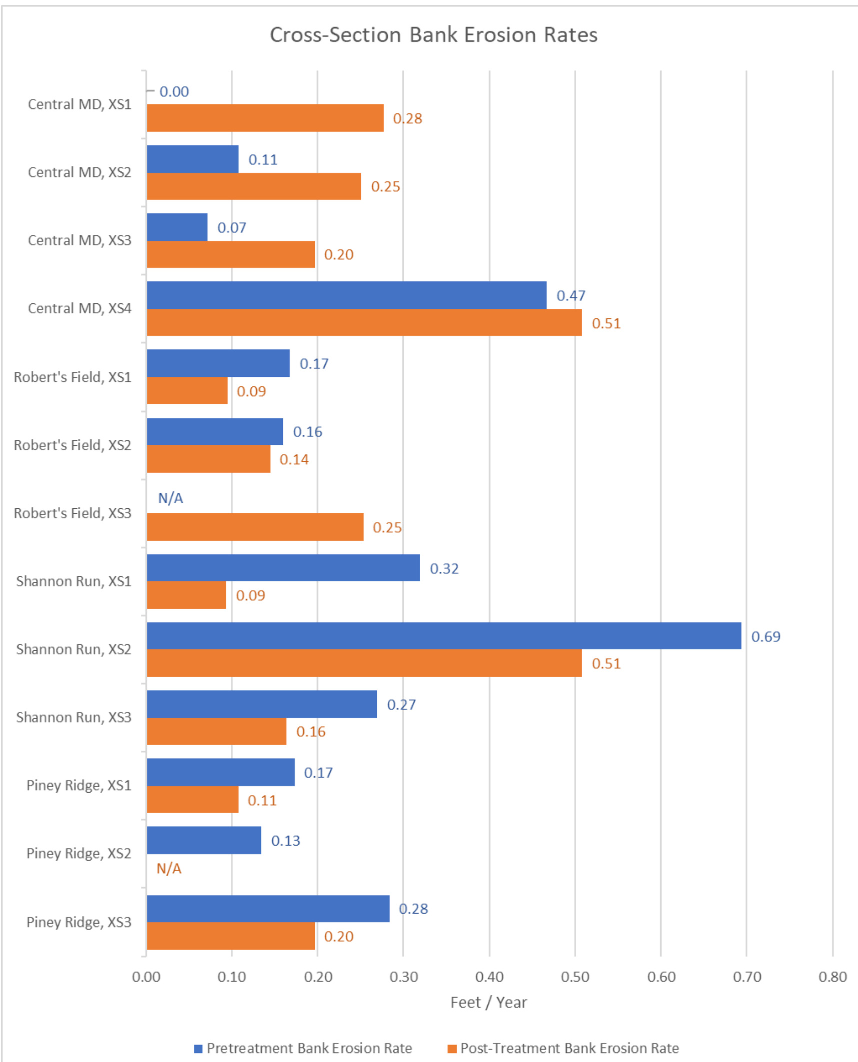

Figure 16. Cross-section bank erosion rates.

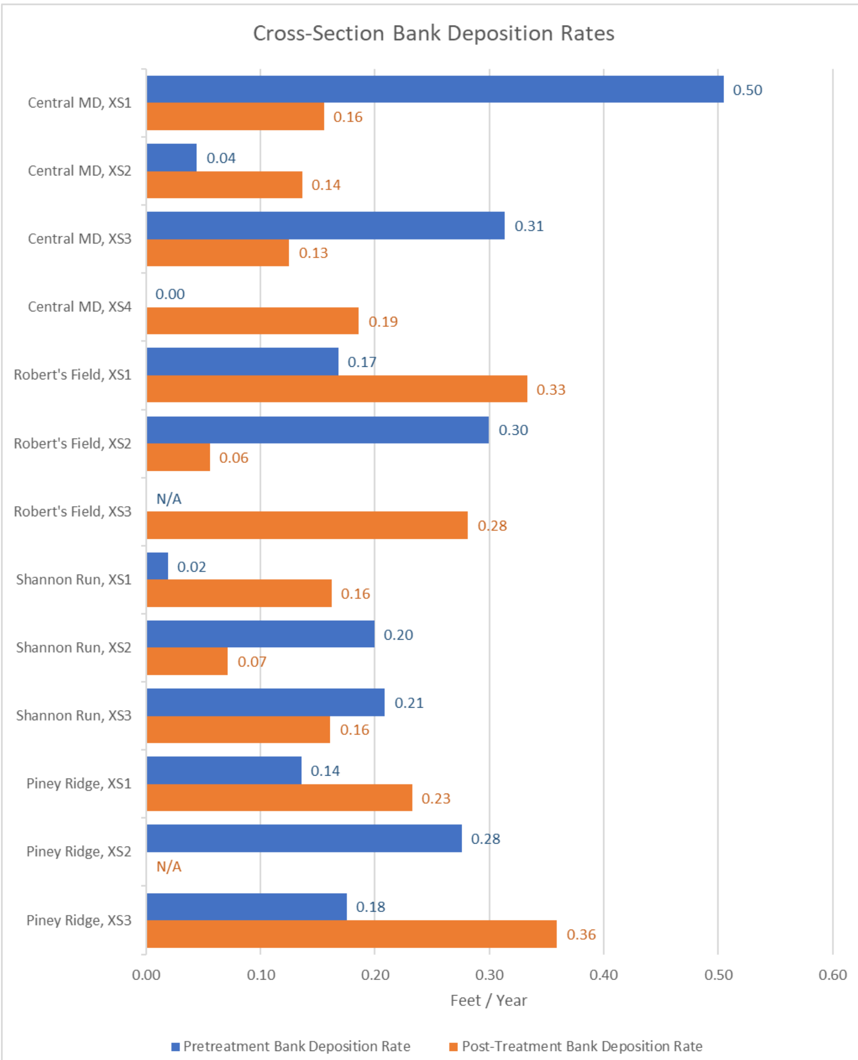

Figure 17. Cross-section bank deposition rates.

Changes in cross-section area were also calculated for both bankfull depth and total channel area extending to the top of bank. Figure 18 and Figure 19 show the total channel area change and bankfull area of change per year comparison across the study sites and monitoring periods.

Total channel area change decreased during the pretreatment period and increased during the post-treatment period for three of the four cross-sections at Central MD SVC (Figure 18). Total channel area change during the post-treatment period was less for all of the study sites (both treatment and control) in comparison to the pretreatment period. The bankfull channel area change showed a similar trend of lower percentages of change during the post-treatment period. However, bankfull channel area change (Figure 19) predominantly decreased across all of the study sites for both the pre- and post-treatment periods, whereas the total channel area change varied between increases and decreases.

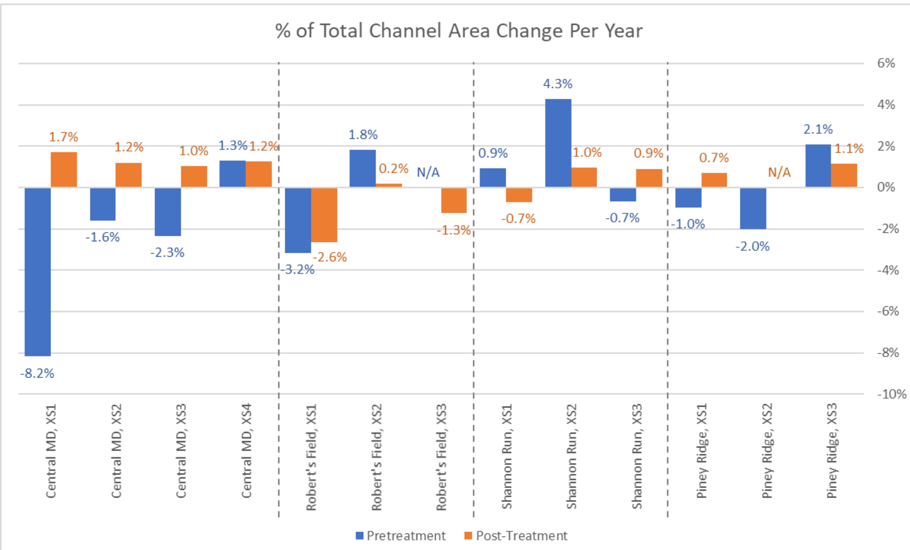

Figure 18. Percentage of total channel area change per year.

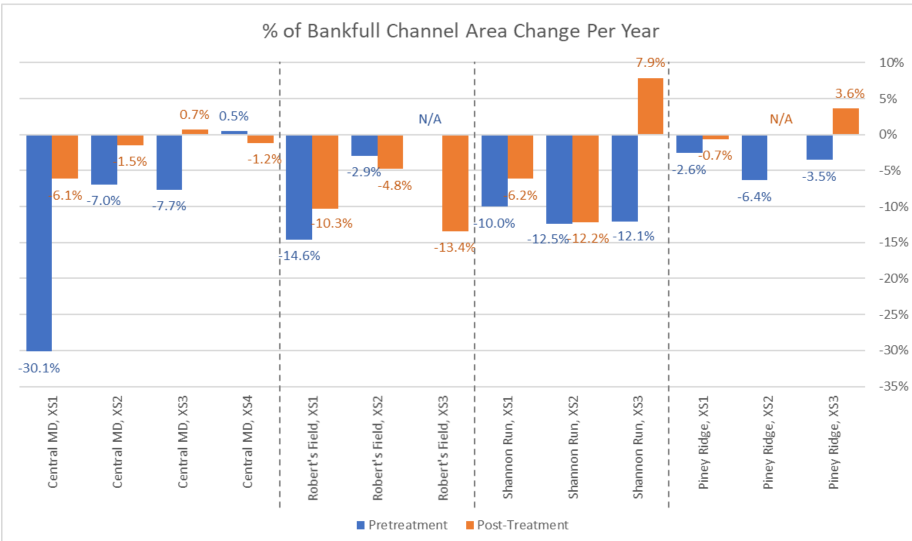

Figure 19. Percentage of bankfull channel area change per year.

The cross-section channel widths at the bankfull depth (Figure 20) and top of bank (Figure 21) were calculated to determine if any patterns of channel widening occurred. No discernable patterns of channel width change were determined.

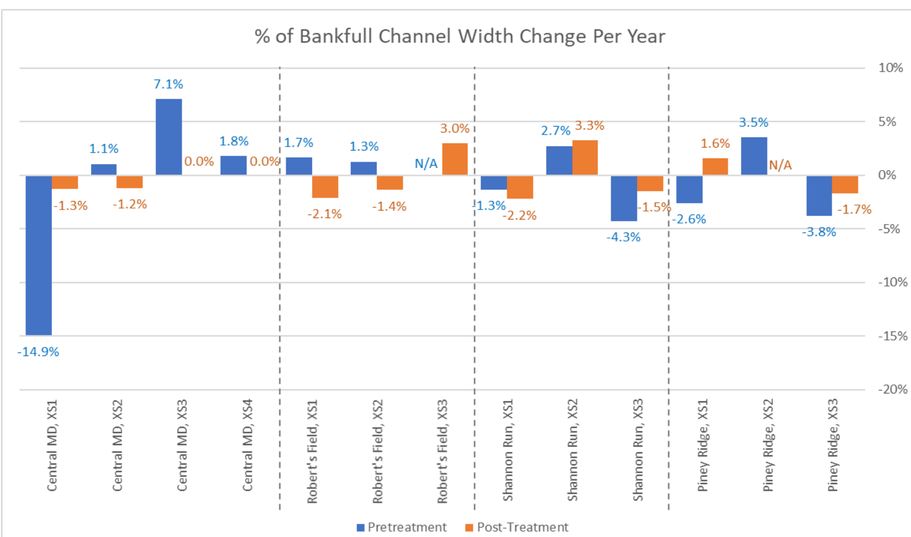

Figure 20. Percentage of bankfull channel width change per year.

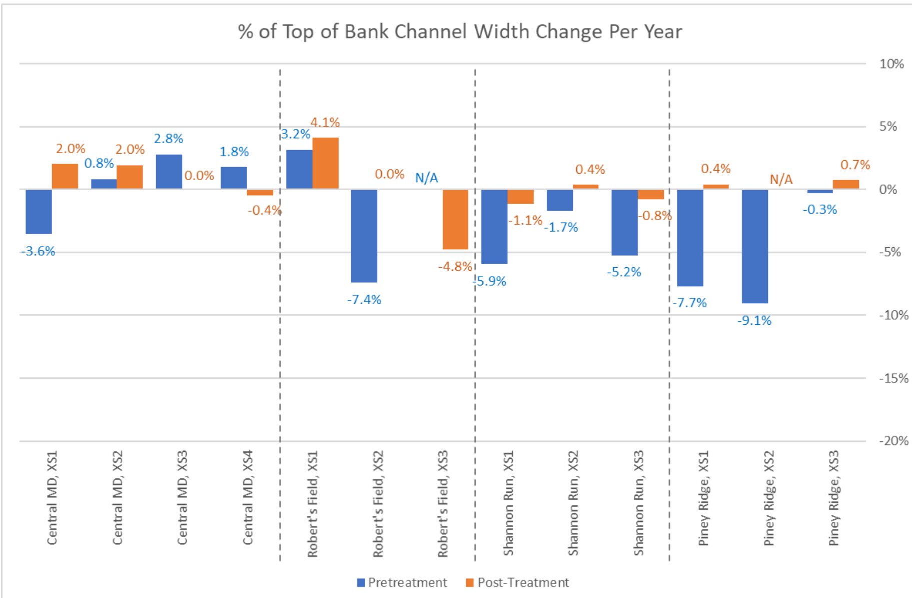

Figure 21. Percentage of top of bank channel width change per year.

Longitudinal Profile Surveys

The top of banks, thalweg, bankfull, and water surface elevations were plotted to generate longitudinal profiles for the study sites. Figure 22 provides an example of the post-treatment longitudinal profile for Shannon Run. The pre- and post-treatment longitudinal profiles for all the study sites are provided in Appendix I.

The water surface slopes for each of the study reaches are provided in Table 13. The slopes were estimated by fitting a linear regression model to the estimated surface elevations from the RiverMorph software. Water surface slopes increased slightly for Shannon Run and decreased for all other watersheds between the pre- and post-treatment periods. None of these changes are statistically significant (based on an ANCOVA analysis testing the change in slope). Further, the changes were not meaningfully different, with the greatest slope change (Shannon Run) being a 0.043% slope difference.

Table 13. Water surface slope.

Study Site	Pretreatment Water Surface Slope	Post-Treatment Water Surface Slope	Change in Slope
Shannon Run (T)	0.01873	0.01916	0.00043
Piney Ridge (C)	0.01529	0.01518	-0.00011
Central MD SVC (T)	0.02458	0.02440	-0.00018
Robert’s Field (C)	0.02643	0.02613	-0.00030

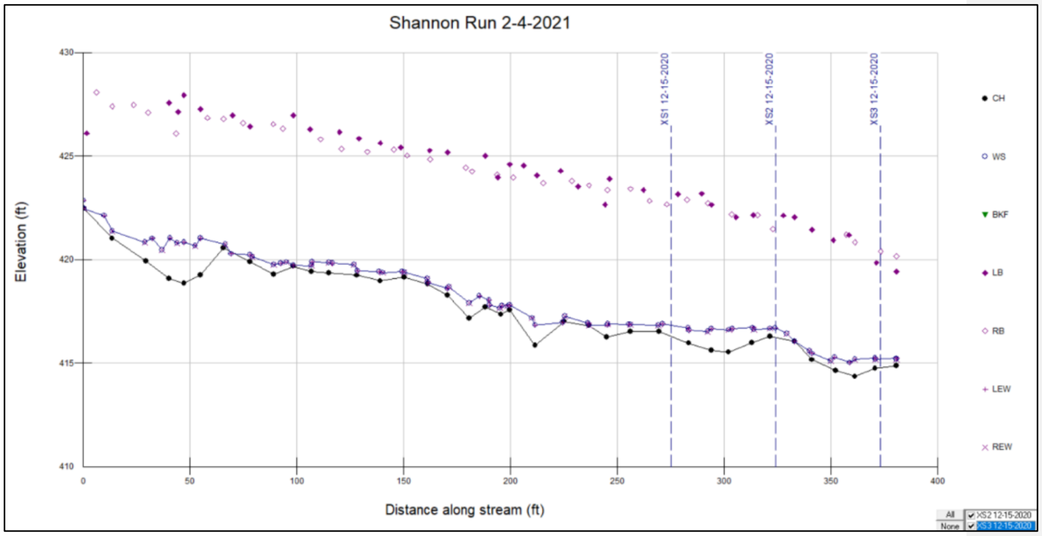

Figure 22. Shannon Run post-treatment longitudinal profile.

The pre- and post-treatment thalweg elevations were also compared at each of the study sites (Figure 23) to determine if patterns of bed aggradation and degradation could be observed. Central MD SVC, a treatment site, exhibited systemwide aggradation indicative of a trend toward stability as per the Channel Evolution Model. However, so did the Robert's Field control site. Shannon Run (treatment) and Piney Ridge (control) exhibited both aggradation and degradation.

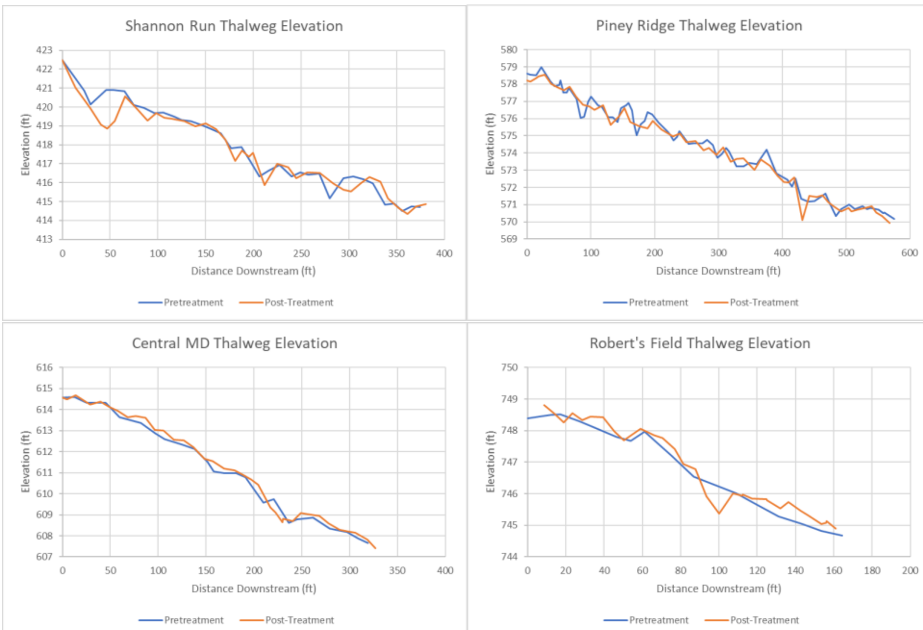

Figure 23. Longitudinal profile thalweg elevation change.

Bank Pins

Average bank erosion rates at the bank pin locations are provided in Figure 24. Results show that the average erosion rates ranged between 0.0 and 0.2 ft/yr. Slight increases in the bank erosion rates occurred at all the sites. Central MD SVC had a decrease in erosion rate at two bank pin locations and an increase at three of the bank pin locations.

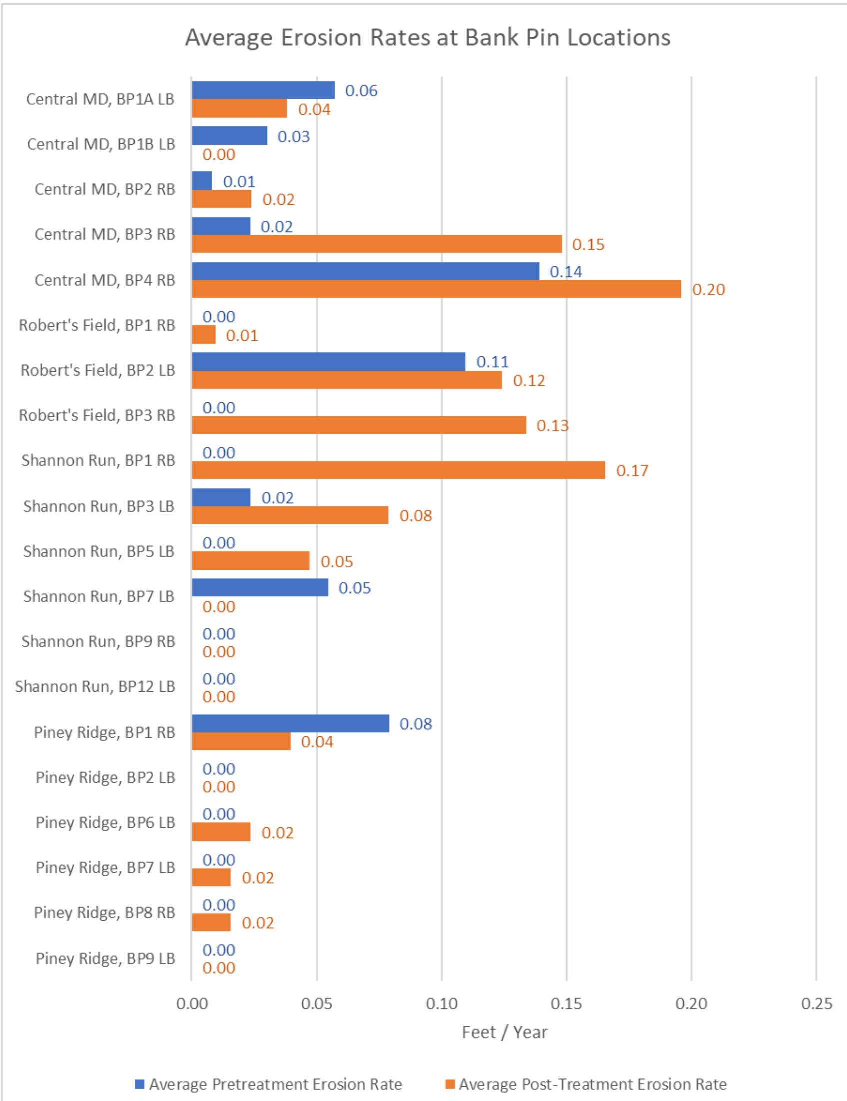

Figure 24. Average erosion rates at bank pin locations.

BANCS Assessment

The BANCS assessment for the pre- and post-treatment periods found most of the streams had a relatively high erosion potential based on the BEHI and NBS ratings. The results of the BANCS assessment for the entire stream reach for all four sites is provided in Appendix J. Figure 25 - Figure 28 summarize the BEHI ratings from the BANCs assessment for the pre and post-treatment periods. The

BANCS assessment results were used to estimate erosion rates and sediment loading presented in the subsequent sections.

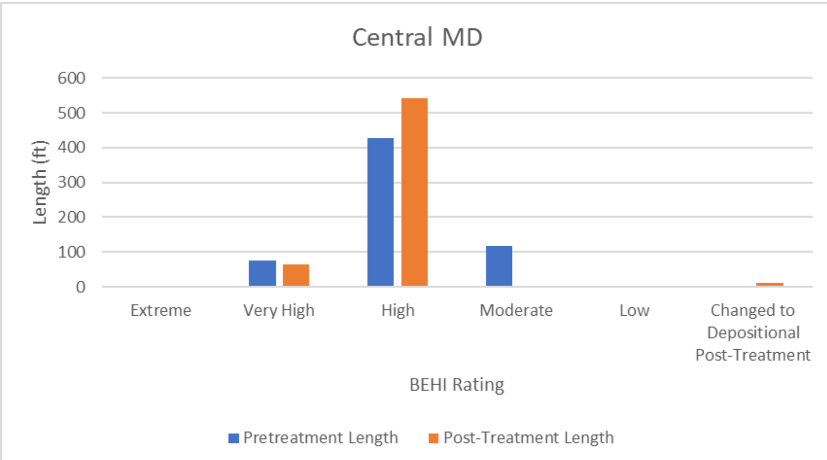

Figure 25. Central MD SVC pre- and post-treatment BEHI lengths.

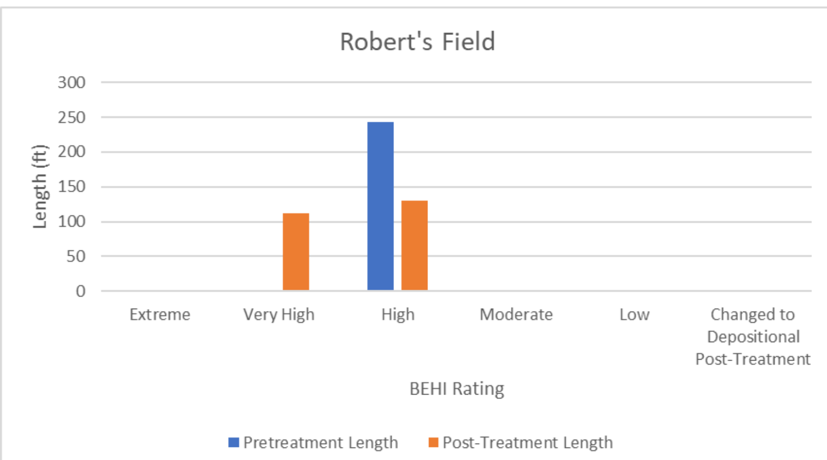

Figure 26. Robert’s Field pre- and post-treatment BEHI lengths.

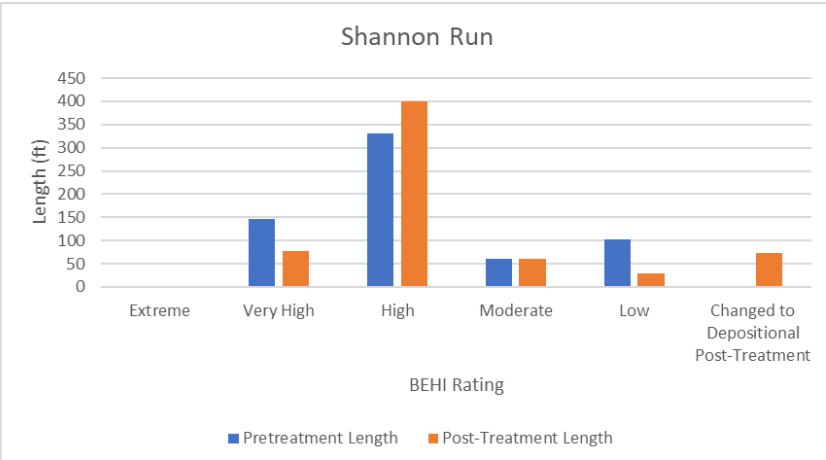

Figure 27. Shannon Run pre- and post-treatment BEHI lengths.

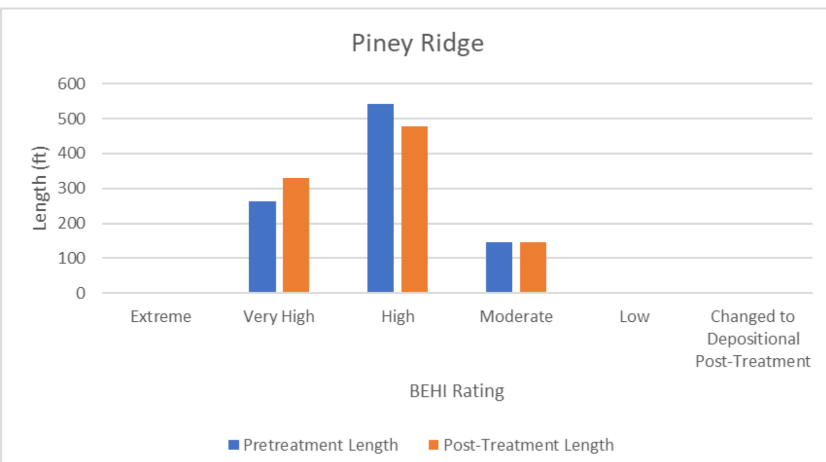

Figure 28. Piney Ridge pre- and post-treatment BEHI lengths.

Comparison of BANCS, Cross-Section, and Bank Pin Results

Cross-sections and bank pins were installed at representative locations based on the BEHI and NBS ratings of the stream banks. 'Representative' was defined based on the distribution of BEHI and NBS ratings. For example, more than one set of bank pins were installed at locations for BEHI-NBS ratings that occurred frequently, while one bank pin set may be installed when a BEHI-NBS rating occurred only a couple of times. Appendix J includes the distribution of bank pins and cross-sections among the BEHI and NBS scores.

Table 14 and Figure 29 provide a comparison between the BANCS estimated erosion rates and the monitored erosion rates from bank pins and cross-sections. This comparison was made at the point where the BANCS assessed reaches and monitoring locations overlap (i.e., the monitored erosion rates correspond to the eroding bank and are not representative of the entire channel). The data includes erosion rates from both the pre- and post-treatment monitoring periods due to the limited sample sizes of comparing each of these monitoring periods individually. Only eroding reaches determined from the BANCS assessments are compared with the monitored erosion rates. All the BANCS estimated erosion rates were higher than those monitored, except for reaches with a BEHI/NBS characterization of low/low. The differences between the estimated and monitored erosion rates become increasingly more pronounced when moving from the low to very high BEHI and NBS characterizations. Less than 5 monitored erosion rates are available for all the BEHI/NBS characterizations, except for high/high (n=12), high/moderate (n=12), and high/low(n=23). Even with these characterizations with higher sample sizes, the monitored erosion rates were lower than estimated from BANCS. Monitored erosion rates across all BEHI/NBS characterizations were less than 0.5 ft/yr, while BANCS ranged from 0.03 to 2.5 ft/yr.

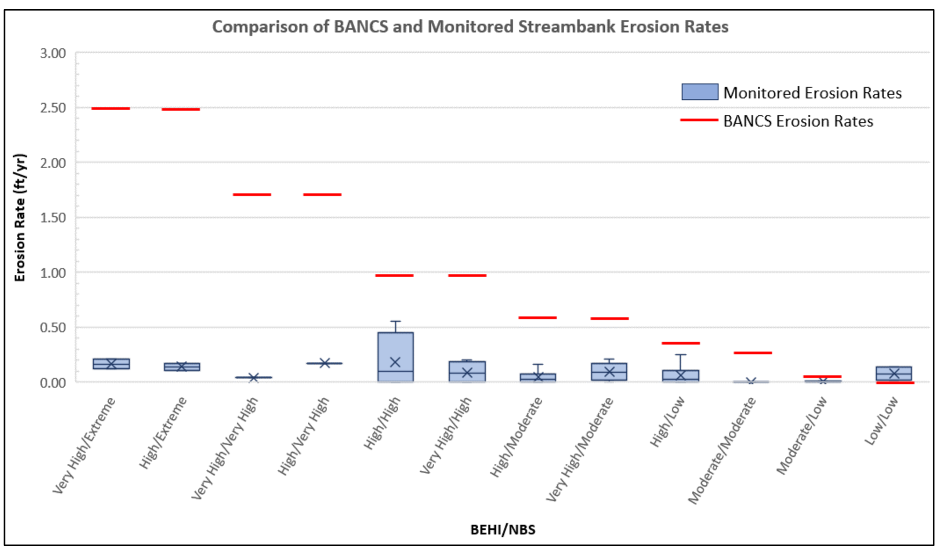

Figure 29. Comparison of BANCS and monitored streambank erosion rates.

Table 14. Comparison of BANCS and monitored streambank erosion rates.

		BANCS BEHI/NBS											
		Very High/Extreme	High/Extreme	Very High/Very High	High/Very High	High/High	Very High/High	High/Moderate	Very High/Moderate	High/Low	Moderate/Moderate	Moderate/Low	Low/Low
Monitored Erosion Rate (ft/yr)	Min	0.12	0.11	0.04	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
	Max	0.21	0.17	0.04	0.17	0.56	0.20	0.16	0.21	0.25	0.00	0.01	0.14
	Quartile 1	0.14	0.12	0.04	0.17	0.00	0.02	0.00	0.04	0.00	0.00	0.00	0.05
	Quartile 3	0.19	0.15	0.04	0.17	0.35	0.15	0.06	0.13	0.11	0.00	0.00	0.11
	Avg	0.16	0.14	0.04	0.17	0.18	0.09	0.04	0.10	0.06	0.00	0.00	0.08
	Median	0.16	0.14	0.04	0.17	0.10	0.08	0.03	0.09	0.02	0.00	0.00	0.08
	n	2	2	1	1	12	4	12	5	23	1	3	2
BANCS Erosion Rate (ft/yr)		2.50	2.50	1.75	1.75	1.00	1.00	0.64	0.64	0.40	0.30	0.13	0.03

Riparian Vegetation

The riparian vegetation was subdivided into five areas to assess the adjacent canopy cover, understory, ground layer and stream bank vegetation. Examples of seasonal streambank vegetation at the study sites is provided in Table 15. Results of the riparian vegetation survey are shown in Table 16.

Table 15. Seasonal comparison of streambank vegetation.

March 2020	**June 2020**	**September 2020**
Central MD SVC		
		
Robert's Field		
		
Shannon Run		
		
Piney Ridge		
		

Table 16. Pre- and post-treatment riparian vegetation survey results. Green = "Functioning"; Yellow = "Functioning at risk"; Red = "Not Functioning"

Metric	Shannon Run (Treatment)		Piney Ridge (Control)		Central MD SVC (Treatment)		Robert's Field (Control)	
	Pretreatment	Post-Treatment	Pretreatment	Post-Treatment	Pretreatment	Post-Treatment	Pretreatment	Post-Treatment
CANOPY COVER								
% Canopy Cover % Native	91 % 100%	80 % 100%	91% 100%	80% 100%	90% 100%	76% 100%	88% 100%	77% 100%
Density (BA), ft^2	83	70 (-)	96	90 (-)	83	101 (+)	97	102 (+)
Representative Species	Black walnut, Red maple, Green ash	J. nigra, A. rubrum	Red maple	A. rubrum	Black walnut, Red maple	Mixed Hardwoods	Red maple; Black cherry	A. rubrum; P. serotina
UNDERSTORY								
Regeneration (# stems/ac)	650	50	500	280	233	3	0	10
Representative species		L. bensoin	Green Ash	I. opaca	Black walnut, Am. holly	J. virginiana	N/A	A. rubrum
Shrub coverage (%)	40%	60% (+)	24%	21% (-)	28%	35% (+)	57%	58% (+)
GROUND LAYER								
Total cover (%)	68%	70% (+)	65%	85% (+)	73%	73% (no change)	49%	35% (-)
% Native species Species	40% Fern, Skunk cabbage	35% Ferns	34% Va. Creeper	1% moss	54% Spicebush	54% L. bensoin	65% Spicebush, Ferns	59% L. bensoin, Ferns
% Non-native species Species	60% Stiltgrass, Multiflora rose	65% M. vimineum, R. multiflora	66% Stiltgrass	99% M. vimineum	46% Jap. honeysuckle	46% Jap. honeysuckle	35% Multiflora rose	41% R. multiflora, L. japonica
STREAM BANK								
Total Cover (%)	30%	40% (+)	30%	8% (-)	23%	10% (-)	14%	7% (-)
% Native species Species	30% Fern	25% Fern	23% Moss	29% Moss	62% Jewelweed	3% I. capensis	65% Jewelweed, ferns	59% I. capensis, ferns
% Non-native species Species	70% Stilt Grass, Multifora rose	75% M. vimineum, R. multiflora	77% Stiltgrass	71% M. vimineum	38% Multifora rose	98% R. multiflora	35% Multifora rose	61% R. multiflora

Post-treatment tree canopy cover and composition changed from pre to post conditions, but these changes were minor as all sites are still in the Functioning category according to USFWS (2013). Two sites (Shannon Run and Piney Ridge) showed modest decrease in basal area and 2 sites (Central MD SVC and Robert's Field) had modest increase in basal area. Tree loss was attributed mostly to tree falling into the stream and green ash mortality due to the Emerald Ash Borer. Sites that increased basal area a dominated by fast growing, early successional trees like red maple (*Acer rubrum*) and yellow poplar (*Liriodendron tulipifera*).

Post-treatment understory-regeneration conditions declined at all sites primarily due to the lack of native tree regeneration; regeneration at all sites is considered Not Functioning, indicating not more than 769 seedlings or 307 saplings per acre as per the USFWS (2013) performance standard. The primary drivers for this decline are a combination of an overabundance of white-tail deer and the continued expansion of well-established non-native plant invasions. Regeneration of native forest trees is mostly limited to species deer do not typically browse including American holly (Ilex opaca) and eastern red cedar (*Juniperus virginiana*). Post-treatment understory-shrub conditions varied across sites, Shannon Run, Central MD SVC, and Robert's Field had modest increases in shrub coverage, however, only Shannon Run is considered Functioning with Central MD SVC and Robert's Field both considered Functioning At Risk. Piney Ridge had slight decrease in shrub coverage and continues to be considered Not Functioning. Blue Ridge had a decrease in shrub coverage and is now considered Functioning At Risk, down from Functioning, however, this was directly a result of clearing by survey crews between pre-treatment and post-treatment vegetation data collections and therefore should not be considered. At all sites the shrub layer was dominated by spicebush (*Lindera benzoin)* with multiflora rose *(Rosa multiflora)* the most prevalent and abundant non-native invasive shrub species*.*

Post-treatment ground cover conditions declined at all sites primarily due to the expansion of non-native invasive plants. One site (Robert's Field) had a decrease in ground cover, one site (Central MD SVC) had no change, and two sites had an increase in ground cover (Shannon Run and Piney Ridge). The increase in ground cover at Shannon Run and Piney Ridge is entirely associated with the expansion of invasive plant populations, particularly Japanese stiltgrass (*Microstegium vimineum*).

Stream bank vegetation coverage declined at 3 sites (Piney Ridge, Central MD SVC, Robert's Field) and increased at 1 site (Shannon Run). However, only Shannon Run is rated as Functioning At Risk all other sites are rates as Not Functioning. Like ground cover most of the increase in stream bank vegetation is associated with non-native invasive plants. Some these plants, like Japanese stiltgrass are annual and only provide vegetative coverage during the growing season. Most of the native vegetation growing on the banks consisted of a variety of ferns, mainly hay scented fern (*Dennstaedtia punctilobula*) and Christmas fern (*Polystichum acrostichoides*), and spotted jewelweed (*Impatiens capensis*).

Post-treatment data collection occurred on November 23, 2020 during leaf-off conditions. As a result, some of the data accuracy is reduced from pre-treatment leaf on conditions, this is most noticeable when estimating canopy coverage and ground cover. Species like skunk cabbage (*Symplocarpus foetidus*) which were identified in the pretreatment assessments at Shannon Run would have been dormant and not visible during the post-treatment site visit. Ground cover estimates did take into consideration visible plant residue from annual plans such as Japanese stiltgrass to provide an estimate.

Sediment Loading Estimation

The following results relate to Hypothesis 3: *"The implementation of runoff reduction BMPs will decrease sediment loadings downstream as a result of reduced bank erosion rates."*

Table 17 provides a comparison of the measured and estimated sediment loading from streambank erosion for the pre- and post-treatment periods. Appendix J provides the complete BANCS sediment loading data and Appendix K provides the sediment loading data for each monitoring location.

The BANCS estimated total TSS load increased during the post-treatment period for all the sites. However, the order of magnitude of the increase was higher at the control sites (28% at Piney Ridge and 12% at Robert's Field) compared to the treatment sites (7% at Central MD SVC and 4% at Shannon Run). In comparison to BANCS, the monitored load estimate was considerably lower due to differences in the BANCS and monitoring data estimated erosion rates presented in Figure 29 and Table 14. The calculated loads from monitoring showed an increase in loads during the post-treatment period for Central MD SVC and Robert's Field, and a decrease in loads for Piney Ridge and Shannon Run. The extent of total bank length that included a representative monitoring location varied from 31% in Piney Ridge to 92% in Robert's Field. The bank lengths that did not include a representative monitoring location were not included in the calculation of loads from monitoring data, which likely resulted in an underestimate of the calculated monitoring loads.

Table 17. Sediment loads estimated from BANCS and monitoring data for the study sites.

	BANCS		**Monitoring Data**		
Study Site	**Pretreatment Total TSS Load[1] (tons/yr)**	**Post-Treatment Total TSS Load[1] (tons/yr)**	**Pretreatment TSS Load (tons/yr)**	**Post-Treatment TSS Load (tons/yr)**	**% of Total Bank Length with Representative Monitoring Location[2]**
Central MD SVC (T)	42.11	45.04	3.42	8.92	89.8%
Piney Ridge (C)	59.25	75.9	0.72	0.40	31.3%
Shannon Run (T)	54.49	56.54	11.06	7.35	52.5%
Robert's Field (C)	24.26	27.21	1.01	1.83	91.5%

[1]The loads represent the total load at edge-of-stream without a sediment delivery factor or stream restoration efficiency applied as per the CBP stream restoration crediting protocols.
[2]Total bank length obtained from the top of bank survey from the longitudinal profile and includes both the left and right bank lines.

Discussion and Recommendations

The results of this study are highly encouraging and show that retrofitting “conventional” (e.g., 2-year peak to post-development peak) stormwater BMPs to meet the Carroll County enhanced sand filter design standard and wet pond design reduces the magnitude, duration and frequency of erosive flow rates. It is extremely valuable that baselines have been established by this study that will be added to the future data the County plans to collect. Hopefully, time and continued monitoring will demonstrate the geomorphic benefits more conclusively.

In general, this study would have benefitted with more time to conduct monitoring to account for variability in the size and intensity of the storms measured during the pre- and post-treatment periods. This is especially true because the geomorphic response of channel geomorphology to changes in the flow regime (e.g., the effect of the retrofits) typically occurs over much longer periods than the duration of this study. It was hoped that the beginning stages of channel adjustments would have been detected in this study and there may well be ongoing adjustments leading to channel stability resulting from the retrofits that the monitoring could not detect. Further, having additional sites to monitor would have been helpful to address issues related to retrofit construction and faulty equipment which can be typical of hydrologic and geomorphic studies. It is encouraging that Carroll County is intending to keep monitoring the study sites and hopefully there will be enough retrofits to expand on the sample size should monitoring resources become available.

A more detailed discussion of how the data relates to each of the three hypotheses is presented below.

H1: The implementation of BMPs retrofitted to meet Carroll County’s sand filter design standard will modify the runoff response from the watershed (hydrograph) resulting in a reduction of the magnitude, duration and frequency of erosive flow rates that meet and or exceed MDE performance standards for stream channel protection.

The analysis of the change in RCNs, storm event metrics, and runoff statistics shows that the retrofits reduce the magnitude, duration and frequency of erosive flow rates. Despite variability in the population of storms monitored between the pre- and post-treatment periods, the average daily peak flow rates decreased at the treatment sites during the post-treatment period while the average daily peak flow rates increased at the control sites (Table *7*). Additionally, the flashiness index decreased at the treatment sites and increased at the control sites. This is to be expected given the added degree of hydraulic control associated with the retrofitting of the BMPs to Carroll County’s sand filter and wet pond design standards. Also as expected, post-treatment runoff (Figure 8) and peak discharge response (Figure 9) relationships showed substantial reductions at the treatment sites compared to the control sites.

The average RCN during the post-treatment period was considerably less than the pretreatment period for the treatment sites, while the RCNs increased slightly at the two control sites (Table 8). MDE’s stream channel performance standard is to reduce the post-construction RCN to “woods in good condition.” There is a difference in the “calculated RCNs” and measured RCNs, which can be expected given the inherent inaccuracies of the RCN method in computing RCNs for single storms. However, it is interesting to note that the measured post-treatment RCN for Central MD SVC was reasonably close to the design standard RCN (woods in good condition) compared to the controls that far exceeded the design standard. For Shannon Run, the RCN was slightly greater than the design standard RCN, which may be related to only 5 storms available for the calculation of the RCN.

It was not possible to evaluate the frequency and exceedance of critical discharges resulting from the retrofits as per Hawley and Vietz (2016) without more detailed pebble count data and a more complete flow record and additional study of these sites would benefit from this type of analysis. Instead, channel stability was evaluated by comparing the number of peak discharges observed above the bankfull rate of discharge between the pre- and post-treatment monitoring periods with the logic that the greater number of exceedances of the bankfull discharge corresponds to a greater erosion potential in the channel. The results (Table 9) indicate that the bankfull discharge was not exceeded at any site during the pretreatment period, but there were a few exceedances in the post-treatment period, with most of the exceedances at Piney Ridge (control), and none at Shannon Run (treatment). Although much more data is needed for a robust analysis such as in Hawley and Vietz (2016), the data are encouragingly showing a decreased rate of bankfull discharge in most cases, which suggests corresponding reductions of shear stress for a range of storm conditions in treatment watersheds.

H2: The implementation of BMPs retrofitted to meet Carroll County's sand filter design standard will create hydraulic conditions that lead to self-recovery of channel stability.

This hypothesis assumed the following:

- The bank erosion rate in treatment reaches will be lower than the control reaches due to reduction in magnitude, duration and frequency in flows that contribute to bank erosion.
- The treatment reaches will be aggrading due to reductions in stream power. These reductions will reduce the sediment transport capacity resulting in sediment deposition on the streambed, which results in aggradation.
- The longitudinal extent of reduced stream bank erosion downstream of the BMP implementation sites will be a function of the total watershed area treated (e.g., x linear ft of stream for every y-acre impervious area treated in the watershed).

Hawley et al. (2019) studied time-series surveys over 10 years at 61 stream monitoring sites on suburban streams and found they followed patterns of evolution consistent with the Channel Evolution Model (CEM) of Schumm et al. (1984). Stage 1 (equilibrium) is typically followed by a period of streambed coarsening and incision (stage 2) which is followed by downcutting and widening (stage 3) to the point that the stream can no longer transport the slumped material from failing banks. This leads to a transition to a period of additional widening and sedimentation (stage 4) and ultimate recovery (stage 5). Ninety percent of the channels were found to be unstable according to the CEM (stage 2-4), with only 1 site approaching geomorphic recovery (stage 4 leading to stage 5) due to an upstream stormwater retrofit. Qualitative observations of all the study sites for this project indicate they are in stages 2 and 3 of channel evolution. Consistent with the findings of Hawley et al. (2019), the retrofits implemented at the treatment sites were expected to result in a trajectory toward stages 4 and 5 much sooner than the control sites.

The bank pin, cross-sectional surveys, and longitudinal profile were done to measure geomorphic change resulting from the retrofits. However, the data were generally inconclusive and did not support this hypothesis. Changes in the cross-sectional area between the treatment and control sites were variable and did not show any effect that can be attributed to the retrofits. Bankfull channel area change did decrease across all the study sites, indicating a potential trend towards stability. In comparison, the cross-sectional surveys did not show any significant patterns of widening that would be indicative of a trajectory towards recovery as per Schumm's CEM (Schumm et al. 1984). Likewise, the bank pin data and longitudinal profiles did not show any conclusive change resulting from the retrofits. This is most likely due to the limited monitoring period of the study.

Schumm et al. (1984) noted that channel evolution from a disturbed to a restored state could take decades. Similarly, Henshaw and Booth (2000) found that in response to urbanization, channel restabilization in the Puget Sound lowlands generally occurs within one or two decades of constant watershed land use. This study is not directly comparable since response to runoff reduction was assessed as a restoration practice and in a different region, but it does provide an indication of the potential timeframe over which responses could be seen. The post-treatment monitoring period of this study ranged from 18 months at Shannon Run and Piney Ridge to 26 months at Robert's Field and Central MD SVC. As noted by Henshaw and Booth (2000), there is no generalizable formula for channel restabilization. When, and if, an individual channel will restabilize depends on a combination of hydrologic and geomorphic characteristics of the channel and its watershed. Schumm et al. (1984) noted that recovery would require the widening (with deposition) of the stream channel until vegetation is established, the stream/floodplain is physically restored to sufficiently resist the excess flow energy, or the input flows to the stream are reduced to levels that decrease the rate of streambed erosion. Although the input flows to the treatment sites have been reduced and qualitative observations have been made of vegetation establishment on the streambanks, the resulting geomorphic change may take a much longer period that that of this study.

Modifications to the channel geomorphology are expected, especially at the treatment sites, as these channels adjust to the "new" flow regime affected by the retrofits and demonstrated in the hydrologic and hydraulic analysis. For these sites, the data shows the calculated RCNs are reasonably close to a wooded condition and are substantially lower than pre-retrofit values. Therefore, it is likely, that over time these channels will begin to stabilize and perhaps show less erosion potential and the development of a new floodplain. It will be interesting to reexamine the geomorphic data after an additional 3-5 years of monitoring as anecdotal observations from Carroll County staff have shown geomorphic stabilization to occur at other retrofit sites.

During the post-treatment period, bank pins generally showed a slight increase in erosion rate at all sites. However, the rates of erosion were much lower compared to the erosion rates observed from the cross-section surveys. This is most likely due to how the pins were installed, with one below bankfull, one just above bankfull, and one mid-top of bank. The upper bank pin at the mid to top of bank was usually located closer to the middle of the bank, except for locations with low bank heights. This positioning was susceptible to missing erosion that occurred at the top of bank that would have been included as part of the cross-section surveys. Generally, more erosion occurred closer to the top of bank due to sloughing that was then deposited at the bottom of the bank. In many instances, the bank pins were found buried in deposition during remeasurement. Future bank pins surveys are suggested to be conducted such that the pins cover a better representation of the middle to top of bank, in addition to the lower portions.

A longer study period can also help to account for differences in precipitation patterns between the pre- and post-treatment periods. The post-treatment period was wetter than normal. Pretreatment average annual rainfall was approximately 40” compared to post-treatment average annual rainfall of approximately 50” and the climate normal average annual rainfall of 42”. It is encouraging that Carroll County plans to continue monitoring these sites, which should help to determine if the precipitation patterns during the post-treatment period significantly impacted the results and document the channel response over a longer timeframe.

H3: The implementation of BMPs will decrease sediment loadings downstream as a result of reduced bank erosion rates.

Streambank sediment loadings were calculating using both a modeling approach (BANCS assessment) and monitoring approach (cross-sections and bank pins), with the results varying substantially between the two. This relates to the variation in erosion rates between the methods, with all the BANCS estimated erosion rates being higher than the erosion rates obtained through monitoring, except for reaches with a BEHI/NBS characterization of low/low. The differences between the estimated and monitored erosion rates become increasingly more pronounced in the high and very high BEHI and NBS characterizations, which accounted for most of the assessed BANCS reaches.

The BANCS assessment is a modeling approach and while many studies have applied the method, there are few that have collected actual measurements of streambank erosion to validate the results and establish a level of accuracy. The literature indicates that the BANCS method generally predicts streambank erosion within an order of magnitude (Schueler and Stack, 2014). It is important to note that the BANCS method accounts for a much larger spectrum of storms than those encountered during this study. The estimated erosion rates from the BANCS assessment were based on an interim regional curve developed for Chesapeake Bay TMDL purposes using data from multiple stream sources, including Hickey Run, but this curve should be used with caution because limited data was used to construct it. The development of new regional bank erosion rate curves was a recommendation of the new updated Chesapeake Bay Protocols (Woods, 2019). However, curve development could take several years as many data points are needed from multiple stream reaches to produce curves that are representative of streambank conditions within similar geographic and geomorphic settings without being skewed by localized influences.

In terms of how the BANCS and monitoring results changed between the pre- and post-treatment periods, the BANCS results showed that all the study sites had increased sediment loading during the post-treatment period. However, the order of magnitude of the increase was higher at the control sites compared to the treatment sites. This same trend was not observed with the monitoring results, which showed an increase in loads during the post-treatment period for Central MD SVC and Robert’s Field, and a decrease in loads for Piney Ridge and Shannon Run. Some of this variation may be related to not all the bank lengths in the study sites being represented by a monitoring location, and therefore having an incomplete estimate of sediment loads from the monitoring data. This is particularly true for Shannon Run and Piney Ridge that showed reductions in loads during the post-treatment period, but also only had 52% and 32% of the total streambank length represented in the monitoring results.

One of the goals of this project was to utilize the results to provide recommendations to credit flow controlling BMPs as a hydrogeomorphic stream stabilization technique for inclusion as part of the nutrient and sediment credits for the Chesapeake Bay TMDL. Given the variation in the sediment loading results, it is not possible to generate recommendations at this time. The geomorphic analysis was inconclusive most likely because of the limited time over which monitoring occurred, so it is no surprise that the measured and predicted reductions in sediment erosion due to the retrofits is also inconclusive. However, as per the above discussion on geomorphic monitoring, there is strong evidence that the channels below the treatment sites will stabilize and adjust as the frequency of erosive flows diminishes. This will likely translate to corresponding decreases in sediment erosion. Continued geomorphic monitoring of the study sites over a longer time may help to provide additional insight into the potential for flow controlling BMPs to be included as an option for TMDL crediting.

Conclusion

The enhanced sand filter and wet pond retrofits performed as designed and reduced the magnitude, duration, and frequency of erosive flow rates, substantially reducing the measured runoff curve numbers and simulating a hydrologic regime close to that of the "woods in good condition" performance standard. Although geomorphic trends did not yet show an undeniable response in the study timeframe, it is likely the channels are on a trajectory leading towards stabilization as anecdotal evidence (which includes photographs) from Carroll County staff suggests. It is anticipated that the results of this study will lead to recommendations that will allow for the "crediting" of reductions in streambank erosion (and attached nutrients) attributed to retrofits meeting Carroll County's design standard. However, more time and continued monitoring will likely be needed to allow bank stability to be fully achieved and measured geomorphic response to be undeniable. This study established baselines for the hydrologic and geomorphic response that will be built upon by the County's continued monitoring efforts.

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Appendix A. Monitoring Plan and Quality Assurance Project Plan

(provided as a separate document)

Appendix B. Pressure Transducer Adjustments

During the monitoring period it was observed that stage measurement from the pressure transducers suddenly adjusted to near zero water depth or in some cases increased depth. Reductions in water depth were observed when scour occurred below the pressure transducer housing and the cord prevented the transducer from moving lower to the new lower elevation of the toe of slope. In some cases, the cord was long enough that the pressure transducer moved further under the water when scour occurred, and the water depth was now recording higher than previous measurements. There were also instances where the pressure transducer housing was covered in deposited sediment and after the transducer was removed for downloading it did not go fully down into the enclosure because it was sitting on top of the deposited sediment. For all these situations, the pressure transducers and housing were adjusted in the field to ensure that the transducers would remain in the housing to minimize damage.

During the post-treatment period, the PTs were discovered missing from Robert's Field and Piney Ridge and are estimated to have been stolen sometime between January and March 2019. To replace the lost PTs and avoid additional loss, the PTs were reinstalled at all sites using a modified approach that involved securing a smaller PVC housing secured directly to the channel bed. This set-up was less visible compared to the initial setup with the PVC housing mounted along the streambank and was assumed would discourage theft. Table B-1 provides a summary of all pressure transducer adjustments.

Table B-1. Compiled summary of all PT adjustments.

XS	8/23/2017	9/8/2017	9/18/2017	5/15/2018	8/3/2018	10/31/2018	6/25/2019	8/28/2019
BR XS1	PT sticking out 3.5" below PVC. Bottom of PVC 10" above channel bottom. Lowered PVC and PT to 6.25" above channel bottom and adjusted cord.	T Post reset. Pre- adjustment water surface to bottom of PVC 1 and 13/16", channel bottom to bottom of PVC was 5 and 9/16". Post adjustment channel bottom to bottom of PVC was 3 and 10/16".		PT sticking out 0.19' below the PVC. Pre-adjustment channel bottom to PVC bottom was 0.45'. Post adjustment channel bottom to PVC bottom was 0.29'. Adjusted PT so flush with PVC bottom.			PT reinstalled. Bottom of original PT housing was buried in sediment and could not be measured. New PT location is 0.26' from the sedimentation on the channel bed.	
BR XS2			PT stick-out: 9/16" Channel bottom to bottom of PVC: 1 13/16". Adjusted PT so flush with PVC bottom.				PT reinstalled. Original setup had the PT sticking out 0.09' from the bottom of the housing and sitting on the channel bed. New PT setup has PT located 0.12' from channel bottom.	
BR XS3	Slid PVC down 4" to cover PT which had slid down to lower channel bottom due to scour and adjusted cord.						PT reinstalled. Measurement from the bottom of the original PVC housing and PT to the bottom of the	

Table B-1. Compiled summary of all PT adjustments.

XS	8/23/2017	9/8/2017	9/18/2017	5/15/2018	8/3/2018	10/31/2018	6/25/2019	8/28/2019
							new setup is 0.45'.	
PR XS1								PT reinstalled. Original setup had PT sitting at the bottom of the PVC housing directly on the channel bed. New setup has the PT located approximately 0.09' above the channel bed.
PR XS2								PT reinstalled. Original setup had PT sitting at the bottom of the PVC housing directly on the channel bed. New setup has the PT located approximately 0.03' above the channel bed.
PR XS3	Sediment covering PVC and PT. No							PT reinstalled. Original setup had PT sitting at the bottom

Table B-1. Compiled summary of all PT adjustments.								
XS	**8/23/2017**	**9/8/2017**	**9/18/2017**	**5/15/2018**	**8/3/2018**	**10/31/2018**	**6/25/2019**	**8/28/2019**
	adjustments made.							of the PVC housing approximately 0.23' above the channel bed. New setup has PT resting on the channel bed.
CM XS1						Pre-adjustment channel bottom to PVC bottom was 0.59'. Post adjustment channel bottom to PVC bottom was 0.38'.	PT reinstalled. Original setup had PT sticking out 0.13' below the PVC housing and sitting on channel bed. New setup has the PT located 0.12' above the channel bed.	
CM XS2						Pre-adjustment channel bottom to PVC bottom was 0.38'. Post adjustment channel bottom to PVC bottom was 0.27'.	PT reinstalled. Original setup had PT sticking out 0.06' below the PVC housing and sitting directly on deposition area at bank toe. New setup also has PT sitting	

Table B-1. Compiled summary of all PT adjustments.								
XS	**8/23/2017**	**9/8/2017**	**9/18/2017**	**5/15/2018**	**8/3/2018**	**10/31/2018**	**6/25/2019**	**8/28/2019**
							directly on bank toe.	
CM XS4 (PT#3)			PT stick-out: 1 15/16" Channel bottom to bottom of PVC: 1 15/16" (PT was resting against channel bottom). Adjusted PT so flush with PVC bottom.		PT sticking out below the PVC. Pre-adjustment PT bottom to channel bottom was 5 and 9/16" and channel bottom to PVC bottom was 7 and 2/16". Post adjustment channel bottom to PVC bottom was 4 and 14/16". Adjusted PT so flush with PVC bottom.	PT Abandoned.		
RF XS1			PT stick-out: 1 10/16" Channel bottom to bottom of PVC: 1 14/16" Adjusted PT so flush with PVC bottom.				PT reinstalled. Original setup had PT sitting directly on the channel bed. New setup has the PT located 0.06' above the channel bed.	
RF XS2			PT stick-out: 13/16"				PT reinstalled. Original setup	

Table B-1. Compiled summary of all PT adjustments.								
XS	**8/23/2017**	**9/8/2017**	**9/18/2017**	**5/15/2018**	**8/3/2018**	**10/31/2018**	**6/25/2019**	**8/28/2019**
			Channel bottom to bottom of PVC: 2 2/16" Adjusted PT so flush with PVC bottom.				had PT sitting directly on the channel bed. New setup has the PT located 0.2' above the channel bed.	
RF XS3						PT Abandoned.		
SR XS1								PT reinstalled. Original setup had the PT sticking out 0.13' below the PVC housing and sitting on channel bed. New PT housing was placed flush with the bank toe.
SR XS2								
SR XS3								PT reinstalled. Original setup had the PT sticking out 0.17' below the PVC housing and sitting on the bank toe. New setup also has PT

Commented [LFM2]: Byron, do you know the date the PT was removed from SR XS2 and moved to the riser?

Table B-1. Compiled summary of all PT adjustments.								
XS	**8/23/2017**	**9/8/2017**	**9/18/2017**	**5/15/2018**	**8/3/2018**	**10/31/2018**	**6/25/2019**	**8/28/2019**
								sitting directly on bank toe.

To adjust the recorded stage data based on adjustments to the pressure transducer position, water depth data were adjusted up or down to match data before the pressure transducer position change was made. This was a manual adjustment using best profession judgement based on previous sensor measurements and future measurements. Sensor position changes were usually due to storm events causing scour or movement of the sensor or sensor support. An example of these adjustments can be found in Figure B-1 and Figure B-2. Note that these recorded stage adjustments were only done for the representative cross-section used to develop the flow rating curves for each site and the paired watershed relationships. The stage data for all other cross-sections was not adjusted.

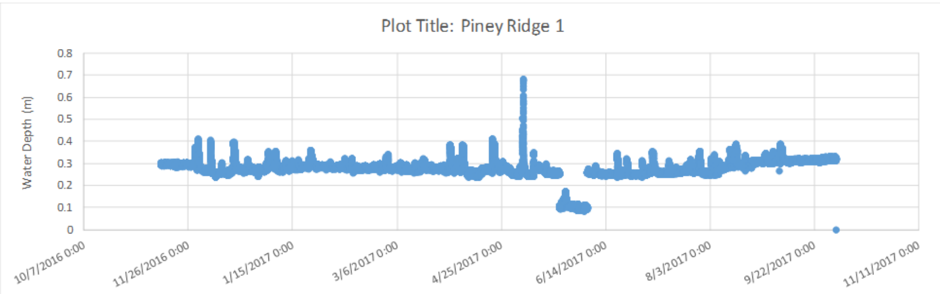


Figure B-1. Pressure transducer data showing water depth at cross section one of the Piney Ridge site. These data have one very noticeable shift in June of 2017 and several other smaller shifts, which were corrected.

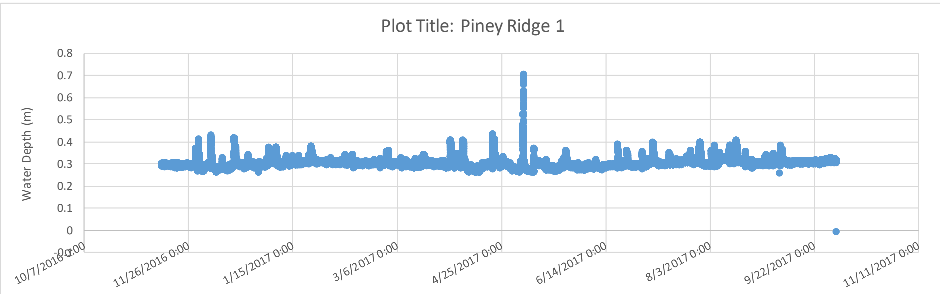
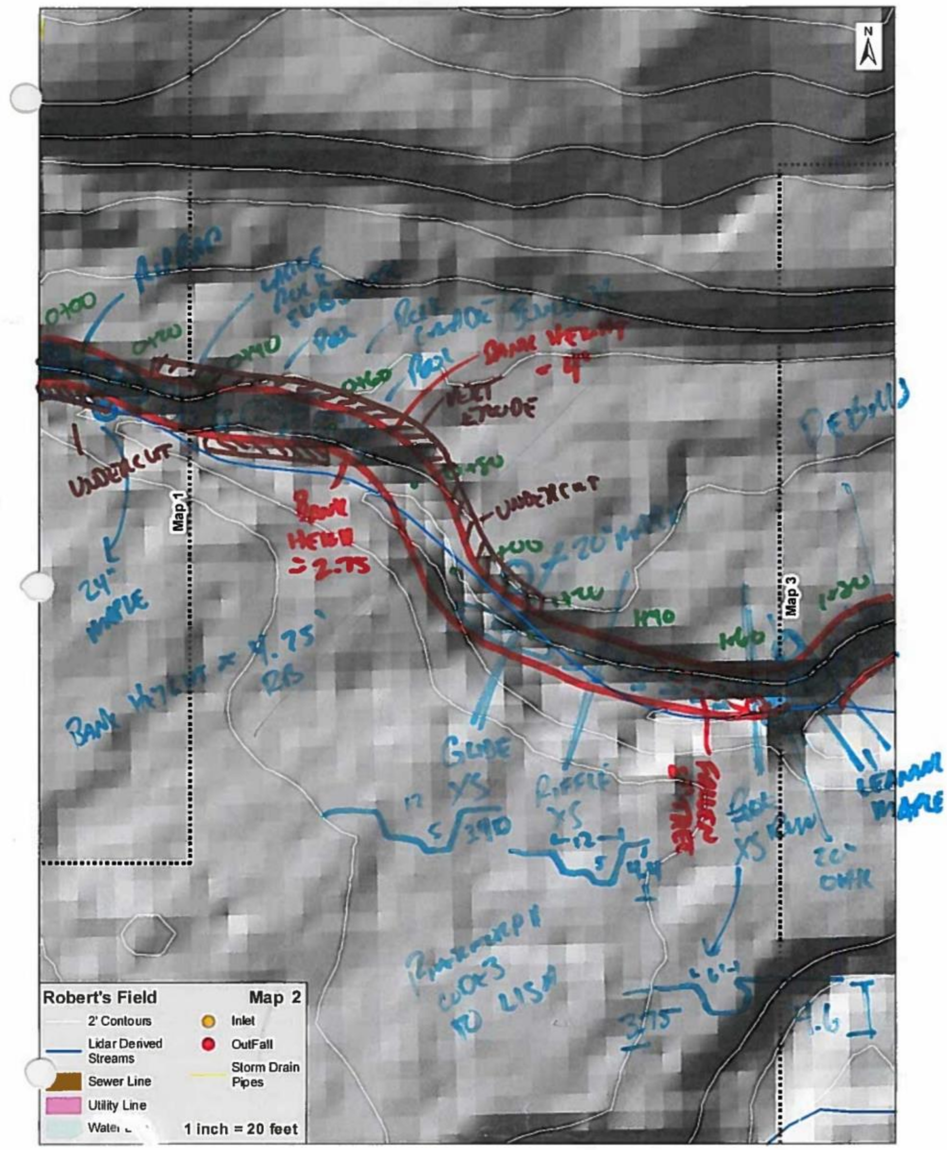
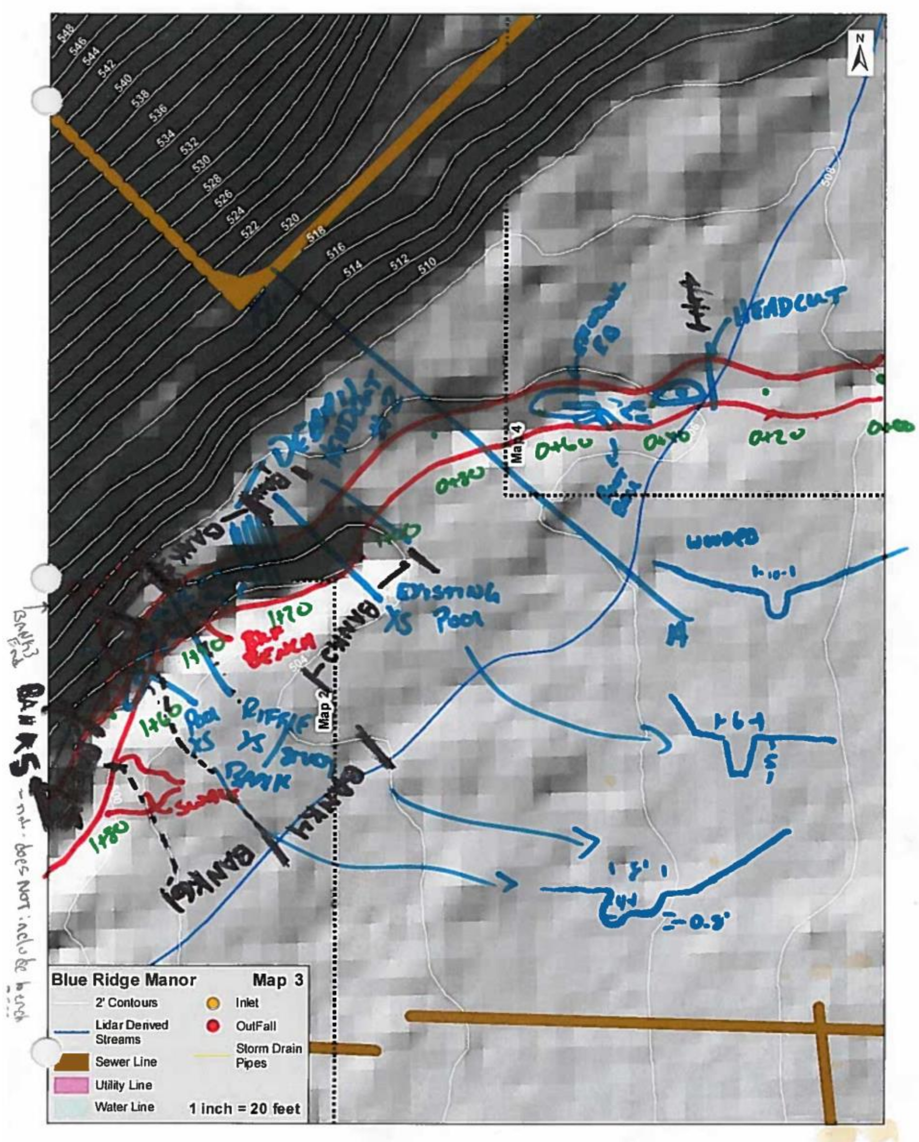


Figure B-2. Pressure transducer data showing water depth at cross section one of the Piney Ridge site. These data have been adjusted.

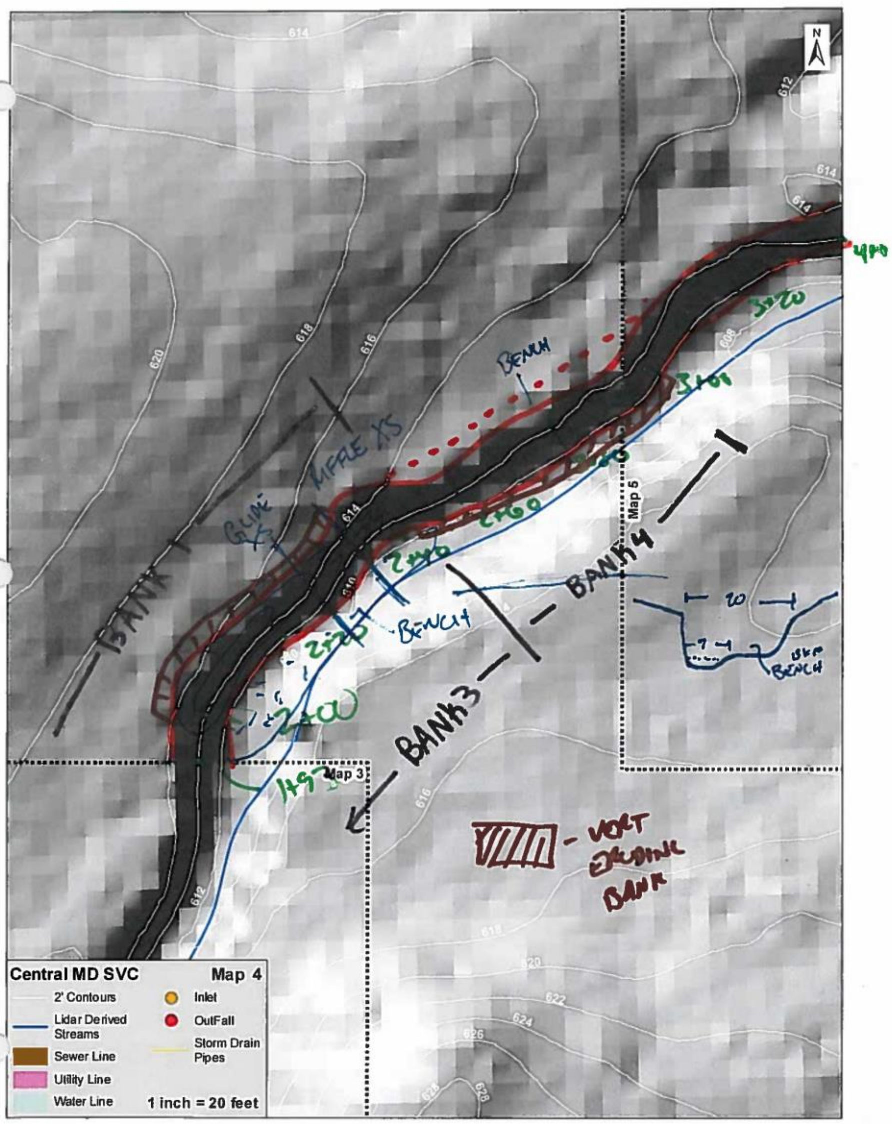
Appendix C. Geomorphic Maps

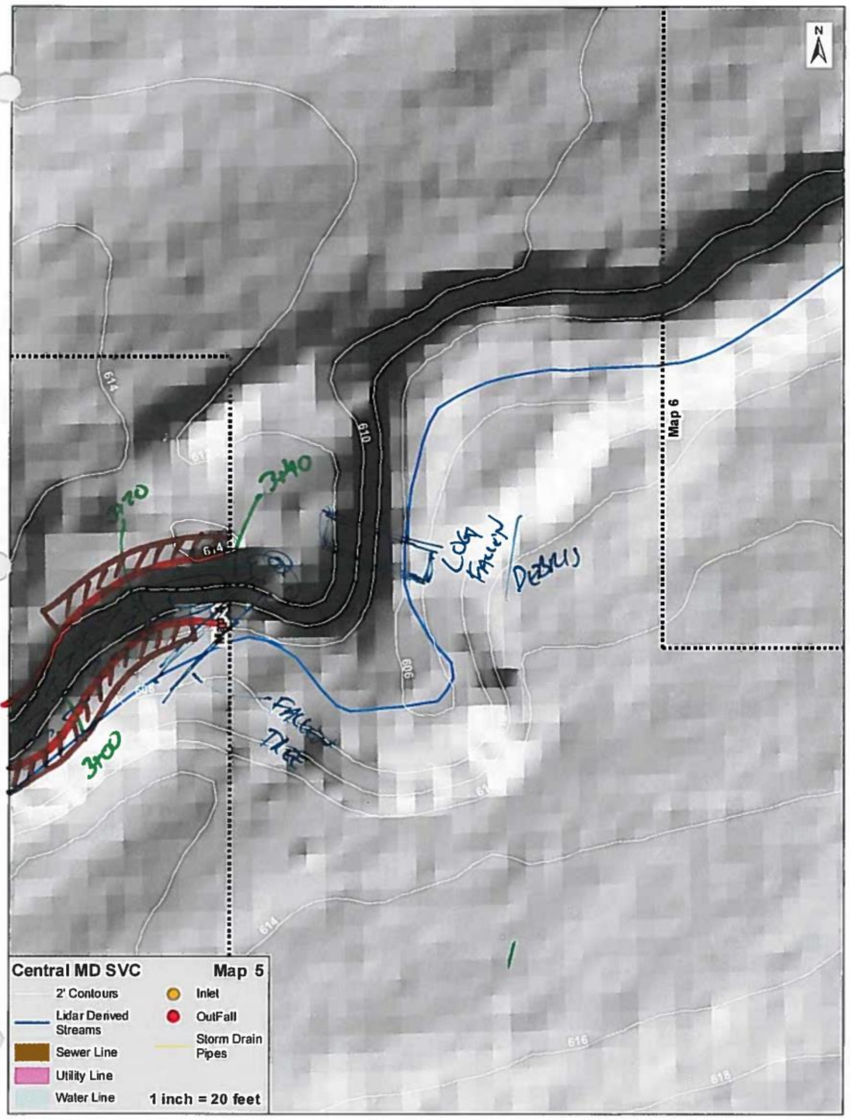
Geomorphic mapping for all sites was conducted in November 2016.

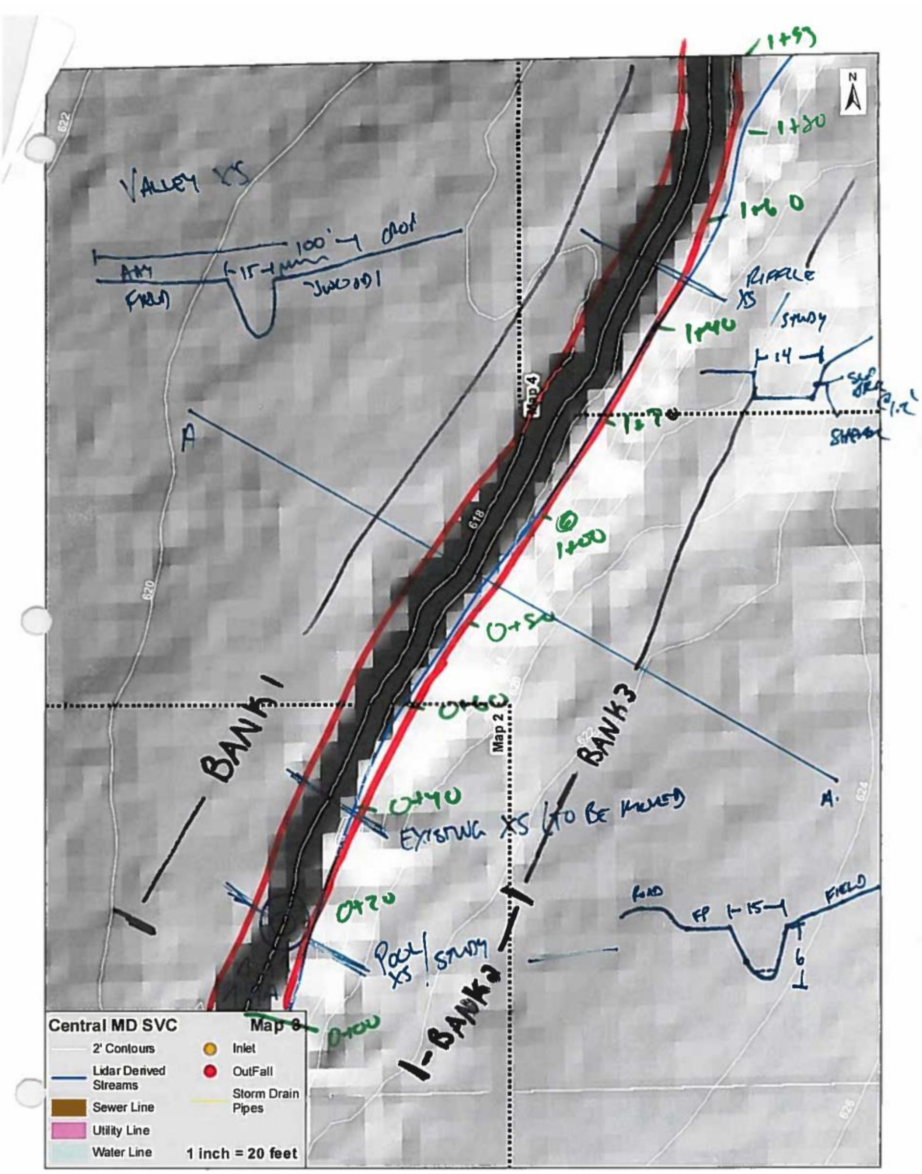


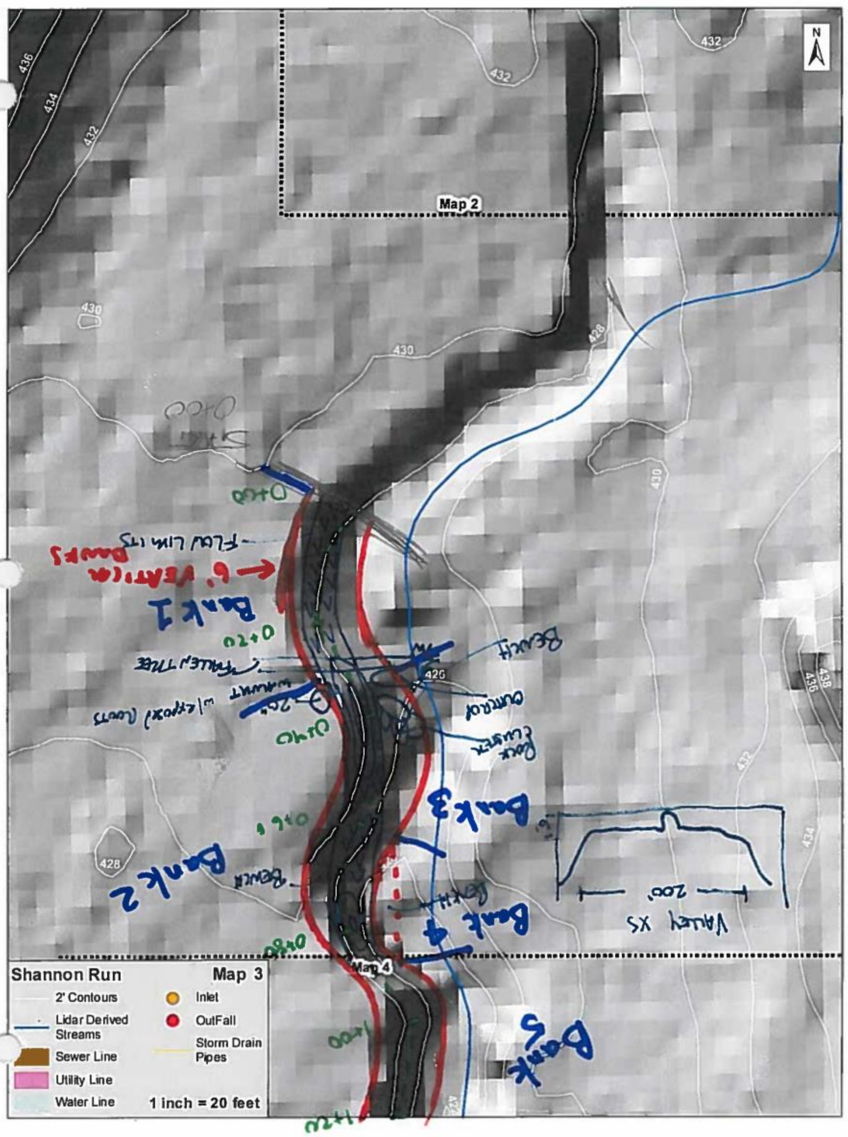


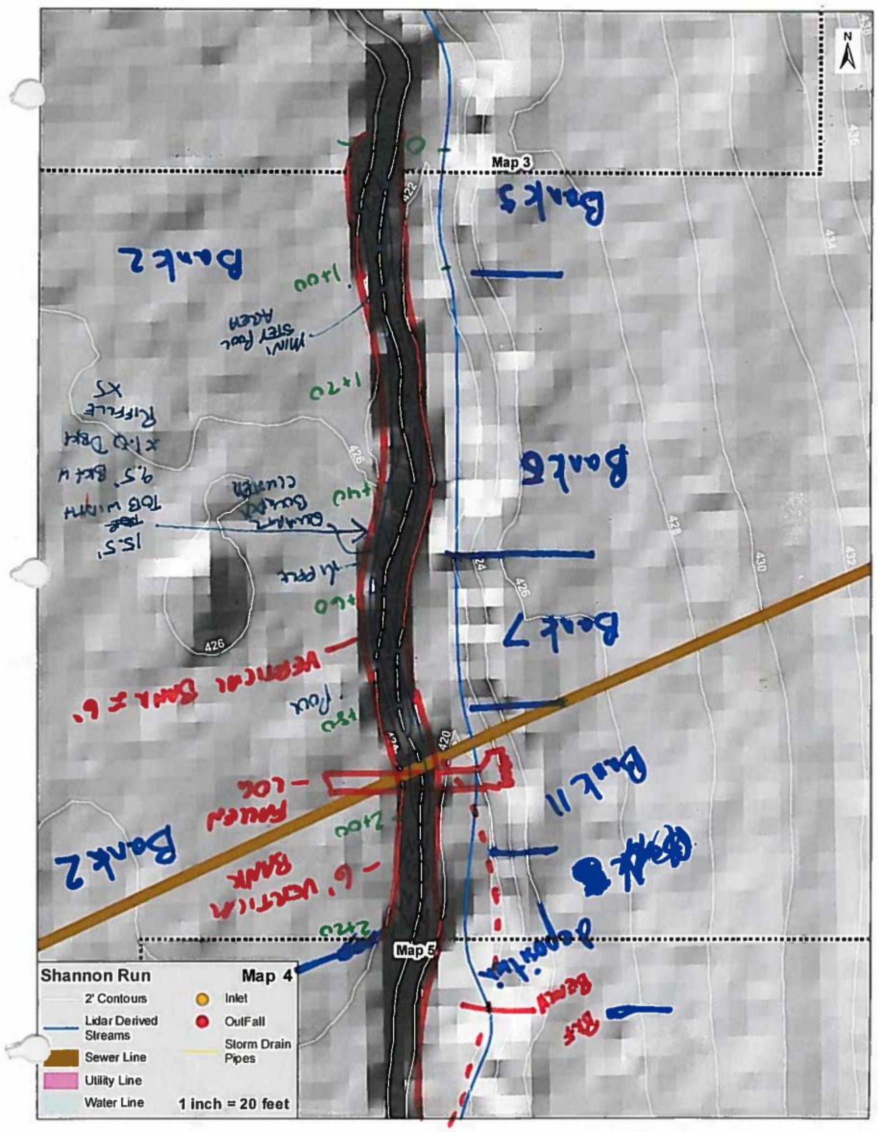
Blue Ridge Manor
Map 3
2' Contours
Inlet
Lidar Derived Streams
OutFall
Sewer Line
Storm Drain Pipes
Utility Line
Water Line
1 inch = 20 feet
N
Map 4
Map 2
HEADCUT
EXISTING XS POOL
POOL XS
RIFFLE XS
0+20
1480

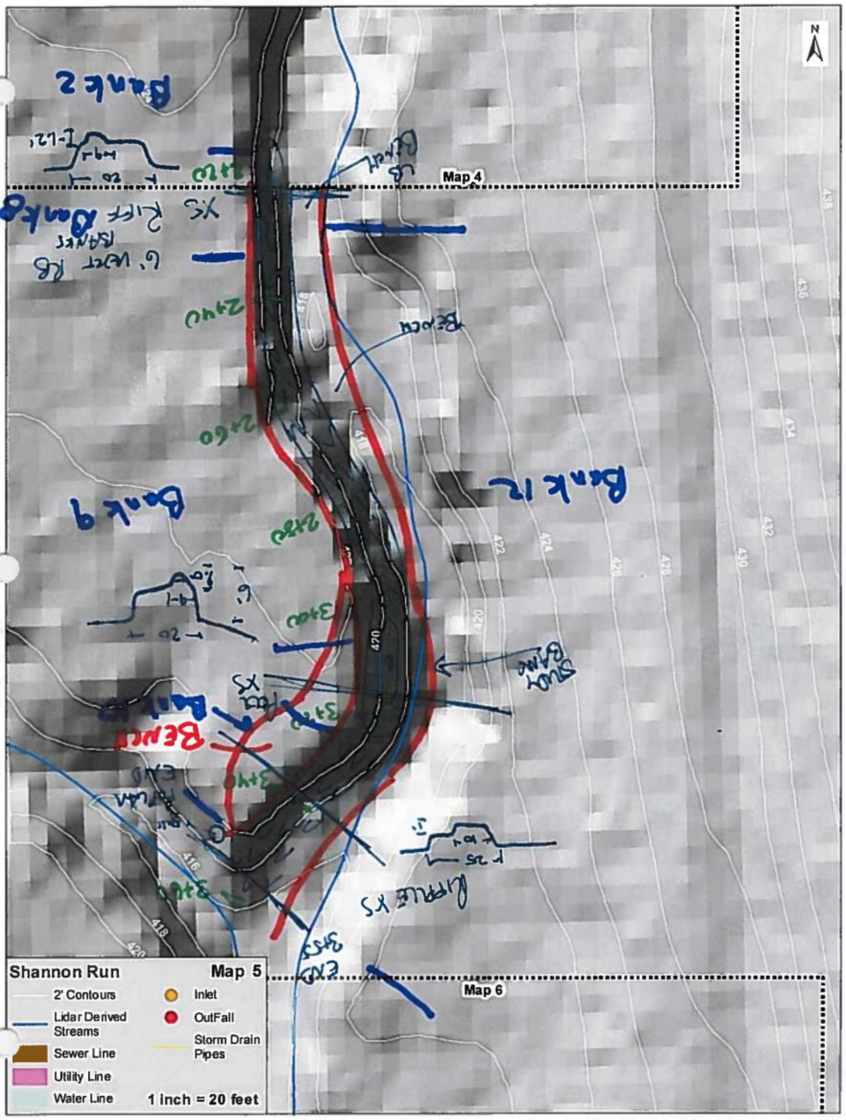

Central MD SVC
Map 4
2' Contours
Lidar Derived Streams
Sewer Line
Utility Line
Water Line
Inlet
OutFall
Storm Drain Pipes
1 inch = 20 feet
Map 3
Map 5
N
614
612
616
618
620
610
608
622
624
626
628
BANK 1
BANK 3
BANK 4
BENCH
RIFFLE XS
GLIDE XS
- VERT ERODING BANK

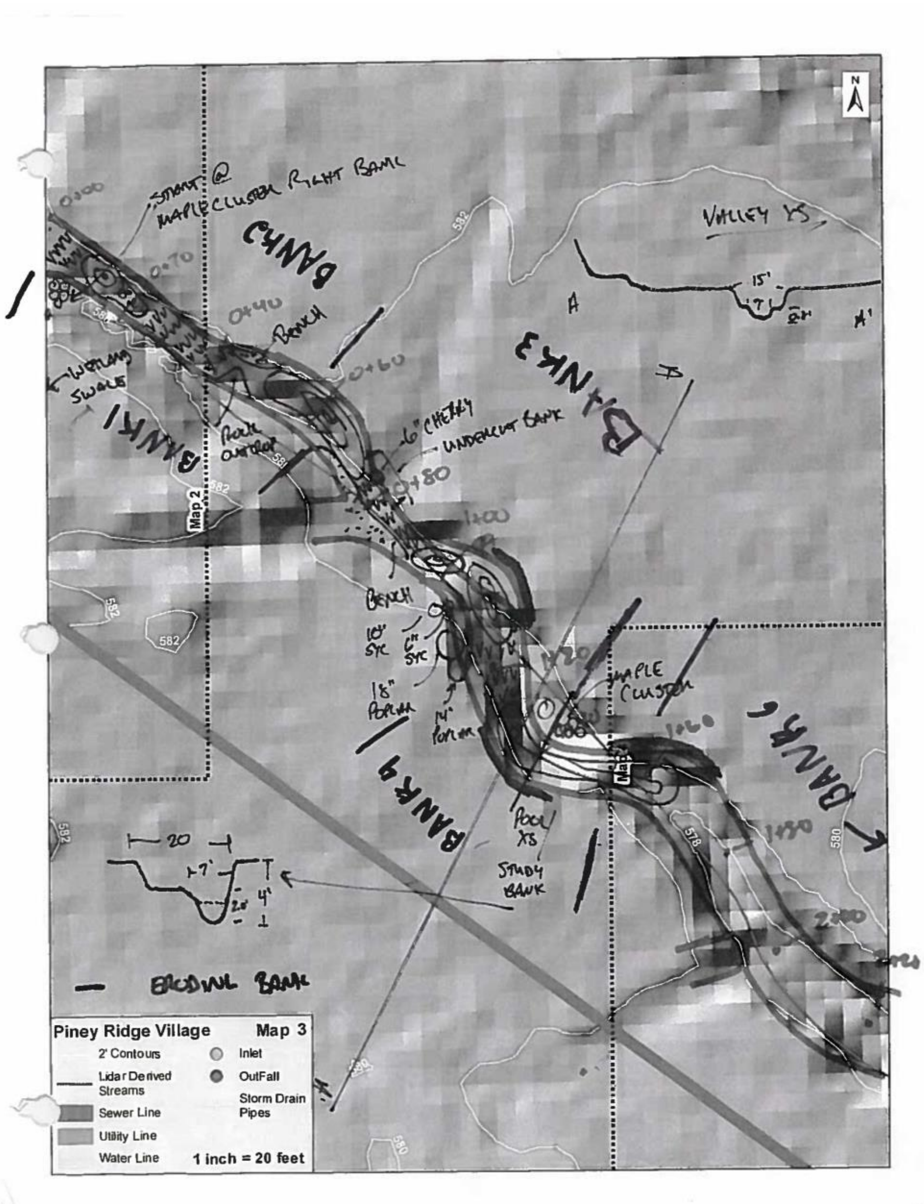

Map 6
Central MD SVC
Map 5
2' Contours
Lidar Derived Streams
Sewer Line
Utility Line
Water Line
Inlet
OutFall
Storm Drain Pipes
1 inch = 20 feet


Central MD SVC
2' Contours
Inlet
Lidar Derived Streams
OutFall
Sewer Line
Storm Drain Pipes
Utility Line
Water Line
1 inch = 20 feet
Map 4
Map 2
618
VALLEY XS
BANK 1
BANK 3
BANK 2
RIFFLE XS / STUDY
POOL XS / STUDY
FIELD

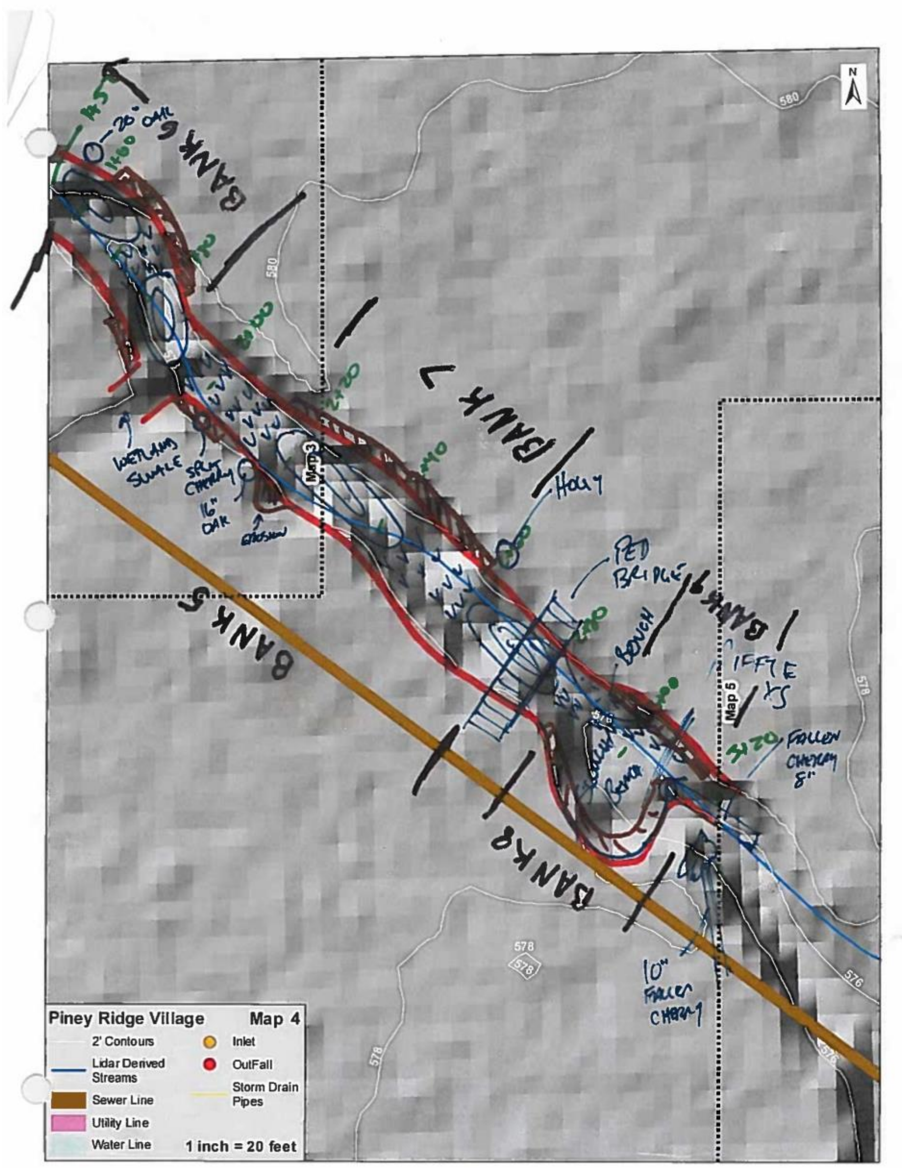

Map 2
Shannon Run
Map 3
2' Contours
Lidar Derived Streams
Sewer Line
Utility Line
Water Line
Inlet
OutFall
Storm Drain Pipes
1 inch = 20 feet
Map 4
N

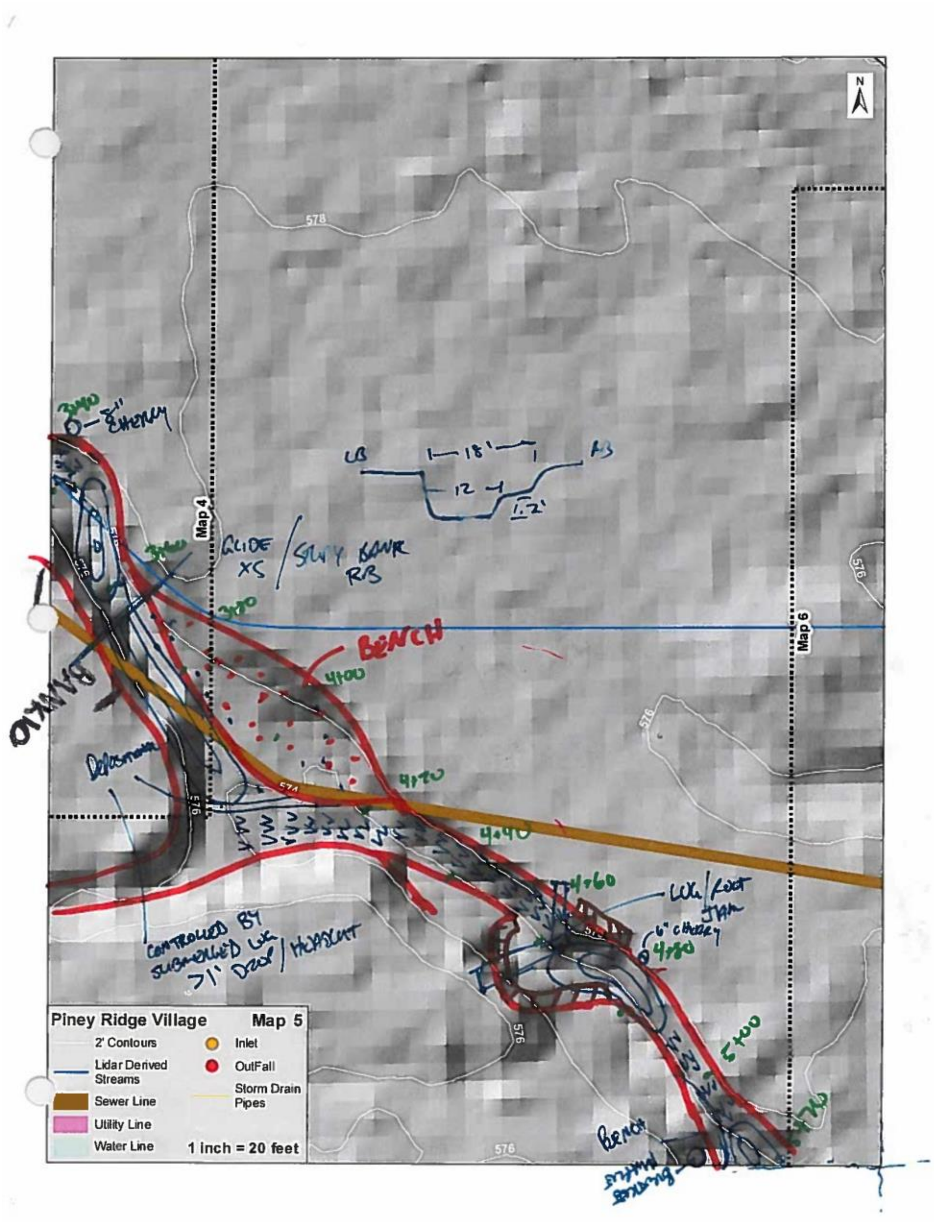

Map 3
Map 5
Shannon Run
Map 4
2' Contours
Lidar Derived Streams
Sewer Line
Utility Line
Water Line
Inlet
OutFall
Storm Drain Pipes
1 inch = 20 feet


Map 4
Map 6
Shannon Run
Map 5
2' Contours
Lidar Derived Streams
Sewer Line
Utility Line
Water Line
Inlet
OutFall
Storm Drain Pipes
1 inch = 20 feet



Piney Ridge Village
Map 3
2' Contours
Lidar Derived Streams
Sewer Line
Utility Line
Water Line
Inlet
OutFall
Storm Drain Pipes
1 inch = 20 feet
Map 2
582
580
578
VALLEY XS
ERODING BANK


Piney Ridge Village
Map 4
2' Contours
Lidar Derived Streams
Sewer Line
Utility Line
Water Line
Inlet
OutFall
Storm Drain Pipes
1 inch = 20 feet
Map 3
Map 5
580
578
576
BANK 5
BANK 6
BANK 7
BANK 8
PED BRIDGE
HOLLY
WETLAND SWALE
16" OAK
FALLEN CHERRY 8"
10" FALLEN CHERRY


Piney Ridge Village
Map 5
2' Contours
Lidar Derived Streams
Sewer Line
Utility Line
Water Line
Inlet
OutFall
Storm Drain Pipes
1 inch = 20 feet
Map 4
Map 6
578
576
574

Appendix D. Stage, Rainfall, and Discharge Measurements

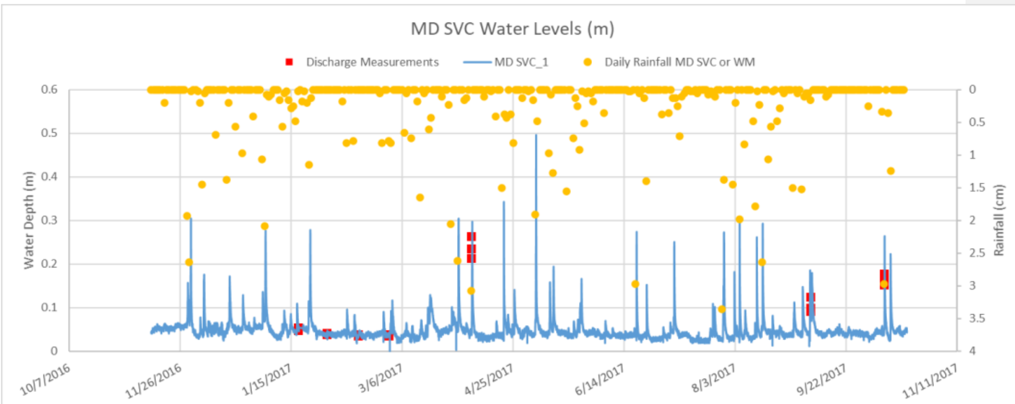


Figure D-1. Pretreatment stage, rainfall, and discharge measurements at Central MD SVC.

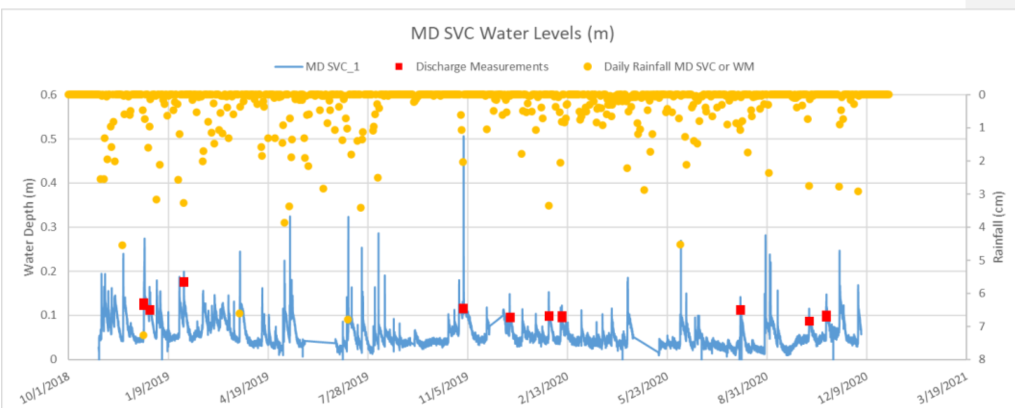


Figure D-2. Post-treatment stage, rainfall, and discharge measurements at Central MD SVC.

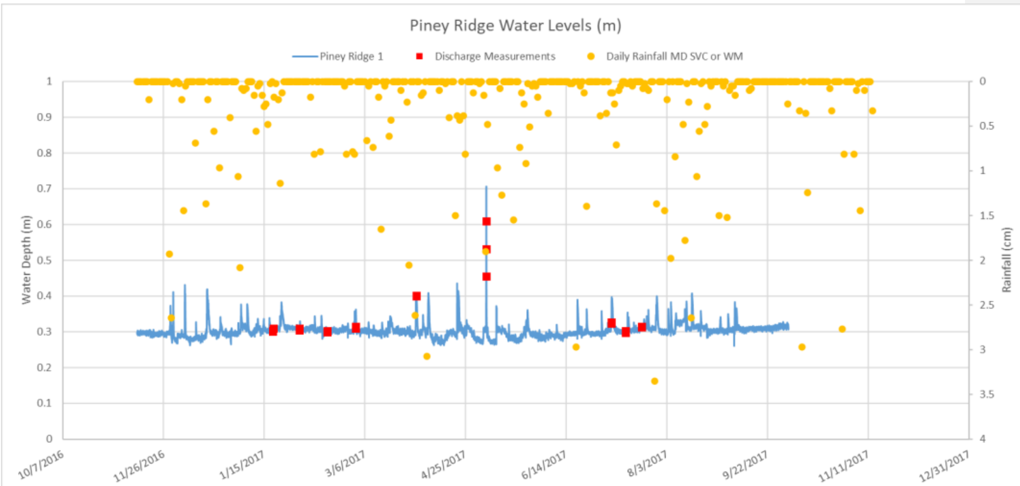


Figure D-3. Pretreatment stage, rainfall, and discharge measurements at Piney Ridge.

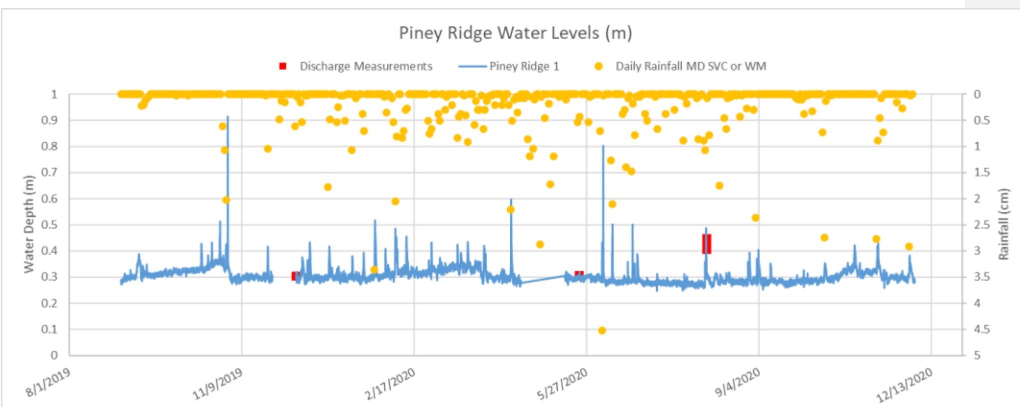


Figure D-4. Post-treatment stage, rainfall, and discharge measurements at Piney Ridge.

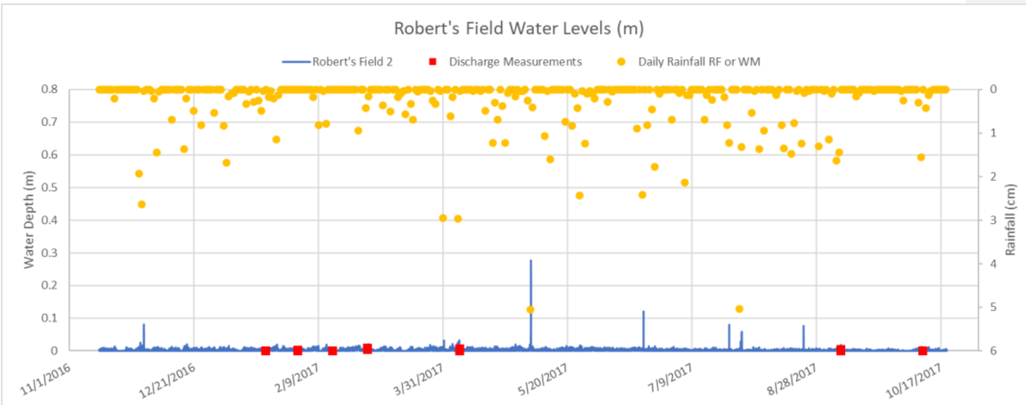


Figure D-5. Pretreatment stage, rainfall, and discharge measurements at Robert's Field.

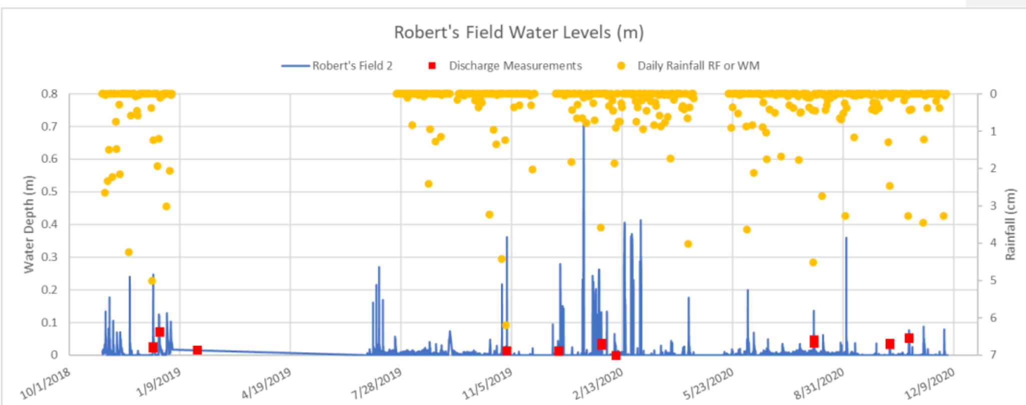


Figure D-6. Post-treatment stage, rainfall, and discharge measurements at Robert's Field.

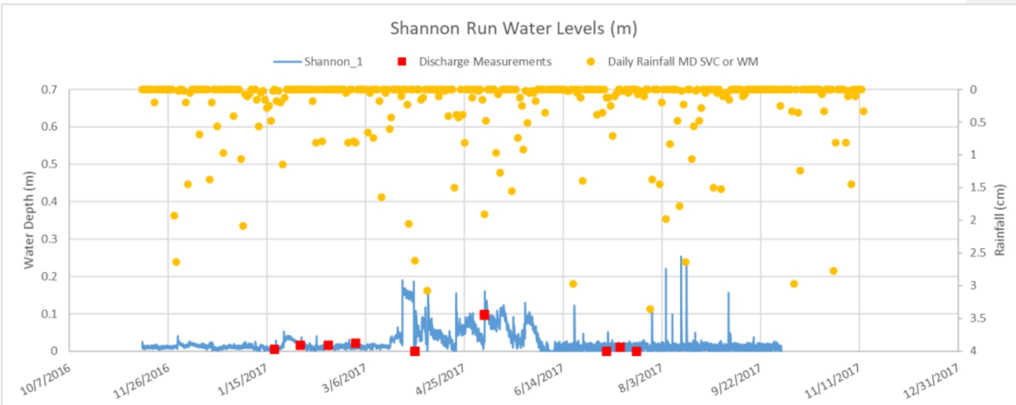


Figure D-7. Pretreatment stage, rainfall, and discharge measurements at Shannon Run.

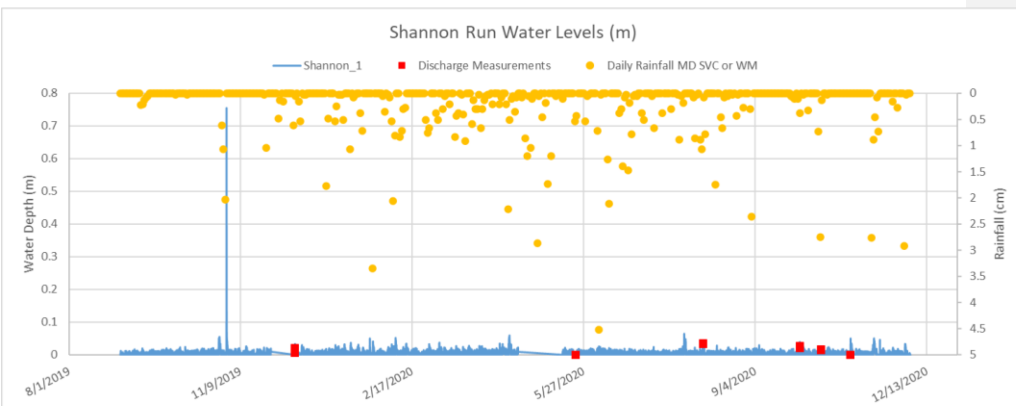


Figure D-8. Post-treatment stage, rainfall, and discharge measurements at Shannon Run.

Appendix E. Flow Rating Curves

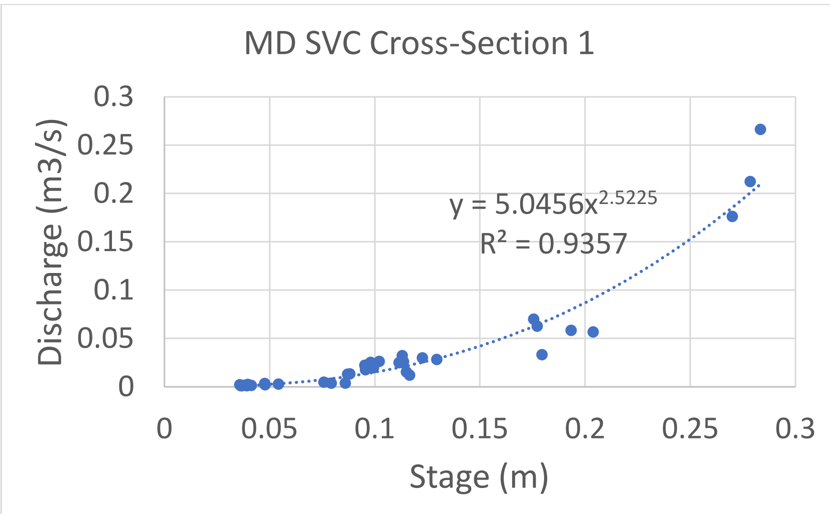


Figure E-1. Flow rating curve for cross-section 1 at Central MD SVC.

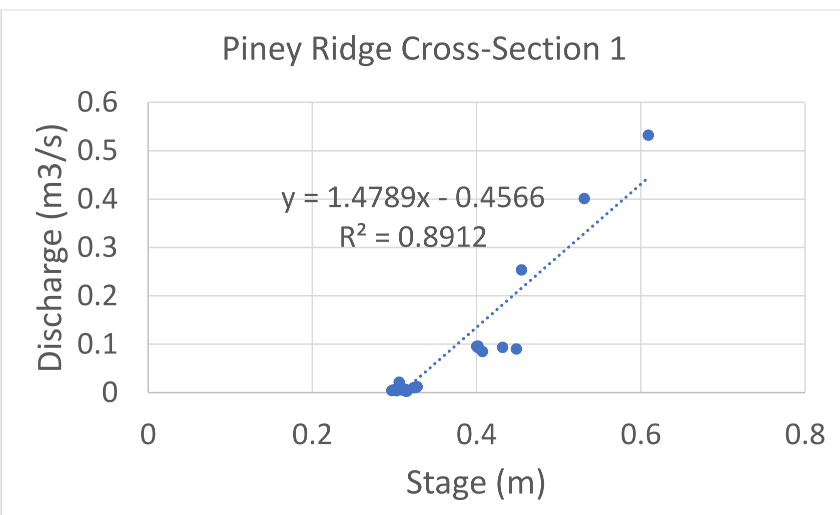


Figure E-2. Flow rating curve for cross-section 1 at Piney Ridge.

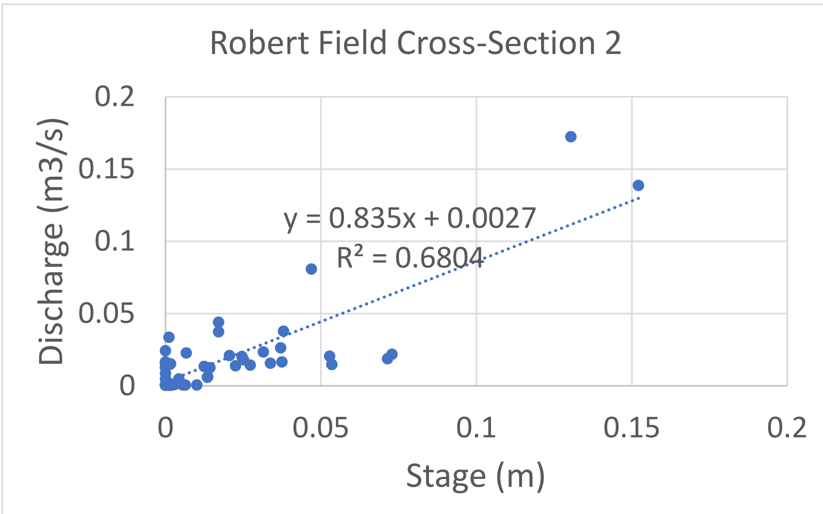


Figure E-3. Flow rating curve for cross-section 2 at Robert's Field.

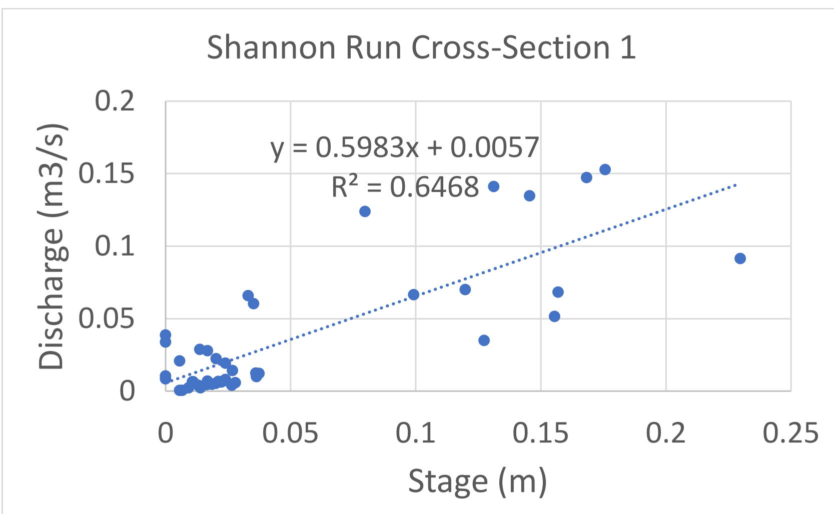


Figure E-4. Flow rating curve for cross-section 1 at Shannon Run.

Appendix F. Paired Runoff and Peak Discharge Relationships

Runoff Depths

The initial data set included runoff depths for the post-developed condition that were much greater than the depths experienced (in the control watersheds) in the pre-developed condition (Figure F-1). Consequently, the datasets were limited as follows:

- Piney Ridge data sets limited to events where the pre-developed runoff depth at Piney Ridge was less than 2 cm.
- Robert's Field-Central Maryland SVC limited to events where Robert's Field runoff depths are less than 1 cm.
- Robert's Field-Shannon Run limited to events where Robert's Field runoff depths are less than 3 cm.

The resulting data set (Figure F-2) was used to develop regression relationships between the control and treatment pairs.

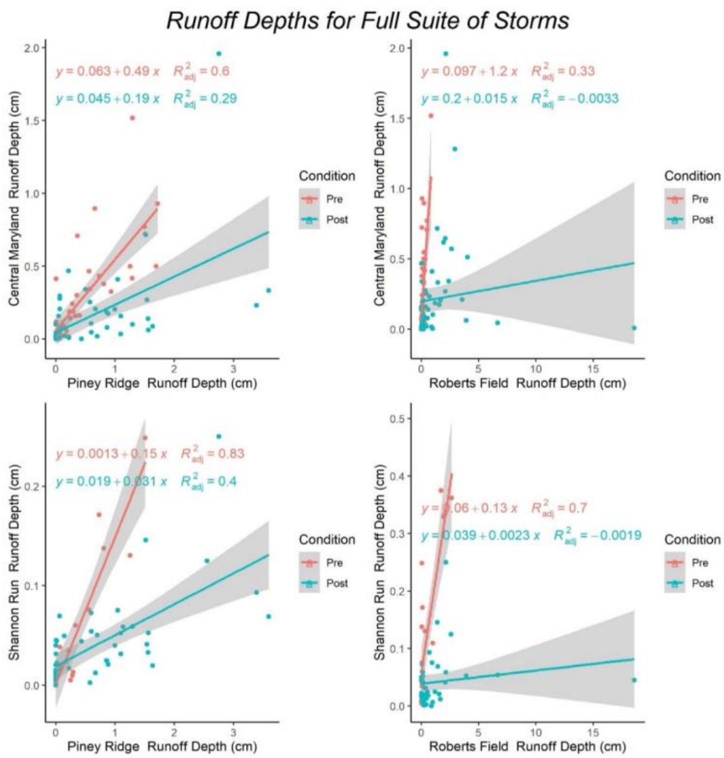


Figure F-1. Full Suite of Storms Runoff Depth Comparisons

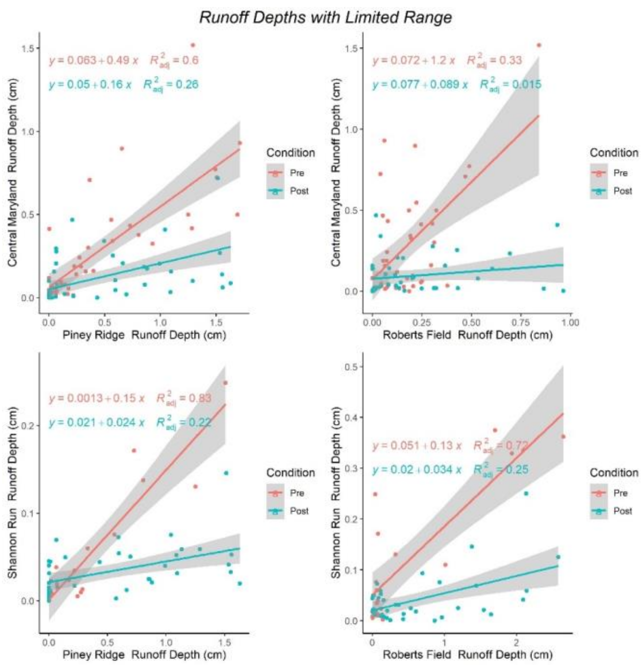


Figure F-2. Restricted Suite of Storms Runoff Depth Comparisons

To test the statistical significance of slope changes, an ANCOVA analysis was completed by developing linear regression models of the following form:

Runoff Depth (Treatment) = Runoff Depth (Control) + Condition (Post- or Pre-) +

Runoff Depth (Control) X Condition (Post- or Pre-)

The last term (the Interaction term) reflects the change in slope between the Pre- and Post- condition, highlighted in model results below. The estimate is the absolute change in slope, while the Pr value reflects significance level.

Runoff Depth Model Results

Piney Shannon Runoff Depth Model

```
Call:
```

```
lm(formula = Treat ~ Condition * Control, data = PSMod)

Residuals:
      Min        1Q    Median        3Q       Max 
-0.056040 -0.016386 -0.004782  0.012531  0.088587 

Coefficients:
                       Estimate Std. Error t value Pr(>|t|)    
(Intercept)            0.001299   0.009526   0.136   0.8921    
ConditionPost          0.019982   0.011079   1.804   0.0772 .  
Control                0.148026   0.015393   9.616 4.81e-13 ***
ConditionPost:Control -0.124357   0.017036  -7.300 1.83e-09 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.02618 on 51 degrees of freedom
Multiple R-squared:  0.7006,	Adjusted R-squared:  0.683 
F-statistic: 39.78 on 3 and 51 DF,  p-value: 2.15e-13
```

Piney Central Maryland Runoff Depth Model

```
Call:
lm(formula = Treat ~ Condition * Control, data = PMMod)

Residuals:
     Min       1Q   Median       3Q      Max 
-0.38552 -0.06306 -0.03767  0.00142  0.82792 

Coefficients:
                      Estimate Std. Error t value Pr(>|t|)    
(Intercept)            0.06306    0.03397   1.856   0.0665 .  
ConditionPost         -0.01275    0.04528  -0.282   0.7788    
Control                0.48534    0.05074   9.566 1.70e-15 ***
ConditionPost:Control -0.32846    0.06657  -4.934 3.52e-06 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.1723 on 93 degrees of freedom
Multiple R-squared:  0.5697,	Adjusted R-squared:  0.5558 
F-statistic: 41.04 on 3 and 93 DF,  p-value: < 2.2e-16
```

Roberts Shannon Runoff Depth Model

```
Call:
lm(formula = Treat ~ Condition * Control, data = RSMod)

Residuals:
      Min        1Q    Median        3Q       Max 
-0.077619 -0.034296 -0.007658  0.021593  0.192396 

Coefficients:
                      Estimate Std. Error t value Pr(>|t|)    
(Intercept)            0.05076    0.01504   3.375  0.00139 ** 
ConditionPost         -0.03046    0.01871  -1.628  0.10942    
Control                0.13485    0.01454   9.273 1.10e-12 ***
ConditionPost:Control -0.10096    0.01867  -5.409 1.55e-06 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.05268 on 53 degrees of freedom
Multiple R-squared:  0.7086,	Adjusted R-squared:  0.6921 
F-statistic: 42.96 on 3 and 53 DF,  p-value: 3.224e-14
```

Roberts Maryland Central Runoff Depth Model

```
Call:
lm(formula = Treat ~ Condition * Control, data = RMMod)

Residuals:
     Min       1Q   Median       3Q      Max 
-0.49526 -0.08868 -0.04615  0.06347  0.78475 

Coefficients:
                       Estimate Std. Error t value Pr(>|t|)    
(Intercept)            0.072217   0.049558   1.457    0.149    
ConditionPost          0.004612   0.065379   0.071    0.944    
Control                1.205014   0.204153   5.903 9.08e-08 ***
ConditionPost:Control -1.115734   0.239031  -4.668 1.26e-05 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.2082 on 77 degrees of freedom
Multiple R-squared:  0.4076,	Adjusted R-squared:  0.3845 
F-statistic: 17.66 on 3 and 77 DF,  p-value: 8.106e-09
```

The initial data set also included peak discharges for the post-treatment condition that were much greater than the depths experienced (in the control watersheds) in the pretreatment condition (Figure F-3). To resolve this issue, data sets were limited to events where the pretreatment control peak discharge was less than 0.25 m^3/s. This limited data set (Figure F-4) was used to evaluate the change in peak discharge (slope between control and treatment watersheds) between the pre- and post-treatment conditions.

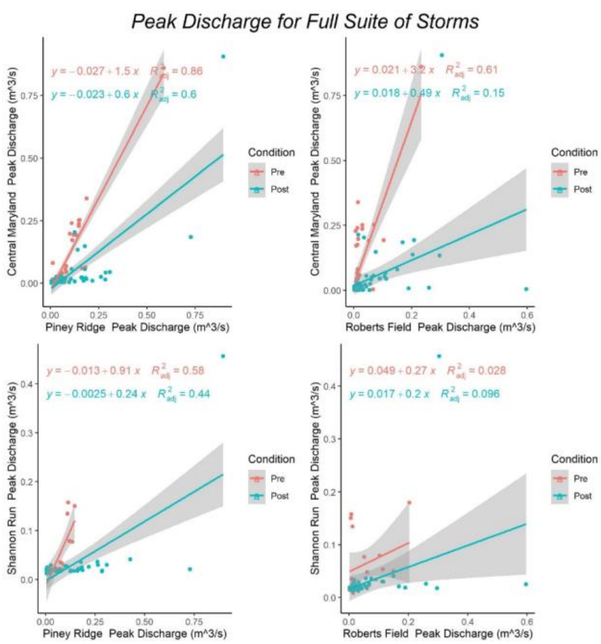


Figure F-3. Full Suite of Storms Peak Discharge Comparison

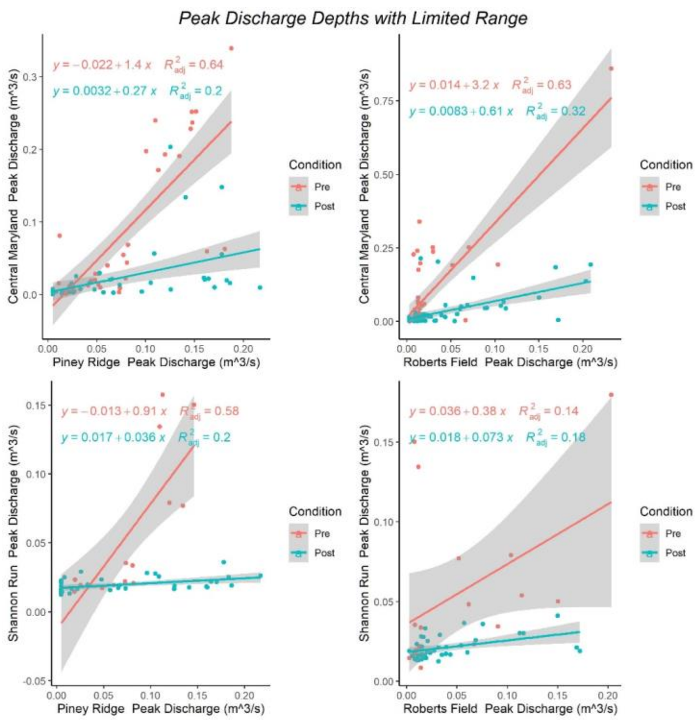


Figure F-4. Restricted Suite of Storms Peak Discharge Comparisons

To test the statistical significance of slope changes, an ANCOVA analysis was completed by developing linear regression models of the following form:

Peak Discharge (Treatment) = Peak Discharge (Control) + Condition (Post- or Pre-) +

Peak Discharge (Control) X Condition (Post- or Pre-)

The last term (the Interaction term) reflects the change in slope between the Pre- and Post- condition, highlighted in model results below. The estimate is the absolute change in slope, while the Pr value reflects significance level.

Peak Discharge Model Results

Peak Discharge Model for Roberts and Central Maryland

```
Call:
lm(formula = Treat ~ Control + Condition + Condition * Control,
    data = RMMod)

Residuals:
      Min        1Q    Median        3Q       Max
-0.224590 -0.025329 -0.011992  0.005227  0.278702

Coefficients:
                       Estimate Std. Error t value Pr(>|t|)
(Intercept)            0.014159   0.013253   1.068    0.288
Control                3.212792   0.288322  11.143  < 2e-16 ***
ConditionPost         -0.005881   0.018147  -0.324    0.747
Control:ConditionPost -2.599525   0.341369  -7.615 2.14e-11 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.06999 on 93 degrees of freedom
Multiple R-squared:  0.6211,   Adjusted R-squared:  0.6089
F-statistic: 50.81 on 3 and 93 DF,  p-value: < 2.2e-16
```

Peak Discharge Model for Roberts and Shannon

```
Call:
lm(formula = Treat ~ Control + Condition + Condition * Control,
    data = RSMod)

Residuals:
      Min        1Q    Median        3Q       Max
-0.042329 -0.007699 -0.003002  0.003760  0.111434

Coefficients:
                       Estimate Std. Error t value Pr(>|t|)
(Intercept)            0.035883   0.008467   4.238 9.25e-05 ***
Control                0.376225   0.109265   3.443  0.00114 **
ConditionPost         -0.017529   0.010332  -1.697  0.09574 .
Control:ConditionPost -0.303059   0.146082  -2.075  0.04299 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.02643 on 52 degrees of freedom
Multiple R-squared:  0.3873,   Adjusted R-squared:  0.352
F-statistic: 10.96 on 3 and 52 DF,  p-value: 1.098e-05
```

Peak Discharge Model for Piney Central Maryland

```
Call:
lm(formula = Treat ~ Control + Condition + Condition * Control,
    data = PMMod)

Residuals:
      Min        1Q    Median        3Q       Max
-0.166104 -0.020711 -0.002745  0.014431  0.165535

Coefficients:
                      Estimate Std. Error t value Pr(>|t|)
(Intercept)           -0.02185    0.01125  -1.943   0.0551 .
Control                1.38678    0.13072  10.609  < 2e-16 ***
ConditionPost          0.02505    0.01434   1.747   0.0842 .
Control:ConditionPost -1.11242    0.16427  -6.772 1.32e-09 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.04604 on 89 degrees of freedom
Multiple R-squared:  0.6243,   Adjusted R-squared:  0.6116
F-statistic: 49.29 on 3 and 89 DF,  p-value: < 2.2e-16
```

Peak Discharge Model for Piney-Shannon

```
Call:
lm(formula = Treat ~ Control + Condition + Condition * Control,
    data = PSMod)

Residuals:
      Min        1Q    Median        3Q       Max
-0.041376 -0.004596 -0.001552  0.004907  0.067081

Coefficients:
                       Estimate Std. Error t value Pr(>|t|)
(Intercept)           -0.012619   0.009332  -1.352   0.1827
Control                0.911208   0.108948   8.364 7.34e-11 ***
ConditionPost          0.029816   0.010314   2.891   0.0058 **
Control:ConditionPost -0.875639   0.117460  -7.455 1.68e-09 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.0182 on 47 degrees of freedom
Multiple R-squared:  0.7004,   Adjusted R-squared:  0.6813
F-statistic: 36.63 on 3 and 47 DF,  p-value: 2.343e-12
```

Appendix G. Curve Numbers

Table G-1. Pretreatment curve numbers for rain events greater than or equal to 1 inch.

	Start Date/Time	End Date/Time	Rainfall (cm)	Stormflow (m^3)	Adjusted Curve Number
Shannon Run	6/19/17 14:52	6/19/17 22:29	2.95	1276.5	87.51
	7/28/17 13:07	7/29/17 2:12	4.62	743.7	78.25
	8/14/17 19:23	8/15/17 13:27	2.84	1617.6	88.74
				Average:	**84.83**
Piney Ridge	1/2/17 1:42	1/3/17 13:47	3.12	651.1	74.06
	6/19/17 14:52	6/19/17 22:29	2.95	2289.2	92.94
	7/28/17 13:07	7/29/17 2:12	4.62	3606.6	89.38
	8/14/17 19:23	8/15/17 13:27	2.84	2057.6	92.86
				Average:	**87.31**
Central MD SVC	1/2/17 1:42	1/3/17 13:47	3.12	2736.1	84.97
	6/19/17 14:52	6/19/17 22:29	2.95	1324.7	90.58
	7/28/17 13:07	7/29/17 2:12	4.62	2659.3	87.42
	8/14/17 19:23	8/15/17 13:27	2.84	2074.7	92.86
	10/8/17 5:57	10/9/17 10:08	3.25	1357.1	89.38
				Average:	**89.04**
Robert’s Field	1/2/17 2:18	1/4/17 12:24	2.67	1082.9	84.67
	3/30/17 23:35	3/31/17 23:13	2.95	568.9	89.25
	4/6/17 5:29	4/6/17 17:28	2.95	450.8	58.25
	5/4/17 21:46	5/5/17 15:00	5.28	1160.9	82.97
	7/28/17 13:30	7/29/17 3:25	5.03	703.8	44.26
	9/5/17 16:55	9/6/17 21:32	3.05	493.2	88.27
				Average:	**74.61**

Table G-2. Post-treatment curve numbers for rain events greater than or equal to 1 inch.

	Start Date/Time	End Date/Time	Rainfall (cm)	Stormflow (m^3)	Adjusted Curve Number
Shannon Run	1/25/20 2:20	1/25/20 10:58	2.82	189.5	48.98
	6/5/20 14:33	6/5/20 18:12	2.95	52.6	65.67
	6/10/20 19:26	6/11/20 2:44	3.15	37.1	80.69
	10/11/20 16:52	10/12/20 20:37	3.40	224.1	81.29
	11/30/20 4:39	11/30/20 16:17	2.79	366.9	51.29
				Average:	**65.58**
Piney Ridge	1/25/20 2:20	1/25/20 10:58	2.82	5786.7	87.92
	2/5/20 21:51	2/7/20 9:46	3.20	16187.0	100.00
	4/12/20 21:44	4/14/20 23:20	2.87	9648.8	99.63
	6/5/20 14:33	6/6/20 2:44	3.12	4103.3	89.07
	6/10/20 19:26	6/11/20 6:19	3.30	4007.4	94.42
	10/11/20 16:52	10/12/20 23:19	3.45	3106.9	92.58
	11/11/20 15:41	11/12/20 2:00	2.84	3972.0	90.54
	11/30/20 4:26	11/30/20 16:17	2.82	2585.5	73.92

				Average:	**91.01**
Central MD SVC	11/15/18 20:39	11/16/18 11:00	2.74	1191.2	64.97
	11/24/18 13:08	11/24/18 20:01	4.47	1622.2	51.27
	12/14/18 18:08	12/16/18 12:19	8.41	6674.1	82.34
	12/20/18 15:31	12/22/18 0:33	2.57	902.5	80.64
	12/27/18 23:57	12/28/18 14:44	3.10	1203.5	89.53
	1/19/19 18:23	1/20/19 7:11	3.71	1755.4	58.83
	1/24/19 1:09	1/24/19 14:02	3.20	945.0	57.57
	2/12/19 9:56	2/13/19 16:25	3.68	2585.5	80.47
	3/21/19 4:28	3/22/19 5:07	6.93	2332.6	39.69
	4/12/19 13:35	4/13/19 5:21	3.40	595.6	71.34
	5/4/19 20:17	5/5/19 18:26	4.65	1361.7	68.18
	5/10/19 8:38	5/10/19 20:56	3.25	538.6	52.75
	7/8/19 1:39	7/8/19 13:48	6.76	1101.8	34.86
	7/21/19 20:19	7/21/19 21:16	3.25	48.9	64.35
	8/7/19 14:22	8/8/19 7:58	2.79	403.3	74.27
	1/25/20 1:05	1/25/20 10:58	3.30	665.2	53.71
	2/5/20 21:51	2/7/20 10:17	3.28	1166.3	88.64
				Average:	**65.49**
Robert’s Field	11/2/18 10:43	11/3/18 6:24	2.57	2923.9	93.99
	11/5/18 6:15	11/6/18 23:49	3.81	5627.6	88.48
	11/24/18 13:29	11/24/18 20:43	4.09	2143.2	65.03
	12/14/18 21:06	12/16/18 3:02	6.07	4100.0	89.41
	12/20/18 15:40	12/21/18 17:45	2.92	4286.0	90.78
	12/28/18 0:31	12/28/18 19:43	3.02	4060.3	88.62
	7/7/19 22:12	7/8/19 12:13	4.78	1800.6	74.70
	7/22/19 15:44	7/23/19 6:55	3.12	1274.4	91.84
	8/22/19 19:23	8/23/19 14:13	3.28	1155.4	90.79
	10/16/19 11:25	10/16/19 16:22	3.15	525.7	88.04
	10/27/19 1:26	10/27/19 10:37	4.32	1200.8	73.55
	10/30/19 18:40	10/31/19 22:00	7.24	2423.8	44.20
	1/25/20 1:13	1/25/20 9:32	3.53	1118.5	61.20
	2/5/20 22:02	2/7/20 11:06	3.10	1388.7	92.34
	4/12/20 21:35	4/13/20 13:07	4.60	2642.6	80.33
	6/4/20 19:35	6/5/20 20:46	4.44	2380.4	90.50
	6/10/20 19:47	6/11/20 6:19	2.79	715.7	90.78
	8/3/20 23:34	8/4/20 10:03	4.42	1035.6	85.68
	8/12/20 14:07	8/12/20 16:47	2.57	161.8	87.44
	9/2/20 18:22	9/3/20 0:07	3.20	992.2	79.83
	10/11/20 15:59	10/12/20 6:56	3.05	1030.2	91.19
	10/29/20 2:57	10/29/20 23:45	3.25	2355.0	94.39
	11/11/20 9:15	11/12/20 6:23	4.50	2227.9	61.90
	11/30/20 3:00	11/30/20 16:10	3.25	1120.8	64.18
				Average:	**81.63**

Appendix H. Cross-Section Data

Table H-1. Pretreatment cross-section data.

Site	XS #	Initial Survey Date	Final Survey Date	Monitoring Timeframe (years)	Left Bank						Channel			Right Bank						Total Cross Section		
					Bank Height (ft)	Total Erosion (ft^2)	Total Deposition (ft^2)	Net Change (ft^2)	Total Erosion Rate (ft/yr)	Net Erosion/ Deposition Rate (ft/yr)	Total Erosion (ft^2)	Total Deposition (ft^2)	Net Change (ft^2)	Bank Height (ft)	Total Erosion (ft2)	Total Deposition (ft2)	Net Change (ft2)	Total Erosion Rate (ft/yr)	Net Erosion/ Deposition Rate (ft/yr)	Total Erosion (ft^2)	Total Deposition (ft^2)	Net Change (ft^2)
Blue Ridge	XS 1	2/21/2017	2/14/2018	0.98	4.8	-2.1	0	-2.1	-0.45	-0.45	-0.4	0.2	-0.2	5.1	-0.2	0.7	0.5	-0.04	0.10	-2.7	0.9	-1.8
Blue Ridge	XS 2	4/20/2017	2/14/2018	0.82	2.4	-0.1	0.1	0	-0.05	0.00	0	0.3	0.3	3.9	-0.2	0.2	0	-0.06	0.00	-0.3	0.6	0.3
Blue Ridge	XS 3	4/20/2017	2/14/2018	0.82	2.4	-1.3	0	-1.3	-0.66	-0.66	-0.2	0.4	0.2	1.8	0	0.2	0.2	0.00	0.14	-1.5	0.6	-0.9
Central MD SVC	XS 1	4/20/2017	2/14/2018	0.82	4.7	0	1.4	1.4	0.00	0.36	0	1.2	1.2	5.8	0	1.2	1.2	0.00	0.25	0.0	3.8	3.8
Central MD SVC	XS 2	4/20/2017	2/14/2018	0.82	5.5	0	0	0	0.00	0.00	0	1	1	4.5	-0.4	0.2	-0.2	-0.11	-0.05	-0.4	1.2	0.8
Central MD SVC	XS 3	4/20/2017	2/14/2018	0.82	5.5	-0.2	1.1	0.9	-0.04	0.20	-0.6	1	0.4	4.4	-0.1	0.5	0.4	-0.03	0.11	-0.9	2.6	1.7
Central MD SVC	XS 4	4/20/2017	2/14/2018	0.82	4.5	-1.1	0	-1.1	-0.30	-0.30	-0.1	0.1	0	4.3	-0.6	0	-0.6	-0.17	-0.17	-1.8	0.1	-1.7
Robert's Field	XS 1	4/20/2017	2/14/2018	0.82	3	0	0.4	0.4	0.00	0.16	0	0.9	0.9	2.9	-0.4	0.1	-0.3	-0.17	-0.13	-0.4	1.4	1.0
Robert's Field	XS 2	4/20/2017	2/14/2018	0.82	3.6	0	0.7	0.7	0.00	0.24	-0.1	0.6	0.5	3.8	-0.5	0.4	-0.1	-0.16	-0.03	-0.6	1.7	1.1
~~Robert's Field~~[1]	~~XS 3~~	~~4/20/2017~~	~~2/14/2018~~																			
Shannon Run	XS 1	4/19/2017	10/1/2018	1.45	5.2	-0.8	0.1	-0.7	-0.11	-0.09	-0.6	4.1	3.5	6.1	-1.9	0	-1.9	-0.21	-0.21	-3.3	4.2	0.9
Shannon Run	XS 2	4/19/2017	10/1/2018	1.45	6.6	-5.3	0	-5.3	-0.56	-0.56	0	2	2	4.5	-0.9	0.9	0	-0.14	0.00	-6.2	2.9	-3.3
Shannon Run	XS 3	4/19/2017	10/1/2018	1.45	5.4	-2	0	-2	-0.25	-0.25	-0.3	4.1	3.8	4.3	-0.1	0.9	0.8	-0.02	0.13	-2.4	5.0	2.6
Piney Ridge	XS 1	4/19/2017	10/1/2018	1.45	2.1	0	0.2	0.2	0.00	0.06	-0.2	3.2	3	4.8	-1.2	0.2	-1	-0.17	-0.14	-1.4	3.6	2.2
Piney Ridge	XS 2	4/19/2017	10/1/2018	1.45	3.7	-0.7	0.5	-0.3	-0.13	-0.05	0	2	2	3.3	0	0.5	0.5	0.00	0.10	-0.7	3.0	2.2
Piney Ridge	XS 3	2/22/2017	10/1/2018	1.61	2.3	0	0.4	0.4	0.00	0.11	0	0.6	0.6	3.7	-1.7	0	-1.7	-0.28	-0.28	-1.7	1.0	-0.7

[1]Robert's Field XS3 pretreatment change could not be calculated due to issues with survey data alignment.

Table H-2. Post-treatment cross-section data.

Site[1]	XS #	Initial Survey Date	Final Survey Date	Monitoring Timeframe (years)	Left Bank						Channel			Right Bank						Total Cross Section		
					Bank Height (ft)	Total Erosion (ft²)	Total Deposition (ft²)	Net Change (ft²)	Total Erosion Rate (ft/yr)	Net Erosion/ Deposition Rate (ft/yr)	Total Erosion (ft²)	Total Deposition (ft²)	Net Change (ft²)	Bank Height (ft)	Total Erosion (ft2)	Total Deposition (ft2)	Net Change (ft2)	Total Erosion Rate (ft/yr)	Net Erosion/ Deposition Rate (ft/yr)	Total Erosion (ft²)	Total Deposition (ft²)	Net Change (ft²)
Central MD SVC	XS 1	10/26/2018	12/18/2020	2.15	4.5	-1.1	0.7	-0.4	-0.11	-0.04	0	0.9	0.9	6	-2.1	0	-2.1	-0.16	-0.16	-3.2	1.6	-1.6
Central MD SVC	XS 2	10/26/2018	12/18/2020	2.15	6.1	-1.9	0	-1.9	-0.15	-0.15	-0.4	0.4	0	4.4	-1	0.6	-0.4	-0.11	-0.04	-3.3	1.0	-2.3
Central MD SVC	XS 3	10/26/2018	12/18/2020	2.15	5.6	-1.3	0.7	-0.6	-0.11	-0.05	-0.8	0.3	-0.5	4.2	-0.8	0	-0.8	-0.09	-0.09	-2.9	1.0	-1.9
Central MD SVC	XS 4	10/26/2018	12/18/2020	2.15	4.4	-4.7	0	-4.7	-0.50	-0.50	-0.4	0.8	0.4	4.3	-0.1	0.8	0.7	-0.01	0.08	-5.2	1.6	-3.6
Robert's Field	XS 1	10/25/2018	12/3/2020	2.11	3.5	-0.7	0.2	-0.5	-0.09	-0.07	0	1.3	1.3	2.9	0	0.8	0.8	0.00	0.13	-0.7	2.3	1.6
Robert's Field	XS 2	10/25/2018	12/3/2020	2.11	3.6	-1.1	0	-1.1	-0.14	-0.14	-0.2	0.5	0.3	3.6	0	0.2	0.2	0.00	0.03	-1.3	0.7	-0.6
Robert's Field	XS 3	10/25/2018	12/3/2020	2.11	3.2	0	0.9	0.9	0.00	0.13	0	1.9	1.9	4.3	-2.3	0	-2.3	-0.25	-0.25	-2.3	2.8	0.5
Shannon Run	XS 1	9/3/2019	12/15/2020	1.28	5.1	0	0.3	0.3	0.00	0.05	0	1.5	1.5	5.8	-0.7	0.6	-0.1	-0.09	-0.01	-0.7	2.4	1.7
Shannon Run	XS 2	9/3/2019	12/15/2020	1.28	6.1	-4	0	-4	-0.51	-0.51	-0.2	1	0.8	4.2	0	0.3	0.3	0.00	0.06	-4.2	1.3	-2.9
Shannon Run	XS 3	9/3/2019	12/15/2020	1.28	5.5	-0.9	0.1	-0.8	-0.13	-0.11	-1.5	0.5	-1	4.2	-0.2	0.6	0.4	-0.04	0.07	-2.6	1.2	-1.4
Piney Ridge	XS 1	9/3/2019	12/11/2020	1.27	2.2	-0.2	0	-0.2	-0.07	-0.07	-1.6	0.4	-1.2	4.3	-0.2	1	0.8	-0.04	0.15	-2.0	1.4	-0.6
~~Piney Ridge~~	~~XS 2~~	~~9/3/2019~~	~~12/15/2020~~	~~1.27~~																		
Piney Ridge	XS 3	9/3/2019	12/11/2020	1.27	2.5	-0.3	0.7	0.4	-0.09	0.13	-1.1	0.5	-0.6	3.8	-0.5	0.3	-0.2	-0.10	-0.04	-1.9	1.5	-0.4

[1]Note Blue Ridge cross-sections were not analyzed due to the site being removed from the analysis. Piney Ridge XS2 was unable to be surveyed due to large bee's nest.

Table H-3. Cross-section total bank erosion and bank deposition rates[1]

Site	XS #	Pretreatment		Post-Treatment	
		Combined Total Bank Erosion Rate (ft/yr)	**Combined Total Bank Deposition Rate (ft/yr)**	**Combined Total Bank Erosion Rate (ft/yr)**	**Combined Total Bank Deposition Rate (ft/yr)**
Central MD SVC	XS1	0.00	0.50	0.28	0.16
Central MD SVC	XS2	0.11	0.04	0.25	0.14
Central MD SVC	XS3	0.07	0.31	0.20	0.13
Central MD SVC	XS4	0.47	0.00	0.51	0.19
Robert's Field	XS1	0.17	0.17	0.09	0.33
Robert's Field	XS2	0.16	0.30	0.14	0.06
Robert's Field[2]	XS3	N/A	N/A	0.25	0.28
Shannon Run	XS1	0.32	0.02	0.09	0.16
Shannon Run	XS2	0.69	0.20	0.51	0.07
Shannon Run	XS3	0.27	0.21	0.16	0.16
Piney Ridge	XS1	0.17	0.14	0.11	0.23
Piney Ridge[3]	XS2	0.13	0.28	N/A	N/A
Piney Ridge	XS3	0.28	0.18	0.20	0.36

[1]Total bank erosion and bank deposition for each cross-section is calculated as the sum of the left and right bank erosion rates and deposition rates.
[2]Robert's Field XS3 pretreatment change could not be calculated due to issues with survey data alignment.
[3]Piney Ridge XS2 post-treatment change could not be calculated because it was not surveyed at the end of the post-treatment period due to hazard from a bee's nest.

Appendix I. Longitudinal Profiles

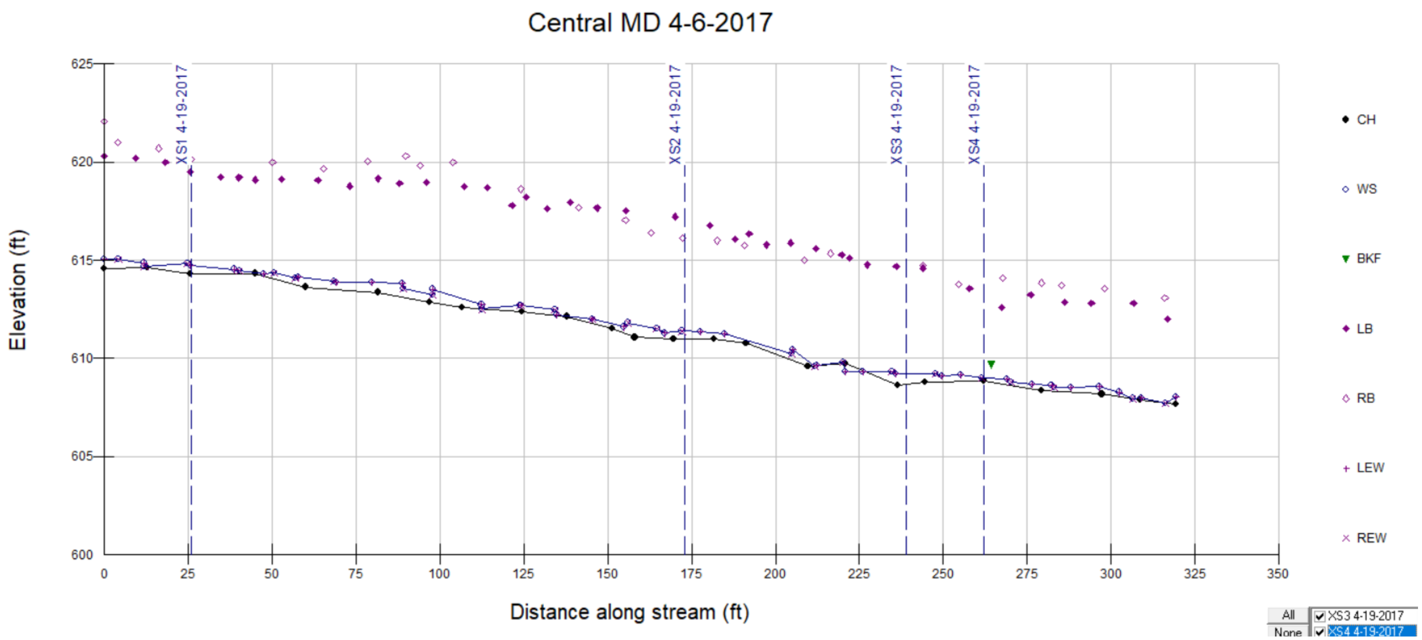


Figure I-1. Central MD SVC pretreatment longitudinal profile.

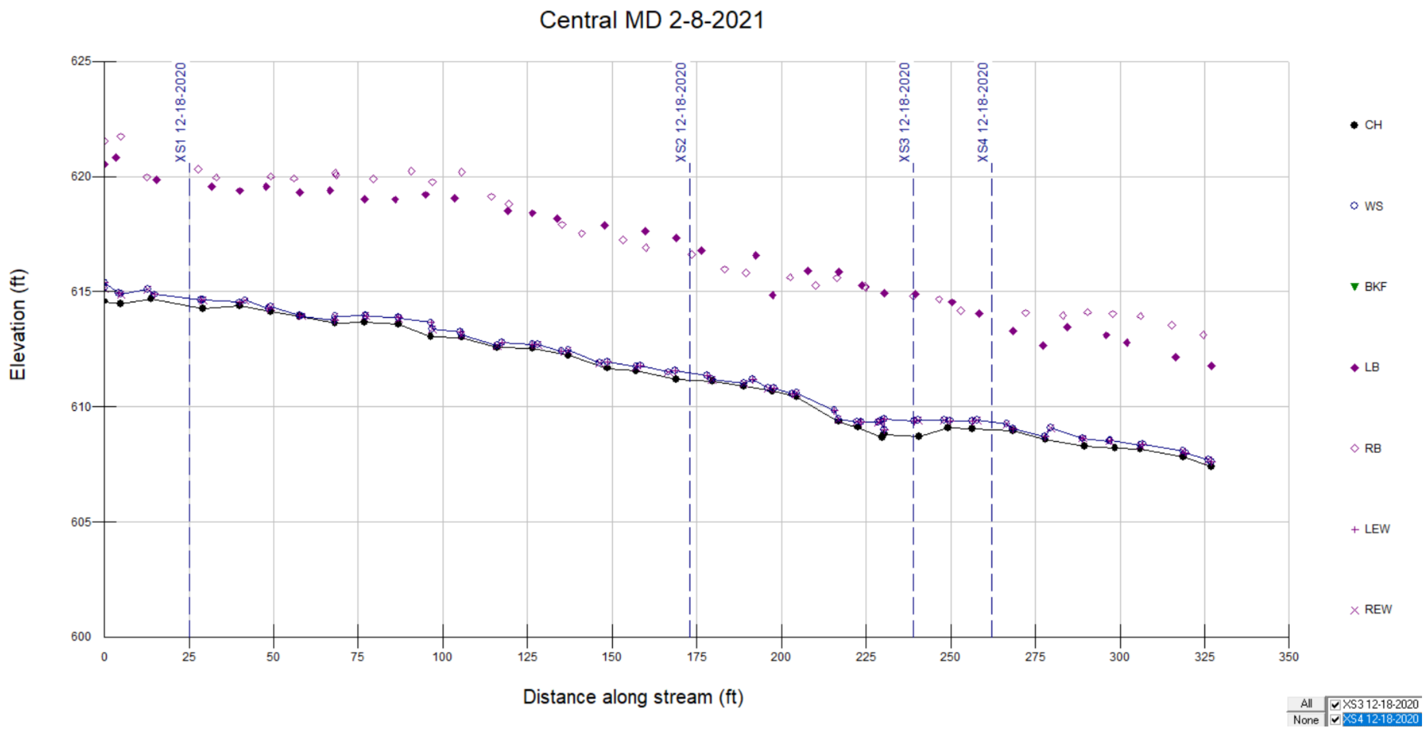


Figure I-2. Central MD SVC post-treatment longitudinal profile.

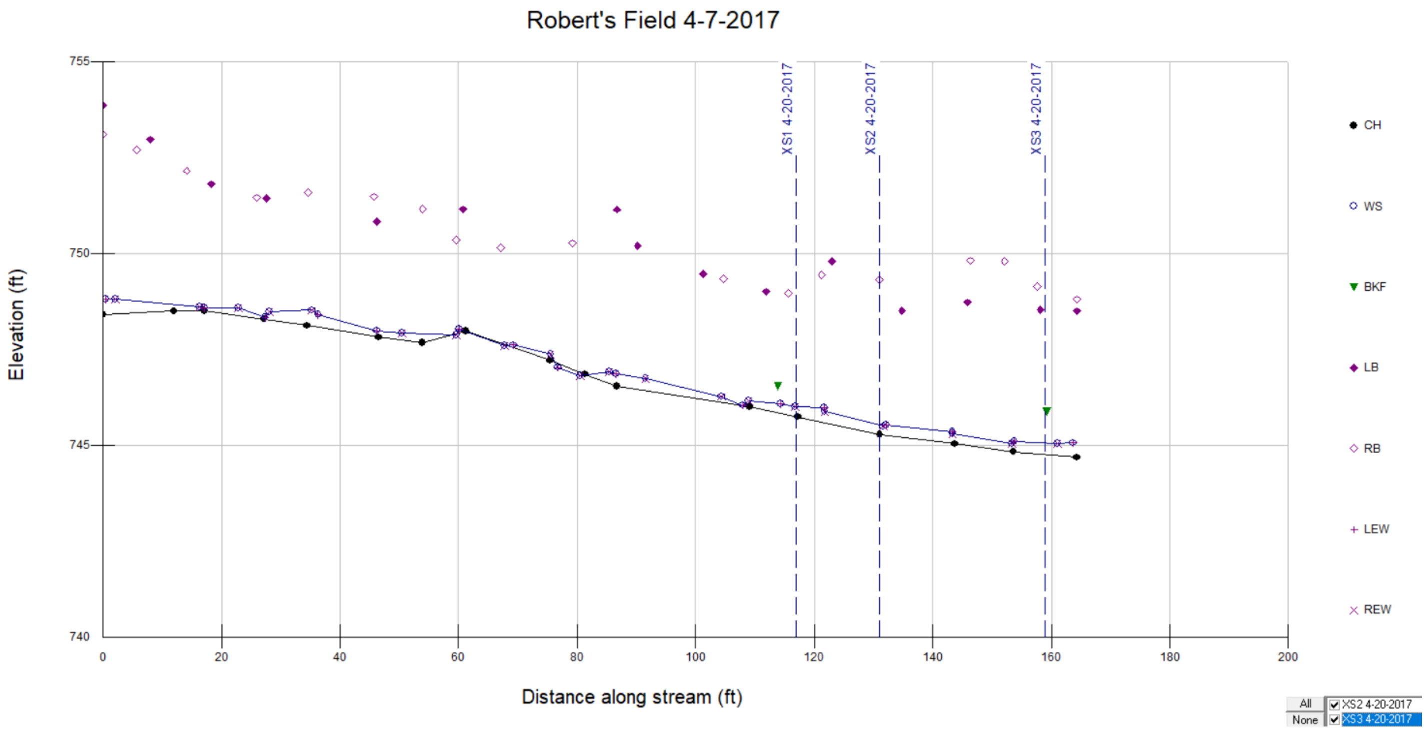


Figure I-3. Robert’s Field pretreatment longitudinal profile.

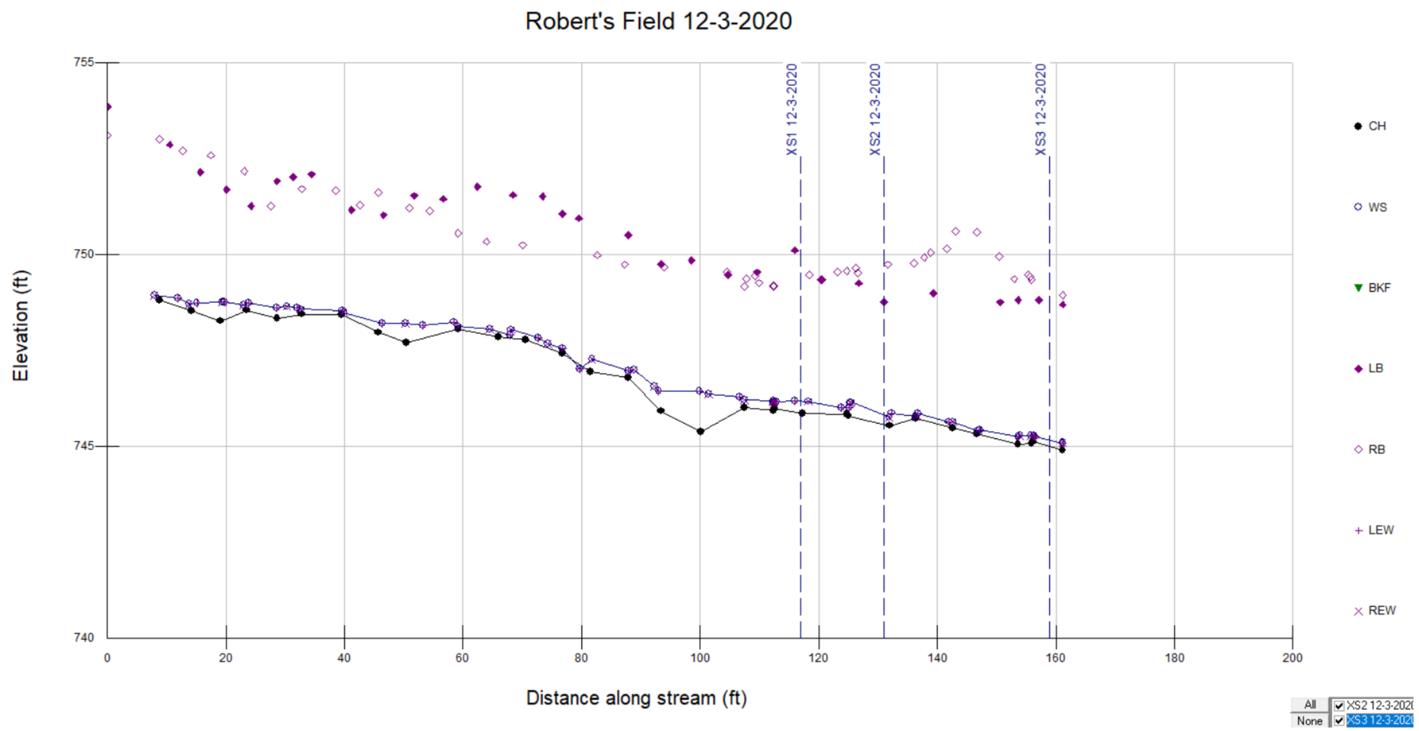


Figure I-4. Robert's Field post-treatment longitudinal profile.

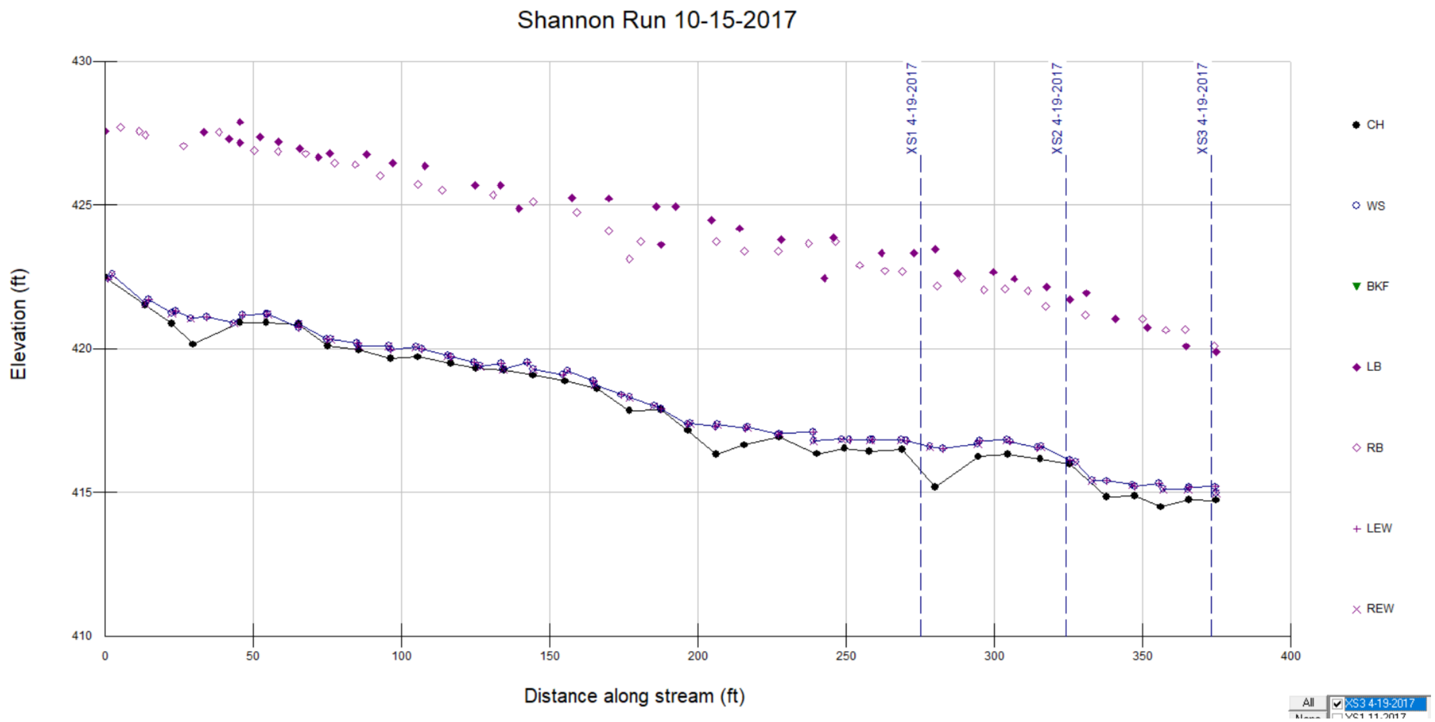


Figure I-5. Shannon Run pretreatment longitudinal profile.

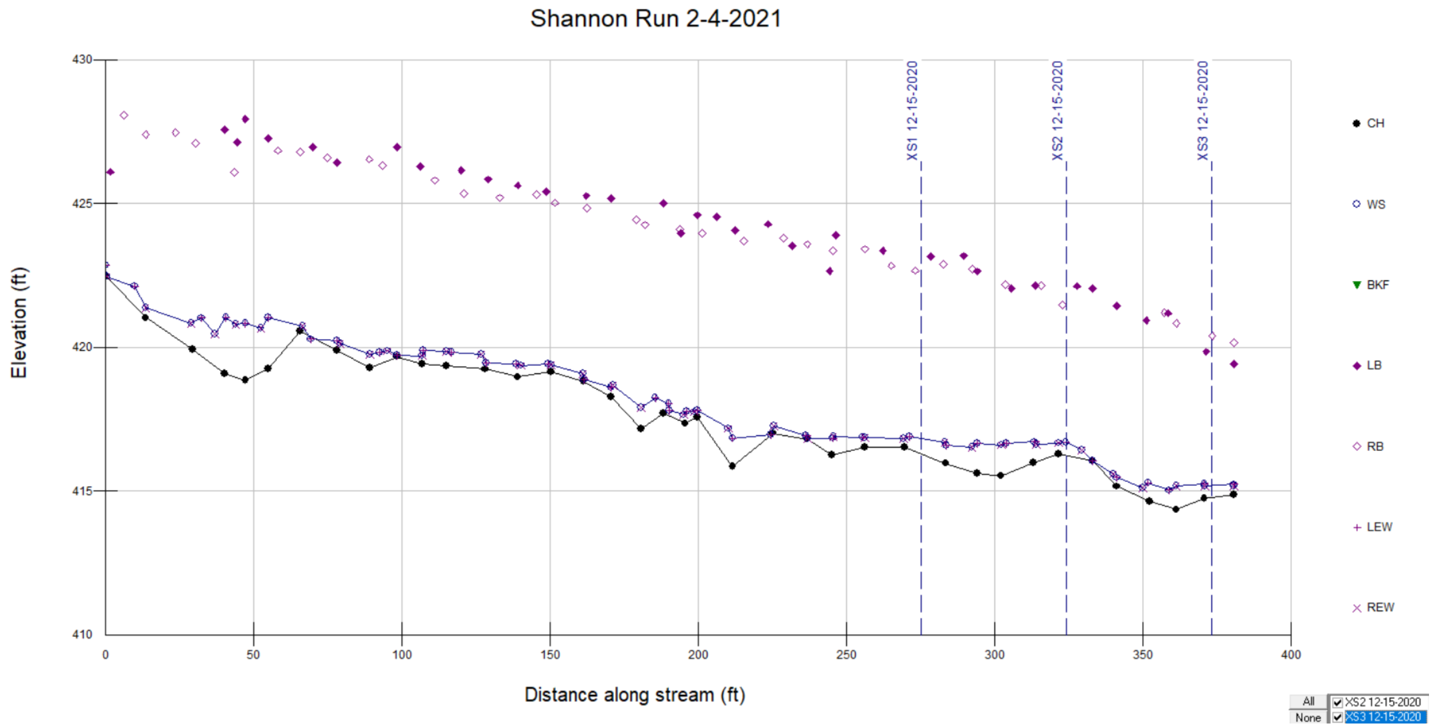


Figure I-6. Shannon Run post-treatment longitudinal profile.

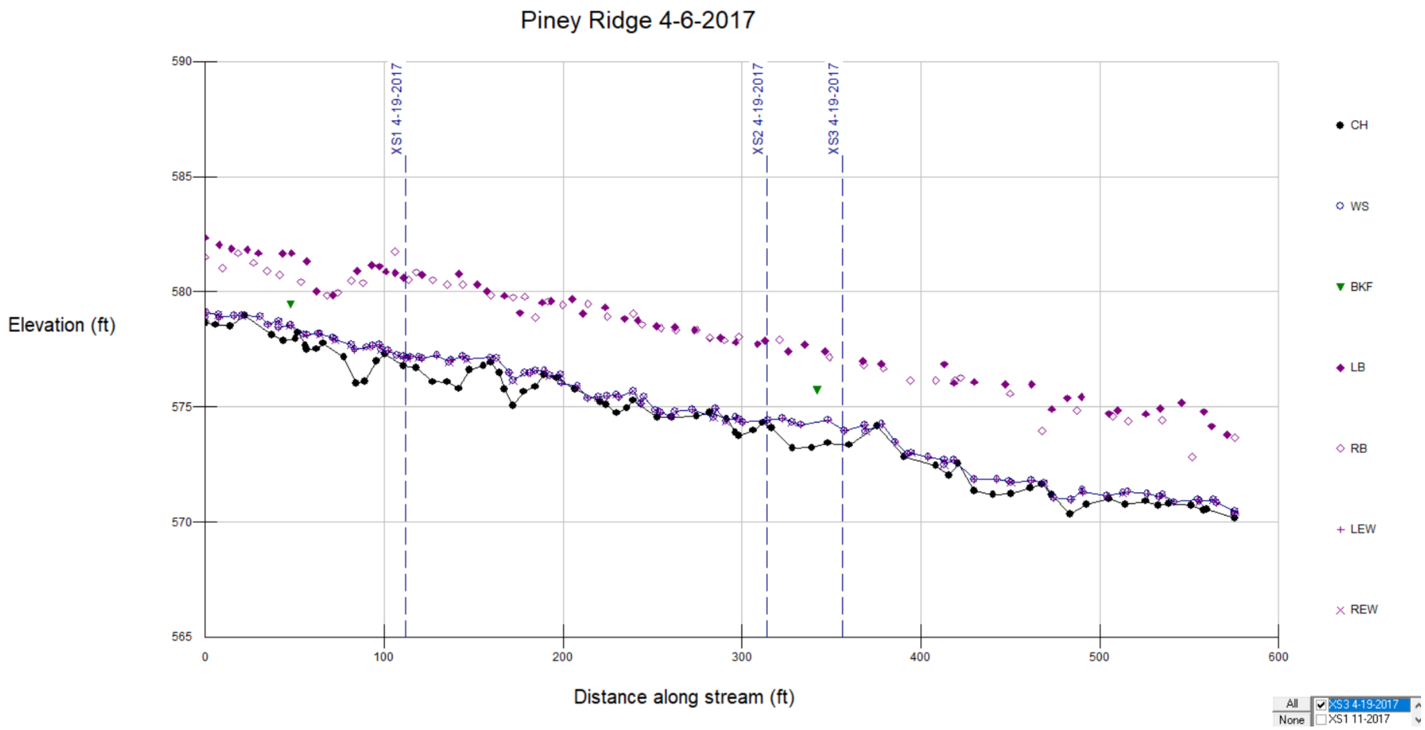


Figure I-7. Piney Ridge pretreatment longitudinal profile.

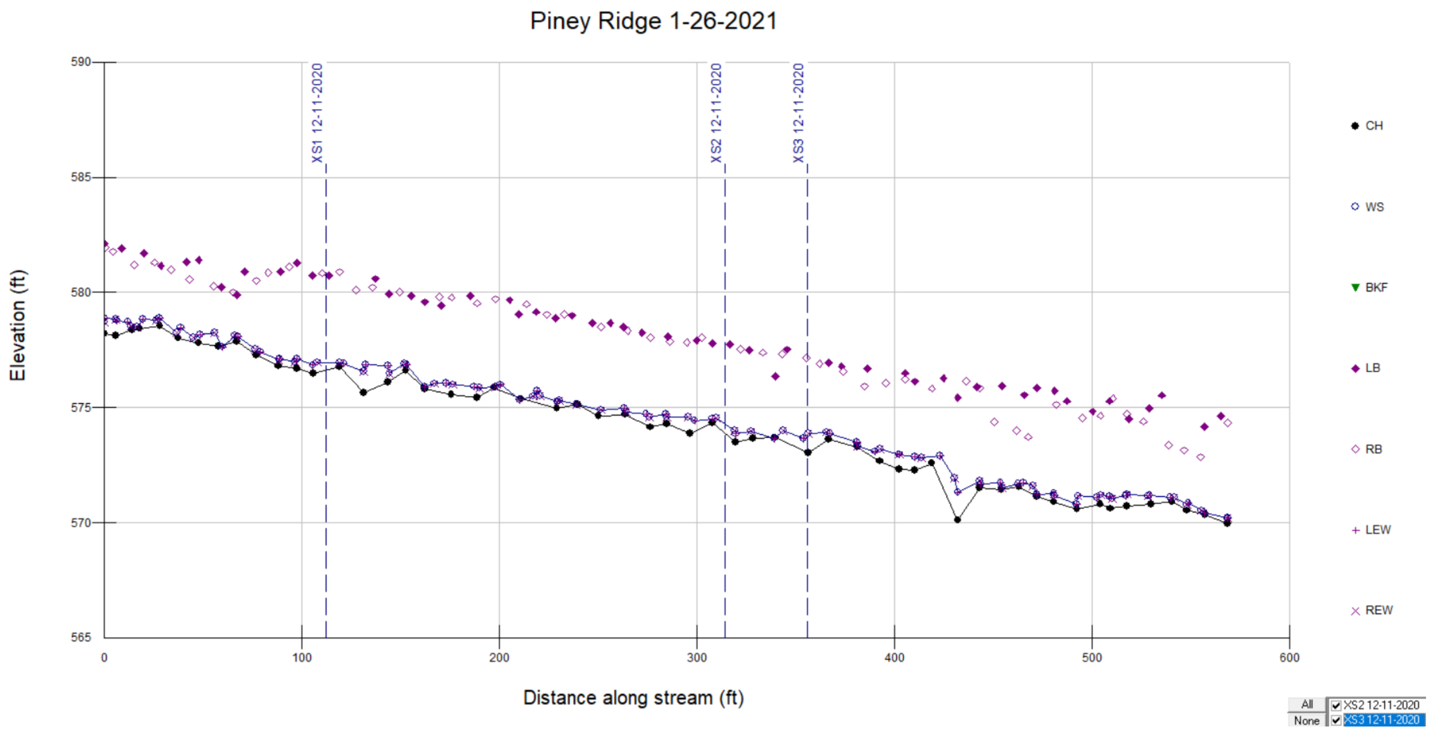


Figure I-8. Piney Ridge post-treatment longitudinal profile.

Appendix J. BANCS Assessment Data

Table J-1. Pretreatment BANCS assessment data.

Site	Bank ID	Length (ft)	BEHI	NBS	Adjusted Length (ft)[1]	Predicted Rate of Bank Erosion (ft/year)	Predicted Erosion Amount (ft^3/year)	Predicted Erosion Amount (tons/year)	Predicted Erosion Rate (tons/year/ft)	Estimated TN (lbs/yr) Load	Estimated TP (lbs/yr) Load	Estimated TSS (tons/yr) Load
Blue Ridge	Bank 10a	30.6	Very High	Extreme	15.3	2.50	191.25	5.06	0.33	11.54	5.31	5.06
Blue Ridge	Bank 10b	30.6	Very High	Very High	15.3	1.75	133.88	3.54	0.23	8.07	3.72	3.54
Blue Ridge	Bank 11	61.1	High	Moderate	61.1	0.64	156.42	4.14	0.07	9.43	4.34	4.14
Blue Ridge	Bank 12	28.8	High	High	28.8	1.00	115.20	3.05	0.11	6.95	3.20	3.05
Blue Ridge	Bank 13	12.7	Very High	Very High	12.7	1.75	77.79	2.06	0.16	4.69	2.16	2.06
Blue Ridge	Bank 14	19.9	High	Extreme	19.9	2.50	174.13	4.61	0.23	10.50	4.84	4.61
Blue Ridge	Bank 15	28.0	High	Moderate	28.0	0.64	35.84	0.95	0.03	2.16	1.00	0.95
Blue Ridge	Bank 16	17.4	High	Moderate	17.4	0.64	27.84	0.74	0.04	1.68	0.77	0.74
Blue Ridge	Bank 7	21.5	High	Very High	21.5	1.75	94.06	2.49	0.12	5.67	2.61	2.49
Blue Ridge	Bank 8	20.3	High	High	20.3	1.00	50.75	1.34	0.07	3.06	1.41	1.34
Blue Ridge	Bank 9a	12.9	Very High	Very High	6.4	1.75	56.00	1.48	0.23	3.38	1.56	1.48
Blue Ridge	Bank 9b	12.9	Very High	High	6.4	1.00	32.00	0.85	0.13	1.93	0.89	0.85
				Total:	253.3	N/A	1145.15	30.29	N/A	69.07	31.81	30.29
Central MD SVC	Bank 1a	286.5	High	High	28.6	1.00	151.58	4.08	0.14	9.29	4.28	4.08
Central MD SVC	Bank 1b	286.5	High	Low	257.8	0.40	546.54	14.70	0.06	33.51	15.43	14.70
Central MD SVC	Bank 2a	116.6	Moderate	Moderate	23.3	0.30	39.14	1.05	0.05	2.40	1.11	1.05
Central MD SVC	Bank 2b	116.6	Moderate	Low	93.3	0.13	65.31	1.76	0.02	4.00	1.84	1.76
Central MD SVC	Bank 3	139.5	High	Low	139.5	0.40	273.48	7.35	0.05	16.77	7.72	7.35
Central MD SVC	Bank 4	47.5	Very High	High	47.5	1.00	261.25	7.03	0.15	16.02	7.38	7.03
				Total:	590.1	N/A	1337.30	35.96	N/A	81.99	37.76	35.96
Piney Ridge	Bank 1a	42.7	High	Moderate	10.7	0.64	16.44	0.50	0.05	1.14	0.53	0.50
Piney Ridge	Bank 1b	42.7	High	Low	32.0	0.40	30.72	0.94	0.03	2.14	0.99	0.94
Piney Ridge	Bank 2	43.4	Moderate	Low	43.4	0.13	10.85	0.33	0.01	0.76	0.35	0.33
Piney Ridge	Bank 3a	67.7	High	High	33.9	1.00	128.48	3.92	0.12	8.95	4.12	3.92
Piney Ridge	Bank 3b	67.7	High	Moderate	33.9	0.64	82.23	2.51	0.07	5.73	2.64	2.51
Piney Ridge	Bank 4a	64.5	High	High	45.2	1.00	158.20	4.83	0.11	11.02	5.07	4.83
Piney Ridge	Bank 4b	64.5	High	Very High	19.4	1.75	118.83	3.63	0.19	8.28	3.81	3.63
Piney Ridge	Bank 5	180.4	High	Moderate	180.4	0.64	369.46	11.29	0.06	25.73	11.85	11.29

Table J-1. Pretreatment BANCS assessment data.												
Site	**Bank ID**	**Length (ft)**	**BEHI**	**NBS**	**Adjusted Length (ft)[1]**	**Predicted Rate of Bank Erosion (ft/year)**	**Predicted Erosion Amount (ft^3/year)**	**Predicted Erosion Amount (tons/year)**	**Predicted Erosion Rate (tons/year/ft)**	**Estimated TN (lbs/yr) Load**	**Estimated TP (lbs/yr) Load**	**Estimated TSS (tons/yr) Load**
Piney Ridge	Bank 6	44.9	Very High	High	44.9	1.00	148.17	4.53	0.10	10.32	4.75	4.53
Piney Ridge	Bank 7a	51.0	High	Low	10.2	0.40	14.69	0.45	0.04	1.02	0.47	0.45
Piney Ridge	Bank 7b	51.0	High	Moderate	40.8	0.64	94.00	2.87	0.07	6.55	3.01	2.87
Piney Ridge	Bank 9	41.7	High	Moderate	41.7	0.64	92.07	2.81	0.07	6.41	2.95	2.81
Piney Ridge	Bank 10	219.3	Very High	Low	219.3	0.25	172.70	5.28	0.02	12.03	5.54	5.28
Piney Ridge	Bank 11	26.8	High	High	26.8	1.00	80.40	2.46	0.09	5.60	2.58	2.46
Piney Ridge	Bank 12a	68.1	High	Very High	34.0	1.75	267.75	8.18	0.24	18.65	8.59	8.18
Piney Ridge	Bank 12b	68.1	High	Moderate	34.0	0.64	97.92	2.99	0.09	6.82	3.14	2.99
Piney Ridge	Bank 13	101.2	Moderate	Low	101.2	0.13	56.93	1.74	0.02	3.96	1.83	1.74
				Total:	951.5	N/A	1939.8	59.25	N/A	135.09	62.21	59.25
Robert's Field	Bank 1	65.4	High	Low	65.4	0.40	88.94	2.28	0.03	5.20	2.39	2.28
Robert's Field	Bank 2a	112.1	High	Low	56.1	0.40	98.74	2.53	0.05	5.77	2.66	2.53
Robert's Field	Bank 2b	112.1	High	Extreme	56.1	2.50	617.10	15.82	0.28	36.07	16.61	15.82
Robert's Field	Bank 3	13.0	High	High	13.0	1.00	48.10	1.23	0.09	2.81	1.29	1.23
Robert's Field	Bank 4	52.0	High	Low	52.0	0.40	93.60	2.40	0.05	5.47	2.52	2.40
				Total:	242.5	N/A	946.48	24.26	N/A	55.32	25.48	24.26
Shannon Run	Bank 1a	43.6	Very High	Extreme	17.4	2.50	200.10	6.23	0.36	14.21	6.54	6.23
Shannon Run	Bank 1b	43.6	Very High	Low	26.1	0.25	30.02	0.93	0.04	2.13	0.98	0.93
Shannon Run	Bank 2a	171.2	High	Moderate	34.2	0.64	126.95	3.95	0.12	9.01	4.15	3.95
Shannon Run	Bank 2b	171.2	High	Low	137.0	0.40	317.84	9.90	0.07	22.57	10.39	9.90
Shannon Run	Bank 3	25.9	Very High	Moderate	25.9	0.64	74.59	2.32	0.09	5.30	2.44	2.32
Shannon Run	Bank 4	34.8	Moderate	Low	34.8	0.13	8.70	0.27	0.01	0.62	0.28	0.27
Shannon Run	Bank 5	32.7	High	Moderate	32.7	0.64	136.03	4.24	0.13	9.66	4.45	4.24
Shannon Run	Bank 6	30.2	Low	Low	30.2	0.03	1.00	0.03	0.00	0.07	0.03	0.03
Shannon Run	Bank 7	20.3	High	Moderate	20.3	0.64	84.45	2.63	0.13	6.00	2.76	2.63
Shannon Run	Bank 8	24.5	Low	Low	24.5	0.03	1.47	0.05	0.00	0.10	0.05	0.05
Shannon Run	Bank 9a	78.0	Very High	High	7.8	1.00	46.80	1.46	0.19	3.32	1.53	1.46
Shannon Run	Bank 9b	78.0	Very High	Moderate	70.2	0.64	269.57	8.40	0.12	19.14	8.82	8.40
Shannon Run	Bank 10	48.7	Low	Low	48.7	0.03	1.46	0.05	0.00	0.10	0.05	0.05
Shannon Run	Bank 11	25.1	Moderate	Low	25.1	0.13	6.28	0.20	0.01	0.45	0.21	0.20

Table J-1. Pretreatment BANCS assessment data.												
Site	**Bank ID**	**Length (ft)**	**BEHI**	**NBS**	**Adjusted Length (ft)[1]**	**Predicted Rate of Bank Erosion (ft/year)**	**Predicted Erosion Amount (ft^3/year)**	**Predicted Erosion Amount (tons/year)**	**Predicted Erosion Rate (tons/year/ft)**	**Estimated TN (lbs/yr) Load**	**Estimated TP (lbs/yr) Load**	**Estimated TSS (tons/yr) Load**
Shannon Run	Bank 12a	105.9	High	Low	52.9	0.40	126.96	3.95	0.07	9.02	4.15	3.95
Shannon Run	Bank 12b	105.9	High	High	52.9	1.00	317.40	9.89	0.19	22.54	10.38	9.89
				Total:	640.8	N/A	1749.61	54.49	N/A	124.24	57.22	54.49

[1]Adjusted length accounts for total reach length divided to account for different NBS characterizations within the same reach.

Table J-2. Post-Treatment BANCS assessment data.											
Site	**Bank ID**	**BEHI**	**NBS**	**Length (ft)**	**Predicted Rate of Bank Erosion (ft/year)**	**Predicted Erosion Amount (ft^3/year)**	**Predicted Erosion Amount (tons/year)**	**Predicted Erosion Rate (tons/year/ft)**	**Estimated TN (lbs/yr) Load**	**Estimated TP (lbs/yr) Load**	**Estimated TSS (tons/yr) Load**
Blue Ridge	Bank 7	High	Very High	21.5	1.75	103.47	2.74	0.13	6.24	2.87	2.74
Blue Ridge	Bank 8	Very High	High	20.3	1.00	54.81	1.45	0.07	3.31	1.52	1.45
Blue Ridge	Bank 9a	Very High	Very High	6.4	1.75	75.04	1.99	0.31	4.53	2.08	1.99
Blue Ridge	Bank 9b	Very High	High	6.4	1.00	42.88	1.13	0.18	2.59	1.19	1.13
Blue Ridge	Bank 10a	Extreme	Extreme	15.3	4.50	516.38	13.66	0.89	31.15	14.34	13.66
Blue Ridge	Bank 10b	Extreme	Extreme	15.3	4.50	516.38	13.66	0.89	31.15	14.34	13.66
Blue Ridge	Bank 11	High	Moderate	61.1	0.64	152.51	4.03	0.07	9.20	4.24	4.03
Blue Ridge	Bank 12	High	High	28.8	1	100.8	2.67	0.09	6.08	2.80	2.67
Blue Ridge	Bank 13	Very High	Very High	12.7	1.75	71.12	1.88	0.15	4.29	1.98	1.88
Blue Ridge	Bank 14	Very High	Extreme	19.9	2.50	164.18	4.34	0.22	9.90	4.56	4.34
Blue Ridge	Bank 15	High	High	28.0	1.00	56.00	1.48	0.05	3.38	1.56	1.48
Blue Ridge	Bank 16	High	Moderate	17.4	0.64	24.50	0.65	0.04	1.48	0.68	0.65
Total:				253.1	N/A	1878.05	49.68	N/A	113.28	52.17	49.68
Central MD SVC	Bank 1a	High	High	28.6	1.00	154.44	4.15	0.15	9.47	4.36	4.15
Central MD SVC	Bank 1b	High	Low	257.8	0.40	556.85	14.97	0.06	34.14	15.72	14.97
Central MD SVC	Bank 2a	High	Moderate	23.3	0.64	87.98	2.37	0.10	5.39	2.48	2.37
Central MD SVC	Bank 2b	High	Low	93.3	0.40	220.19	5.92	0.06	13.50	6.22	5.92
Central MD SVC	Bank 3	High	Low	139.5	0.40	284.64	7.65	0.05	17.45	8.04	7.65
Central MD SVC	Bank 4	Very High	High	47.5	1.00	251.75	6.77	0.14	15.43	7.11	6.77
Central MD SVC	Bank 5	Very High	High	17.0	1.00	119.00	3.20	0.19	7.30	3.36	3.20
Total:				607.0	N/A	1674.85	45.04	N/A	102.68	47.29	45.04
Piney Ridge	Bank 1a	High	Moderate	10.7	0.64	16.44	0.50	0.05	1.14	0.53	0.50
Piney Ridge	Bank 1b	High	Low	32.0	0.40	30.72	0.94	0.03	2.14	0.99	0.94
Piney Ridge	Bank 2	Moderate	Low	43.4	0.13	11.39	0.35	0.01	0.79	0.37	0.35
Piney Ridge	Bank 3a	High	High	33.9	1.00	128.82	3.93	0.12	8.97	4.13	3.93
Piney Ridge	Bank 3b	High	Moderate	33.9	0.64	82.44	2.52	0.07	5.74	2.64	2.52
Piney Ridge	Bank 4a	Very High	High	45.2	1.00	158.20	4.83	0.11	11.02	5.07	4.83
Piney Ridge	Bank 4b	Very High	Very High	19.4	1.75	118.83	3.63	0.19	8.28	3.81	3.63

Table J-2. Post-Treatment BANCS assessment data.											
Site	**Bank ID**	**BEHI**	**NBS**	**Length (ft)**	**Predicted Rate of Bank Erosion (ft/year)**	**Predicted Erosion Amount (ft^3/year)**	**Predicted Erosion Amount (tons/year)**	**Predicted Erosion Rate (tons/year/ft)**	**Estimated TN (lbs/yr) Load**	**Estimated TP (lbs/yr) Load**	**Estimated TSS (tons/yr) Load**
Piney Ridge	Bank 5	High	Moderate	180.4	0.64	369.46	11.29	0.06	25.73	11.85	11.29
Piney Ridge	Bank 6	Very High	High	44.9	1.00	179.60	5.49	0.12	12.51	5.76	5.49
Piney Ridge	Bank 7a	High	Low	10.2	0.40	14.69	0.45	0.04	1.02	0.47	0.45
Piney Ridge	Bank 7b	High	Moderate	35.7	0.64	82.25	2.51	0.07	5.73	2.64	2.51
Piney Ridge	Bank 7c	High	High	5.1	1.0	18.4	0.6	0.1	1.3	0.6	0.6
Piney Ridge	Bank 9	High	High	41.7	1.00	145.95	4.46	0.11	10.16	4.68	4.46
Piney Ridge	Bank 10a	Very High	Moderate	175.4	0.64	359.30	10.97	0.06	25.02	11.52	10.97
Piney Ridge	Bank 10b	Very High	Very High	43.9	1.75	245.62	7.50	0.17	17.11	7.88	7.50
Piney Ridge	Bank 11	High	Very High	26.8	1.75	140.70	4.30	0.16	9.80	4.51	4.30
Piney Ridge	Bank 12a	High	Very High	34.0	1.75	238.00	7.27	0.21	16.57	7.63	7.27
Piney Ridge	Bank 12b	High	Moderate	34.0	0.64	87.04	2.66	0.08	6.06	2.79	2.66
Piney Ridge	Bank 13	Moderate	Low	101.2	0.13	56.93	1.74	0.02	3.96	1.83	1.74
Total:				951.8	N/A	2484.73	75.90	N/A	173.04	79.69	75.90
Robert's Field	Bank 1	High	Low	65.4	0.40	82.40	2.11	0.03	4.82	2.22	2.11
Robert's Field	Bank 2a	Very High	Moderate	56.1	0.64	143.62	3.68	0.07	8.39	3.87	3.68
Robert's Field	Bank 2b	Very High	Extreme	56.1	2.50	561.00	14.38	0.26	32.79	15.10	14.38
Robert's Field	Bank 3	High	High	13.0	1.00	42.90	1.10	0.08	2.51	1.15	1.10
Robert's Field	Bank 4	High	High	52.0	1.00	231.40	5.93	0.11	13.52	6.23	5.93
Total:				242.6	N/A	1061.32	27.21	N/A	62.03	28.57	27.21
Shannon Run	Bank 1a	High	Extreme	17.4	2.50	200.10	6.23	0.36	14.21	6.54	6.23
Shannon Run	Bank 1b	High	Low	26.1	0.40	48.02	1.50	0.06	3.41	1.57	1.50
Shannon Run	Bank 2a	High	Moderate	34.2	0.64	126.95	3.95	0.12	9.01	4.15	3.95
Shannon Run	Bank 2b	High	Low	137.0	0.40	317.84	9.90	0.07	22.57	10.39	9.90
Shannon Run	Bank 3	High	High	25.9	1.00	116.55	3.63	0.14	8.28	3.81	3.63
Shannon Run	Bank 4	Moderate	Low	34.8	0.13	8.70	0.27	0.01	0.62	0.28	0.27
Shannon Run	Bank 5	High	Moderate	32.7	0.64	136.03	4.24	0.13	9.66	4.45	4.24
Shannon Run	Bank 6	Low	Low	30.2	0.03	1.00	0.03	0.00	0.07	0.03	0.03
Shannon Run	Bank 7	High	Moderate	20.3	0.64	84.45	2.63	0.13	6.00	2.76	2.63
Shannon Run	Bank 8 – REMOVED[1]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table J-2. Post-Treatment BANCS assessment data.

Site	Bank ID	BEHI	NBS	Length (ft)	Predicted Rate of Bank Erosion (ft/year)	Predicted Erosion Amount (ft^3/year)	Predicted Erosion Amount (tons/year)	Predicted Erosion Rate (tons/year/ft)	Estimated TN (lbs/yr) Load	Estimated TP (lbs/yr) Load	Estimated TSS (tons/yr) Load
Shannon Run	Bank 9a	Very High	High	7.8	1.00	46.80	1.46	0.19	3.32	1.53	1.46
Shannon Run	Bank 9b	Very High	Moderate	70.2	0.64	269.57	8.40	0.12	19.14	8.82	8.40
Shannon Run	Bank 10 – REMOVED[1]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Shannon Run	Bank 11	Moderate	Moderate	25.1	0.30	15.06	0.47	0.02	1.07	0.49	0.47
Shannon Run	Bank 12a	High	Low	52.9	0.40	126.96	3.95	0.07	9.02	4.15	3.95
Shannon Run	Bank 12b	High	High	52.9	1.00	317.40	9.89	0.19	22.54	10.38	9.89
Total:				567.5	N/A	1815.43	56.54	N/A	128.91	59.37	56.54

[1]Shannon Run Bank 8 and Bank 10 removed due to being depositional during the post-treatment period.

Table J-3. BANCS BEHI and NBS ratings pre and post-treatment.					
		Pretreatment		**Post Treatment**	
BEHI	**NBS**	**Length**	**% of Total Assessed Length**	**Length**	**% of Total Length**
Central MD SVC (Treatment)					
Very High	High	76	12.3%	65	10.4%
High	High	29	4.6%	29	4.6%
High	Moderate	0	0.0%	23	3.8%
High	Low	397	64.2%	491	79.3%
Moderate	Moderate	23	3.8%	0	0.0%
Moderate	Low	93	15.1%	0	0.0%
Changed to Depositional Post-Treatment		N/A	N/A	12	1.9%
	Total:	619	100.0%	619	100.0%
Robert's Field (Control)					
Very High	Extreme	0	0.0%	56	23.1%
Very High	Moderate	0	0.0%	56	23.1%
High	Extreme	56	23.1%	0	0.0%
High	High	13	5.4%	65	26.8%
High	Low	174	71.5%	65.4	27.0%
	Total:	243	100.0%	243	100.0%
Shannon Run (Treatment)					
Very High	Extreme	17	2.7%	0	0.0%
Very High	High	8	1.2%	8	1.2%
Very High	Moderate	96	15.0%	70	11.0%
Very High	Low	26	4.1%	0	0.0%
High	Extreme	0	0.0%	17	2.7%
High	High	53	8.3%	79	12.3%
High	Moderate	87	13.6%	87	13.6%
High	Low	190	29.6%	216	33.7%
Moderate	Moderate	0	0.0%	25	3.9%
Moderate	Low	60	9.4%	35	5.4%
Low	Low	103	16.1%	30	4.7%
Changed to Depositional Post-Treatment		N/A	N/A	73	11.4%
	Total:	641	100.0%	641	100.0%
Piney Ridge (Control)					
Very High	Very High	0	0.0%	63	6.7%
Very High	High	45	4.7%	90	9.5%
Very High	Moderate	0	0.0%	175	18.4%
Very High	Low	219	23.0%	0	0.0%
High	Very High	53	5.6%	61	6.4%
High	High	106	11.1%	81	8.5%

High	Moderate	341	35.9%	295	31.0%
High	Low	42	4.4%	42	4.4%
Moderate	Low	145	15.2%	145	15.2%
	Total:	952	100.0%	952	100.0%

Table J-4. Pretreatment distribution of bank pins and cross sections among the BEHI and NBS scores and percentage of the assessed BANCS reach length that also includes these monitoring strategies.

Study Site and Monitoring Locations (Cross section, XS or Bank Pin, BP)	BANCS Assessment[1]		Length (ft)	% of Total Streambank Length
	BEHI	NBS		
Central MD SVC (Treatment)				
BP1A (left bank)	High	Low	397.3	60.5%
BP3 (right bank)				
XS1 (left bank)				
XS2 (right & left bank)				
XS3 (right bank)				
BP1B (left bank)	High	High	28.6	4.4%
XS3 (left bank)				
XS 4 (left bank)				
BP2 (right bank)	Moderate	Low	93.3	14.2%
BP4 (right bank)	Very High	High	47.5	7.2%
XS1 (right bank)	Moderate	Moderate	23.3	3.5%
Depositional Bank (No BANCS Assmt)	N/A	N/A	66.8	10.2%
		Total:	656.8	100.0%
Shannon Run (Treatment)				
BP1 (right bank)	Very High	Extreme	17.4	2.3%
XS1 (right bank)	Very High	Moderate[3]	96.1	12.8%
BP3 (left bank)				
BP9 (right bank)				
BP5 (left bank)	High	Moderate	53.0	7.1%
BP7 (left bank)				
XS2 (left bank)	High	High	52.9	7.1%
BP12 (left bank)	High	Low	52.9	7.1%
XS3 (left bank)				
XS2 (right bank)	Low	Low	48.7	6.5%
XS3 (right bank)				
No Monitored BP or XS[2]	High	Low	137.0	18.3%
	High	Moderate	34.2	4.6%
	Low	Low	54.7	7.3%
	Moderate	Low	59.9	8.1%
	Very High	High	7.8	1.0%
	Very High	Low	26.1	3.5%
Depositional Bank (No BANCS Assmt)	N/A	N/A	108.1	14.4%
		Total:	748.8	100.0%
Robert's Field (Control)				
BP1 (right bank)	High	Low	117.4	37.1%
BP3 (right bank)				

Table J-4. Pretreatment distribution of bank pins and cross sections among the BEHI and NBS scores and percentage of the assessed BANCS reach length that also includes these monitoring strategies.				
Study Site and Monitoring Locations (Cross section, XS or Bank Pin, BP)	**BANCS Assessment[1]**		**Length (ft)**	**% of Total Streambank Length**
	BEHI	**NBS**		
XS2 (right bank)				
XS3 (right bank)				
BP2 (left bank)	High	Extreme	56.1	17.7%
No Monitored BP or XS[2]	High	High	13.0	4.1%
	High	Low	56.1	17.7
Depositional Bank (No BANCS Assmt)	N/A	N/A	73.7	23.3%
		Total:	316.3	100.0%
Piney Ridge (Control)				
BP2 (left bank)	Moderate	Low	43.4	3.9%
BP6 (left bank)	Very High	High	44.9	4.0%
BP7 (left bank)	High	Low	10.2	0.9%
BP8 (right bank)	High	Moderate	232.8	20.8%
BP9 (left bank)				
BP1 (right bank)				
XS2 (right & left bank)				
XS1 (right bank)	High	Very High	19.4	1.7%
No Monitored BP or XS[2]	High	High	105.9	9.4%
	High	Low	32.0	2.9%
	High	Moderate	108.7	9.7%
	High	Very High	34.0	3.0%
	Moderate	Low	101.2	9.0%
	Very High	Low	219.3	19.6%
Depositional Bank (No BANCS Assmt)	N/A	N/A	169.7	15.1%
		Total:	1,121.5	100.0%

[1] Note that cross-sections that are located at the transition between two bank delineations for the BEHI were not included in this table.
[2]Average erosion rate based on measured erosion rates for all sites as this provided all BEHI/NBS categories.
[3]BP9 at Shannon Run has an NBS of either moderate or high based on the Shannon Run Bank 9 BANCS assessment. Documentation for the specific NBS was missed when installing BP9. A conservative NBS estimate of moderate was used here.

Appendix K. Monitoring Sediment Load Data

Table K-1. Sediment load estimated from monitoring data.

Site	Monitoring Station	Bank Height (ft)	Bank Length Represented by Monitoring Station (ft)	Pretreatment Measured Erosion Rate (ft/yr)	Pretreatment Measured Erosion Amount (ft3/year)	Bulk Density (lbs/ft3)	Pretreatment TSS Load (tons/yr)	Post-Treatment Measured Erosion Rate (ft/yr)	Post-Treatment Measured Erosion Amount (ft3/year)	Post-Treatment TSS Load (tons/yr)
Central MD	BP1A LB	5.3	85.93	0.06	26.06	53.78	0.70	0.04	18.22	0.49
Central MD	BP1B LB	5.3	9.53	0.03	1.52	53.78	0.04	0.00	0.00	0.00
Central MD	BP2 RB	5.6	93.3	0.01	4.24	53.78	0.11	0.02	10.45	0.28
Central MD	BP3 RB	4.9	46.5	0.02	5.32	53.78	0.14	0.15	34.18	0.92
Central MD	BP4 RB	5.5	47.5	0.14	36.31	53.78	0.98	0.20	52.25	1.41
Central MD	XS 1 LB	5.3	85.93	0.00	0.00	53.78	0.00	0.11	50.10	1.35
Central MD	XS 1 RB	5.6	23.3	0.00	0.00	53.78	0.00	0.16	20.88	0.56
Central MD	XS 2 LB	5.3	85.93	0.00	0.00	53.78	0.00	0.15	68.32	1.84
Central MD	XS 2 RB	4.9	46.5	0.11	24.64	53.78	0.66	0.11	25.06	0.67
Central MD	XS 3 LB	5.3	9.53	0.00	0.00	53.78	0.00	0.11	5.56	0.15
Central MD	XS 3 RB	4.9	46.5	0.00	0.00	53.78	0.00	0.09	20.51	0.55
Central MD	XS 4 LB	5.3	9.53	0.30	15.03	53.78	0.40	0.50	25.26	0.68
Central MD	XS 4 RB	4.3	19	0.17	13.89	53.78	0.37	0.01	0.82	0.02
Piney Ridge	BP1 RB	2.4	10.7	0.08	2.03	61.09	0.06	0.04	1.03	0.03
Piney Ridge	BP2 LB	2	43.4	0.00	0.00	61.09	0.00	0.00	0.00	0.00
Piney Ridge	BP6 LB	3.3	44.9	0.00	0.00	61.09	0.00	0.02	2.96	0.09
Piney Ridge	BP7 LB	3.6	10.2	0.00	0.00	61.09	0.00	0.02	0.73	0.02
Piney Ridge	BP8 RB	3.2	90.2	0.00	0.00	61.09	0.00	0.02	5.77	0.18
Piney Ridge	BP9 LB	3.5	20.85	0.00	0.00	61.09	0.00	0.00	0.00	0.00
Piney Ridge	XS 1 RB	3.5	19.4	0.17	11.76	61.09	0.36	0.04	2.72	0.08
Piney Ridge	XS 2 LB	3.5	20.85	0.13	9.81	61.09	0.30	N/A	N/A	N/A
Piney Ridge	XS 2 RB	3.2	90.2	0.00	0.00	61.09	0.00	N/A	N/A	N/A
Robert's Field	BP1 RB	3.4	65.4	0.00	0.00	51.27	0.00	0.01	2.22	0.06
Robert's Field	BP2 LB	4.4	56.1	0.11	27.06	51.27	0.69	0.12	29.62	0.76
Robert's Field	BP3 RB	4.5	17.33	0.00	0.00	51.27	0.00	0.13	10.14	0.26
Robert's Field	XS 2 LB	3.6	21.5	0.00	0.00	51.27	0.00	0.14	10.84	0.28

Table K-1. Sediment load estimated from monitoring data.

Site	Monitoring Station	Bank Height (ft)	Bank Length Represented by Monitoring Station (ft)	Pretreatment Measured Erosion Rate (ft/yr)	Pretreatment Measured Erosion Amount (ft3/year)	Bulk Density (lbs/ft3)	Pretreatment TSS Load (tons/yr)	Post-Treatment Measured Erosion Rate (ft/yr)	Post-Treatment Measured Erosion Amount (ft3/year)	Post-Treatment TSS Load (tons/yr)
Robert's Field	XS 2 RB	4.5	17.33	0.16	12.49	51.27	0.32	0.00	0.00	0.00
Robert's Field	XS 3 LB	3.2	21.5	N/A	N/A	51.27	N/A	0.00	0.00	0.00
Robert's Field	XS 3 RB	4.3	17.33	N/A	N/A	51.27	N/A	0.25	18.63	0.48
Shannon Run	BP1 RB	4.6	17.4	0.21	16.78	62.29	0.52	0.17	13.61	0.42
Shannon Run	BP12 LB	6	26.45	0.00	0.00	62.29	0.00	0.00	0.00	0.00
Shannon Run	BP3 LB	4.5	25.9	0.13	15.38	62.29	0.48	0.08	9.32	0.29
Shannon Run	BP5 LB	6.5	32.7	0.03	6.80	62.29	0.21	0.05	10.63	0.33
Shannon Run	BP7 LB	6.5	20.3	0.00	0.00	62.29	0.00	0.00	0.00	0.00
Shannon Run	BP9 RB	6	35.1	0.04	9.22	62.29	0.29	0.00	0.00	0.00
Shannon Run	XS 1 LB	5.2	72	0.11	41.18	62.29	1.28	0.00	0.00	0.00
Shannon Run	XS 1 RB	6	35.1	0.21	45.03	62.29	1.40	0.09	18.95	0.59
Shannon Run	XS 2 LB	6	52.9	0.56	176.60	62.29	5.50	0.51	161.87	5.04
Shannon Run	XS 2 RB	1	24.35	0.14	3.35	62.29	0.10	0.00	0.00	0.00
Shannon Run	XS 3 LB	6	26.45	0.25	40.26	62.29	1.25	0.13	20.63	0.64
Shannon Run	XS 3 RB	1	24.35	0.02	0.39	62.29	0.01	0.04	0.97	0.03

Notes:

- *Bank heights were obtained from BANCS assessments as representative of the reach the monitoring location represents.*
- *In cases were a XS does not correspond to a BANCS assessed reach, the bank height from the XS survey was used.*
- *Monitoring lengths were estimated using the length of individual BANCS assessed reaches as a guide.*
- *Piney XS 1 LB and XS 3 were not included since they were in transitional areas between 2 BANCS reaches and representative lengths could not be determined.*
- *Robert's Field XS1 was not included since it was in a transitional area between 2 BANCS reaches and representative length could not be determined.*