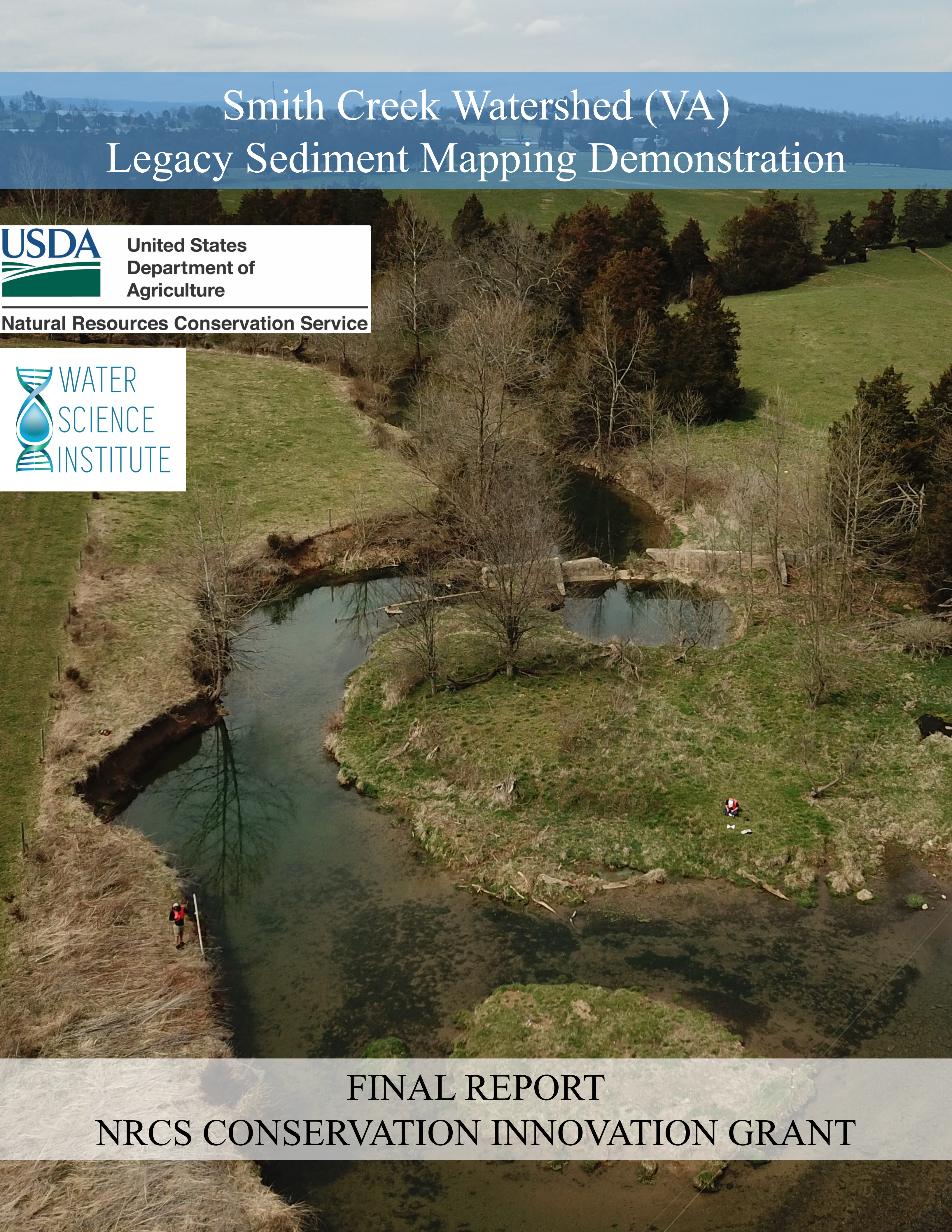
Smith Creek Watershed (VA) Legacy Sediment Mapping Demonstration

USDA United States Department of Agriculture
Natural Resources Conservation Service

WATER SCIENCE INSTITUTE



FINAL REPORT
NRCS CONSERVATION INNOVATION GRANT

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Final Report

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Executive Summary:

Legacy sediment, an environmental consequence of post-European settlement farming, damming, and forestry practices, has become a commonly recognized source of water quality impairment throughout the Coastal Plain, Piedmont, and Ridge and Valley physiographic provinces of the mid-Atlantic United States. Valley bottoms that often-contained spring fed, multi-thread stream channels and wetlands, were routinely dammed to power the production of flour, grain, gunpowder, lumber, and other milling requirements of early settlers. The local valley bottom hydrology was first drowned and then buried by thick deposits of fine silts and clays (legacy sediment) contributed by adjacent upland erosion. When dams are breached, the impounded millpond legacy sediment is quickly mobilized, long covered banks are exposed, and the ensuing erosion from natural processes continues to remove the sediment at substantial rates for decades. This is a “Legacy” contribution of earlier generations to our current water quality challenges.

When evaluating entire watersheds, classic methods of detecting stream bank change, such as pins and cross sections, can be limited in accuracy and scale. The addition of airborne lidar (light detection and ranging) technology to environmental science and stream restoration practice allows for more comprehensive analyses of landscape change over time. Combining lidar and DEM (digital elevation model) differencing methodologies has proven to be highly effective at targeting areas that contribute high stream bank sediment loads. This combination of accuracy, scale, and efficiency allows conservation managers to develop more comprehensive prioritization and resource allocation strategies. It is also a cost-effective tool for management decision making. The WSI Smith Creek watershed project’s primary objective was to demonstrate the use of lidar as a method to identify and prioritize legacy sediment “hotspots” in the watershed. To compensate for the state of Virginia’s limited repeat lidar data, we also exhibited an additional mapping tool, UAV (unmanned aerial vehicle) photogrammetry, to generate DEMs for differencing. Photogrammetry is the process of digitally aligning hundreds of site-specific photographic images with GPS control points to create high resolution three-dimensional models, which can be converted into DEMs.

We identified 21 historical milldam locations in the Shenandoah and Rockingham County portions of Smith Creek watershed and mapped approximately eight million tons of legacy sediment stored in valley bottom terraces adjacent to third and fourth order streams. Close to 420 miles of streams were mapped in the watershed, which consists of over 80% first and second order streams. Samples of legacy sediment collected at five different locations in the watershed contained on average 25% clay (range = 8-44%), 30% silt (range = 11-45%), 38% sand (range = 27-65%), and 7% fine gravel (range = <1-36%). Grain sizes are similar to other observations made of historic millpond sediment in the Chesapeake Bay watershed. From nutrient analyses, we determined N and P loads are relatively consistent in legacy sediment throughout the watershed (2.2-2.5 lbs N/ton and 0.5-0.7 lbs P/ton), and bank sediments decreased in N and P concentrations with depth from the terrace surface. Concentrations of N in bank sediments are comparable to that of other millpond sediments in region, while P concentrations are substantially lower. We also discovered a buried hydric soil containing 13.3% organic matter, in contrast to the 1-3% range for other legacy sediment samples. This indicates that wetlands were likely present at the site and suggests a potential stream and wetland restoration opportunity.

UAV surveys were successfully conducted at four separate sites and from DEM differencing we calculated erosion rates of ~0.01-0.04 tons/ft/yr (~20-80 lbs/ft/yr) between 857-1440 feet lengths of stream. Along shorter stretches (100-200 feet) within the four sites, we measured erosion rates at high as 0.11 tons/ft/yr (220 lbs/ft/yr).

Previous studies by the USGS and others have indicated that stream bank erosion is a primary contributor to water quality impairment in the Smith Creek watershed. Our project provides further evidence that legacy sediment terraces constitute a significant sediment source produced by natural processes and exacerbated by poor agricultural practices such as unfenced stream banks. Identification of legacy sediment terraces and erosion rates will provide NRCS managers with a useful guide when developing cost effective BMP implementation strategies, including stream and wetland restoration. Our primary recommendation is that NRCS and Virginia partners should consider acquiring next generation lidar datasets to further support planning watershed conservation and restoration implementation strategies. Results from this project suggest that investing in next generation lidar datasets can increase successful conservation outcomes and design more cost-effective restoration strategies when legacy sediment sites are recognized as nutrient reduction and ecosystem service opportunities. The counties of the Smith Creek watershed, given its designation as an NRCS National Water Quality Initiative, may be useful locations to consider an initial investment.

I. Scope and Objectives of his Report:

Previous mapping efforts funded by both National and Pennsylvania NRCS CIG awards helped develop the project program and the current funding allowed WSI to expand the work to Virginia where repeat lidar data is not widely available (Water Science Institute 2018, 2020). Smith Creek was recommended by Virginia NRCS because of its designation as a NRCS National Water Quality Initiative watershed that has received significant conservation investments. The current project proposed to use lidar to locate potential legacy sediment hotspots, determine historic mill dam locations, record precise and accurate site data including dam breach status, and perform nutrient and grain size analyses of legacy sediment deposits at selected sites in the watershed. Lidar is one of the most advanced tools available to evaluate high resolution, three-dimensional landscape change over large geographical areas. We also exhibited the use of UAV photogrammetric methodologies to produce DEMs for estimating rates of stream bank erosion where repeat lidar datasets are unavailable. This report is intended to assist NRCS in its watershed policy and management goals by demonstrating how the use of lidar can guide the selection of high nutrient and sediment load sites for targeted BMP implementation.

A. Scope of this Report

In this report, we provide watershed wide data on historical milldam locations, lengths of custom mapped streams, estimated volumes of legacy sediment stored in valley bottoms adjacent to third and fourth order streams, rates of stream bank erosion in stream corridors at select sites, and concentrations of nutrients and grain size analyses of stream bank sediments sampled at the same sites. Rates of bank erosion were calculated using DEM differencing, a method that enables detection of landscape change with high accuracy and precision. With the absence of repeat lidar datasets for Smith Creek, additional DEMs for differencing of selected sites were created using UAV photogrammetry methodologies. Typically, where repeat lidar is accessible, field sites are initially screened using bank erosion rates in focused areas of interest. Here, UAV flights were paired with RTK (real-time kinematic) GPS surveys to construct highly detailed DEMs for differencing. Sites for field investigation were determined by a combination of NRCS, United States Geological Survey (USGS) and James Madison University (JMU) recommendations and WSI produced data, including historical milldam locations, legacy sediment terrace characteristics, canopy density, and bank vegetation density developed by the project team.

B. Objectives of this Report

The project demonstrates mapping capabilities using lidar and drone photogrammetry to identify legacy sediment sites within the Smith Creek watershed. The specific objectives of this project are:

1.) Provide a clear understanding of lidar as a tool for use in the identification and prioritization of stream sites impaired by legacy sediment; and
2.) Demonstrate an alternative mapping tool using UAV photogrammetry and DEM differencing for determining erosion rates in areas underserved by repeat lidar data.

II. Background:

A. Milldams, Valley Bottom Sediments, and Stream Bank Erosion

The dense concentration of historical milldams that accumulated sediment for centuries throughout the Eastern United States has had a striking and largely ignored impact on the original function of valley bottom ecosystems. Large reservoirs behind milldams filled with fine grained sediment (legacy sediment), from post-European settlement land use practices. The millponds and subsequent sedimentation drowned and buried thousands of acres of valley bottoms that originally constituted wetland stream systems (Walter and Merritts, 2008). Stratigraphically, legacy sediment typically sits atop a Holocene era dark, organic-rich hydric soil that represents the thriving wetland ecosystems that were sustained for thousands of years (Figure 1). Between the hydric soil and underlying bedrock of the region's streams are pre-Holocene sediments characterized as fine-grained toe-of-slope colluvium ("white toe") and coarser grained debris fans, tributary junction fans and basal gravels (Merritts et al., 2011). The basal gravel is characterized as angular to subangular and cobble to boulder in size, where it commonly occupies valley bottoms with streams that cannot achieve the shear stresses needed to move them as bedload (Merritts et al., 2011). Basal gravel has been determined to be colluvial or periglacial in origin, but often is misinterpreted as recent fluvial features. Bedload transported in modern, incised channels are medium sand to gravel in size and are deposited inside the channel corridor, commonly along sharp bends, and meanders.

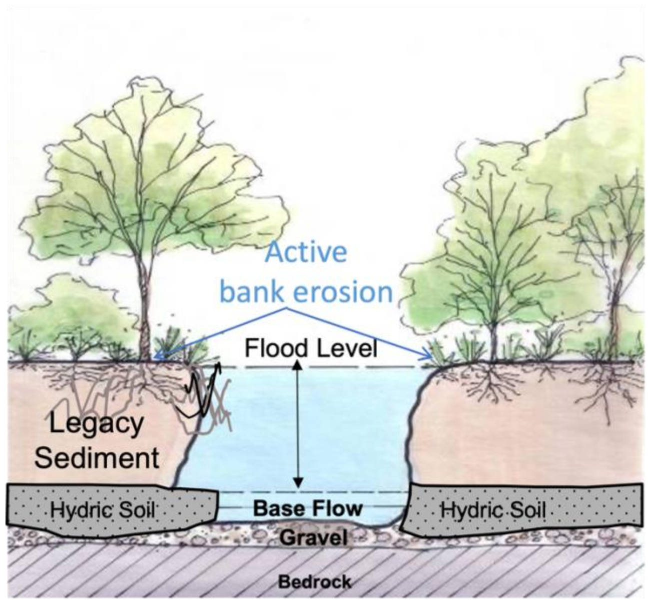


Figure 1. Illustration of typical stream bank influenced by milldams and deposition of legacy sediment over a hydric soil, courtesy PA DEP.

Breaching of milldams for safety, fish passage, structural failure, liability, and other reasons, are continuously releasing millions of tons of previously impounded nutrients and sediment, posing an additional threat to underwater grasses, crabs, fish, and birds that inhabit the Chesapeake Bay. After a milldam breaches, large amounts of impounded channel and bank sediment are released and continue to erode at high rates for approximately 10 years. Significant lateral bank erosion will continue to contribute large sediment and nutrient loads for many additional decades to centuries. (Merritts et al., 2013). Post dam breach incision into millpond sediment again alters the valley bottom hydrology and leaves a single thread channel experiencing lateral migration into the paired legacy sediment terraces, which are typically now exposed on both sides of the new stream channel. Bank heights are roughly equivalent to the height of the breached dam and will exhibit continual thinning 1-2 miles upstream from dam locations. That distance is the typical length of millpond slack water formed by the original dam. Bank retreat can be recognized by the undercutting and slumping of bank material, freeze-thaw processes, and often from fences and vegetation falling into the stream. Point-bar deposition is often observed adjacent to a rapidly eroding bank. Recognizing and understanding the large loads associated with stream systems impaired by milldam sediment is crucial to developing comprehensive strategies to improve watershed health throughout the Chesapeake Bay.

B. Motivation in Smith Creek Watershed

Smith Creek's designation as a National Water Quality Initiative watershed has made it the focus of a variety of restoration practices and scientific studies that address water quality. Between 2010-2019, over 40 miles of streambank fencing were put in place, over 3,000 acres of cover crops planted, and over 1,300 acres of prescribed grazing land were implemented (VA NRCS-Smith Creek Factsheet, 2020). While none of these practices directly address legacy sediment impairments, recent scientific investigations have shed light on the nutrient and sediment transport dynamics present in the watershed. Using a sediment finger printing approach, Gellis et al. (2018) identified streambanks as the primary supplier, 70-76%, of suspended sediment in the watershed. The influence of milldams in the watershed has also been recognized by Eaton et al. (2015), who identified 15 separate millpond locations in the watershed from historical maps and field work.

III. Methodology:

A. GIS Analyses

1. DEMs and CHMs

The lone lidar dataset available for Smith Creek was generated for NRCS in 2011 by Dewberry and Davis, LLC., and processed by project partner Mike Rahnis of TOPOMATRIX, LLC. From this lidar, we generated both a DEM and CHM (canopy height model) of the watershed for further analyses. DEMs are fine-scale representations of landscape relief at a single point in time that can be used for a variety of purposes. CHMs are the same cell resolution but are representations of the difference between ground level and the peak canopy height. Canopy height and density is an important factor for UAV analysis and can be a helpful management metric when planning BMP implementation. DEMs and CHMs of the same area created at different points in time makes it possible to evaluate landscape changes over short and extended periods with high accuracy.

2. Stream Centerlines

The enhanced streamlines for our work were created using a blend of custom and open-source algorithmic code developed by TOPOMATRIX. These one-meter resolution centerlines are more accurate than the current ten-meter resolution USGS NHDPlus High Resolution Hydrography dataset, providing the project with a more detailed view of the watershed's stream erosion sources. More accurate centerlines are capable of mapping stream segments (first and second order) that are commonly missed in other datasets. Accurate centerlines are important for mapping all the stream segments in a watershed to improve identification of potential restoration opportunities.

3. Legacy Sediment Terrace Locations and Volume Estimates

Applying both lidar and stream centerlines, it is possible to locate legacy sediment terraces and accurately estimate sediment volume present in valley bottoms. Once all likely terraces are identified, their elevations are compared with that of the elevations along our stream centerlines. This process is completed for all mapped terraces to produce a new legacy sediment thickness dataset. Thickness of sediment and the area of mapped terraces produces an estimated volume of sediment for each terrace and the cumulative total in the watershed. As noted, the legacy sediment from breached impoundments may continue to erode for very long periods and it can take decades for a stream to cut down to the original stream channel. The methodology used here assumes the water level is at base flow and close to a hydric layer, gravel, and/or bedrock, so we believe our estimates of sediment volumes are accurate but slightly lower than the estimated total present in a surveyed area.

4. Dem Differencing

DEM differencing is the process of subtracting two DEMs produced at different time periods to evaluate landscape change with a high degree of accuracy. To subtract DEMs, datasets are brought into ArcGIS Pro where the Minus tool (3D Analyst) is used to create a difference raster representing vertical change, on a cell-by-cell basis, between input DEMs. To produce data with low uncertainty, we perform a level of detection change analysis with a 90% confidence interval. Areas of change are then converted from a raster to individual polygons that can be edited to quantify volume and rate of sediment loss based on three-dimensional change. Differencing methodology undergoes continual minor refinement as higher quality lidar data and higher resolution DEMs from photogrammetry are produced.

B. Historical Milldam Identification

WSI, in collaboration with Franklin & Marshall College, have mapped over 3,000 historical milldam locations in the Mid-Atlantic region (see WSI Data Guide, 2020 - https://storymaps.arcgis.com/stories/9e3d307249284d64a8b7e40082c3a974). Dam sites are established using a variety of historical atlases, maps and documents, aerial imagery, regulatory records, national data bases, and DEM analysis. Historical atlases and maps do not have the spatial accuracy of a digitized map but can be georeferenced based on land features such as road intersections, large stream bends, the confluence of two streams or similar points that are unlikely to have significantly changed over time. After a historical dam location is determined, the sites can be compared with modern satellite imagery to establish breached or intact status. Intact dams represent modern sinks in the landscape for legacy sediment deposition, while areas behind breached dams likely have high, exposed, eroding stream banks that are experiencing discernable retreat into the previously impounded sediment.

C. Field Site Identification

Sites for field investigation for this project were selected through a combination of recommendations from colleagues at NRCS (Cory Guilliams and Mike Philips), USGS (Allen Gellis), and JMU (Scott Eaton) and our own research into the Smith Creek watershed. Because repeat lidar was not available, the project utilized the single dataset to map historical milldam locations, find legacy sediment terraces and estimate sediment thicknesses, create long profiles to verify the presence of vertical stream banks and determine canopy heights and densities. Additional aerial and satellite imagery (Google Earth) were used to pinpoint field sites with low amounts of tall bank vegetation/canopy, which is the most favorable condition for UAV survey results. The typical procedure for field investigation uses DEM differencing results from repeat lidar datasets to establish exactly where the most stream bank erosion is occurring in an area of interest. Using the existing combination of resources, we expected to select sites with high erosion, but not necessarily the highest rates or "hotspots" in the watershed.

D. Legacy Sediment Sampling

Legacy sediment was sampled in close reference to previous methods utilized at F&M (Walter and Merritts, 2013) and from PADEP Bureau of Clean Water - Water Quality Monitoring Protocols for Streams and Rivers (2021). Stainless steel trowels, plastic bags, stadia rod and flexible soil tape were used for sample collection. Legacy sediment was sampled at the top, middle, and bottom of banks, and additional investigation was conducted to identify samples of potential buried organic-rich soils and pre-Holocene sediments. Sampling began at the base of the bank and worked up to avoid disturbing sediment where sampling would next occur. Plastic sample bags were washed with native stream water to avoid potential contamination. Sample locations were recorded with RTK GPS to identify both the bank sample area within the project site and with field tape to locate the individual samples relative to the top of the bank. Samples were immediately labeled, photographed, and placed in storage after collection and sent to the Pennsylvania State University Agricultural Analytical Services Lab for nutrient and grain size analyses.

E. Drone Survey/Photogrammetry

Once a field site was determined, DJI Flight Planner software was used to create the bounds of our UAV survey area. Flight Planner allowed us to determine the altitude of flights, path of flights, and location of photo captures. A minimum of four overlapping flights, at altitudes of 100-150ft above ground, were generated for each survey area. Canopy cover obstructs the UAV camera's ability to gather information from the ground surface and this lack of optical data translates to a lack of ground surface elevation data, creating data "holes" or gaps in DEMs. Ensuring multiple survey flight paths that overlap at different angles is one way to mitigate the interference of canopy, while performing UAV photogrammetry. Surveys under "leaf-off" conditions is another. However, bare branches, if concentrated densely enough, can have a similar effect to mature leaves in obscuring the ground surface. Flight plans were uploaded into the Litchi mobile phone app for field use. All flight planning was done before on-site investigations to minimize potential in field troubleshooting and delays.

UAV flights were paired with RTK GPS to create the DEMs from photogrammetry (Figure 2). RTK base data was recorded for a minimum of four hours and 20 wooden “tile” pads (~1ft x 1ft) were placed in the survey area so their locations can be recorded with an RTK GPS mobile receiver (Figure 2). An equal number of pads were placed on each side of the stream, with some pads placed close to the stream banks and others on terrace locations away from the bank edge. Between 400-600 UAV photos were taken during each survey for post-processing using Agisoft Metashape software. As noted, holes in DEMs, primarily caused by vegetation, were manually clipped to reduce overall error in the final differencing analysis. Clipping the data close to the channel also eliminated distortion near the edges of DEMs from the UAV camera lens. Due to the recent emergence of UAVs in the environmental field and evolving technology for photogrammetry, the described field and post-processing methodologies undergo minor adjustments to maximize potential and limit uncertainty in the data.

Figure 2. UAV survey field methodology: 1) Evan Lewis and Sam Feibel setting up RTK base station at Seller’s Mill, 2) Logan Lewis using RTK rover to survey a tile pad location at Bruce’s Mill, 3) Sam Feibel beginning UAV flight at Moore’s Mill, and 4) Logan Lewis and Evan Lewis monitoring UAV during flight at Moore’s Mill.

IV. Results:

A. Smith Creek Watershed Overview

Smith Creek, a fourth order tributary to the North Fork of the Shenandoah River, drains the Valley and Ridge Province in the Chesapeake Bay and we mapped 424 miles of streams (first through fourth order streams) within the 105 square mile watershed. In total, third and fourth order streams represent approximately 70 miles of stream and the lower order streams represent over 350 miles. Major third order tributaries to Smith Creek are War Branch, Mountain Run and Dry Fork. Compiling historical records and modern imagery, we identified 21 historical milldam locations in the watershed (Figure 3), all of which have been breached (See Appendix 1 for additional information). Primarily, two Shenandoah and Rockingham County historical atlases, from 1875 (J. Hotchkiss) and 1885 (D.J. Lake and Co.), were used in milldam identification, but additional maps were utilized for identifying individual dam positions with more certainty. We mapped ~7,800,000 tons of legacy sediment that constitute a surface area of ~1,300 acres in valley bottoms adjacent to third and fourth order streams (Figure 4). Mapped legacy sediment on average was ~5 feet thick, reaching ~9 feet on Smith Creek and up to ~6 feet on its tributaries. At project field locations, we measured vertical legacy sediment banks between three and nine feet in height. Bank degradation and retreat into legacy sediment was commonly inferred on-site from fences falling into streams, undercut trees, and unfenced banks with open cow access.

A total of 27 samples of legacy sediment were collected at five different locations in the watershed (Moore's Mill, Seller's Mill, War Branch, Bruce's Mill, and Pine Forge) and featured an average consistency of 25% clay (range = 8-44%), 30% silt (range = 11-45%), 38% sand (range = 27-65%), and 7% fine gravel (range = <1-36%) (Figure 5, see Appendix 2.1 for additional information). Legacy sediment had a median particle size of ~0.07 mm (range = ~0.02-0.24 mm), while average sizes ranged from 0.03-0.1 mm between the five sites. Particle sizes also slightly varied by positions in stream bank, displaying finer sediments at the base of banks (~0.05 mm) than at the middle and top (~0.07-0.08 mm). Sampled legacy sediment was primarily a clay loam but stretched to a sandy loam and a silty clay loam (Figure 6). We also sampled a dark, organic-rich hydric soil and coarser material deposited in legacy sediment and on the terrace surface. The buried hydric soil contained 13.3% organic matter, while legacy sediment from the watershed ranged between 1-3%. Gravel bars were only identified at the Pine Forge location and were noticeably less coarse than pre-Holocene basal gravel observed elsewhere in the watershed.

From nutrient analyses, we measured legacy sediment ranging between 410-2710 ppm N (average = 1210 ppm), 100-560 ppm P (average = 330 ppm), and 2,720-73,800 ppm C (average = 30,890 ppm), which is proportional to an average loading of 2.42 N/ton (range = 0.82-5.42 lbs/ton), 0.65 lbs P/ton (range = 0.21-1.12 lbs/ton), and 61.8 lbs C/ton (range = 5.4-147.6 lbs/ton) of eroded sediment (See Appendix 2.2 for additional information). Evaluation of nutrients in legacy sediment from individual field sites shows that, on average, concentrations of carbon increases with depth from terrace surface, while concentrations of nitrogen, phosphorus, and organic matter decreases with depth (See Appendix 2.3 for additional information). Little variation was found between average N and P loads independent of sample depth at our five sample sites (2.2-2.5 lbs N/ton and 0.5-0.7 lbs P/ton), but C measurements varied widely

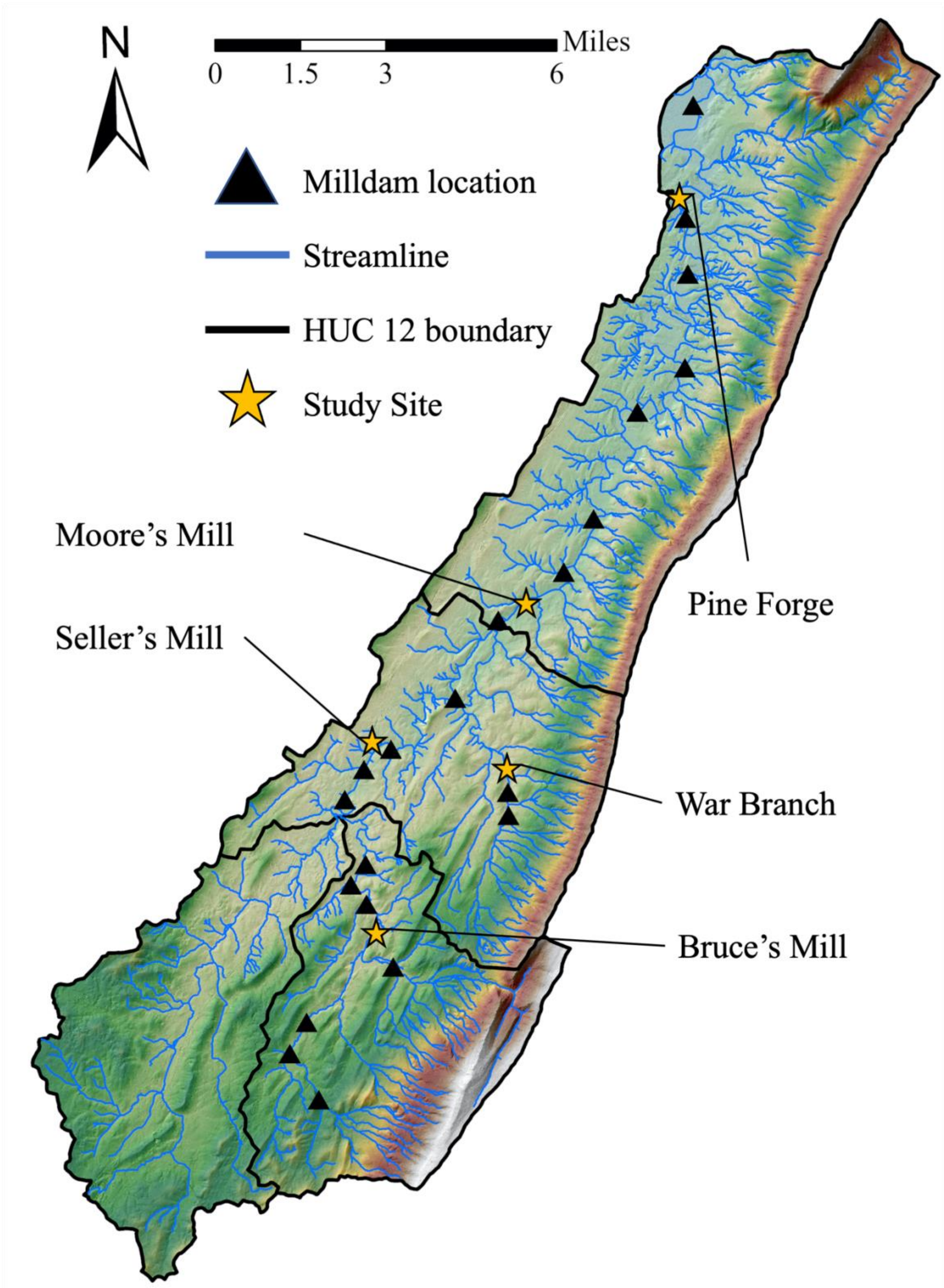


Figure 3. Smith Creek watershed with custom mapped streamlines, historic milldam location, and study sites for this project above DEM derived from 2011 lidar. The four HUC12 watershed boundaries that compose the larger HUC10 Smith Creek watershed are also mapped (black lines).

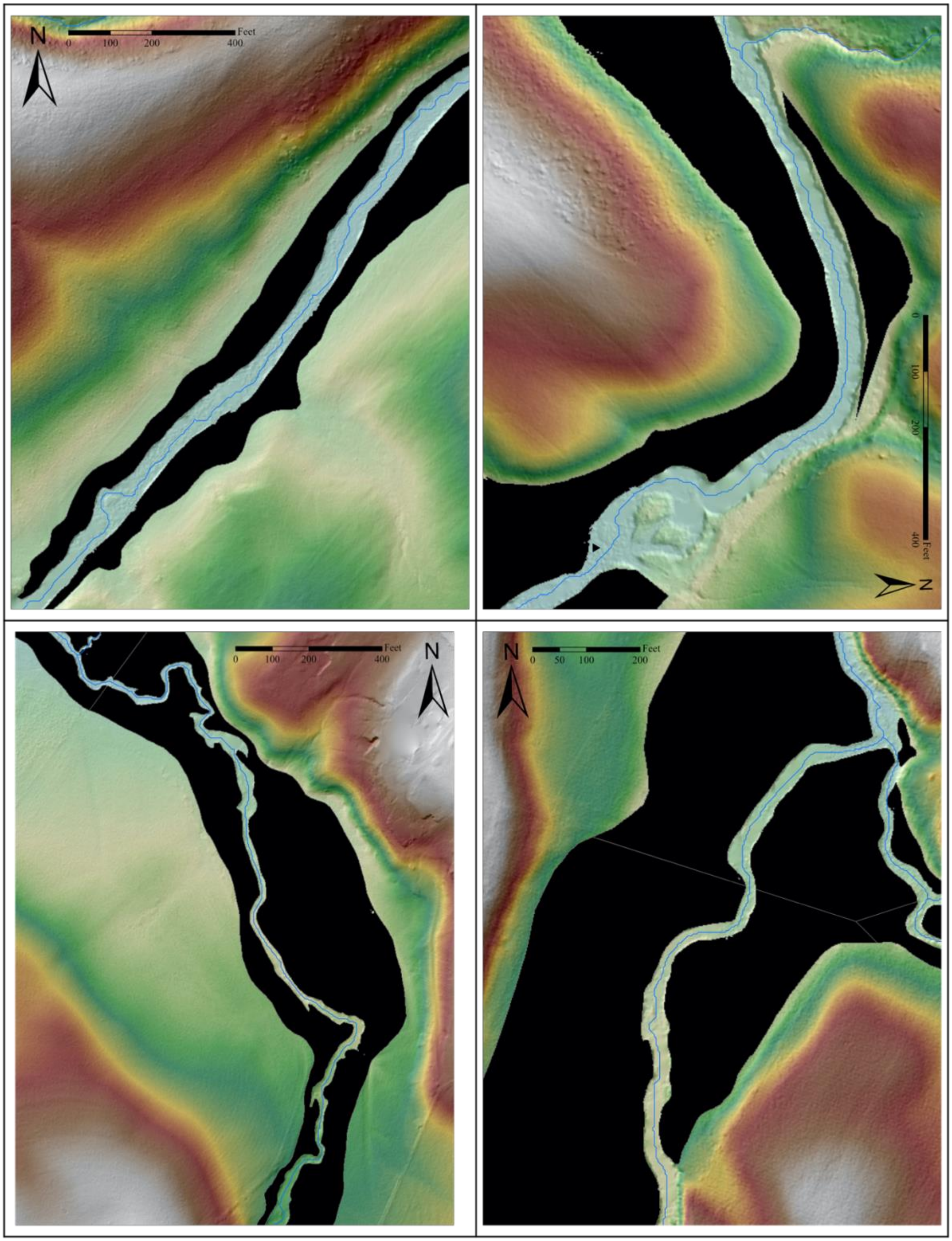


Figure 4. Terrace locations (mapped in black) at four UAV survey sites from this project: Moore's mill (top-left), Seller's mill (top-right), War Branch (bottom-left) and Bruce's mill (bottom-right). Stream centerlines are mapped in blue.

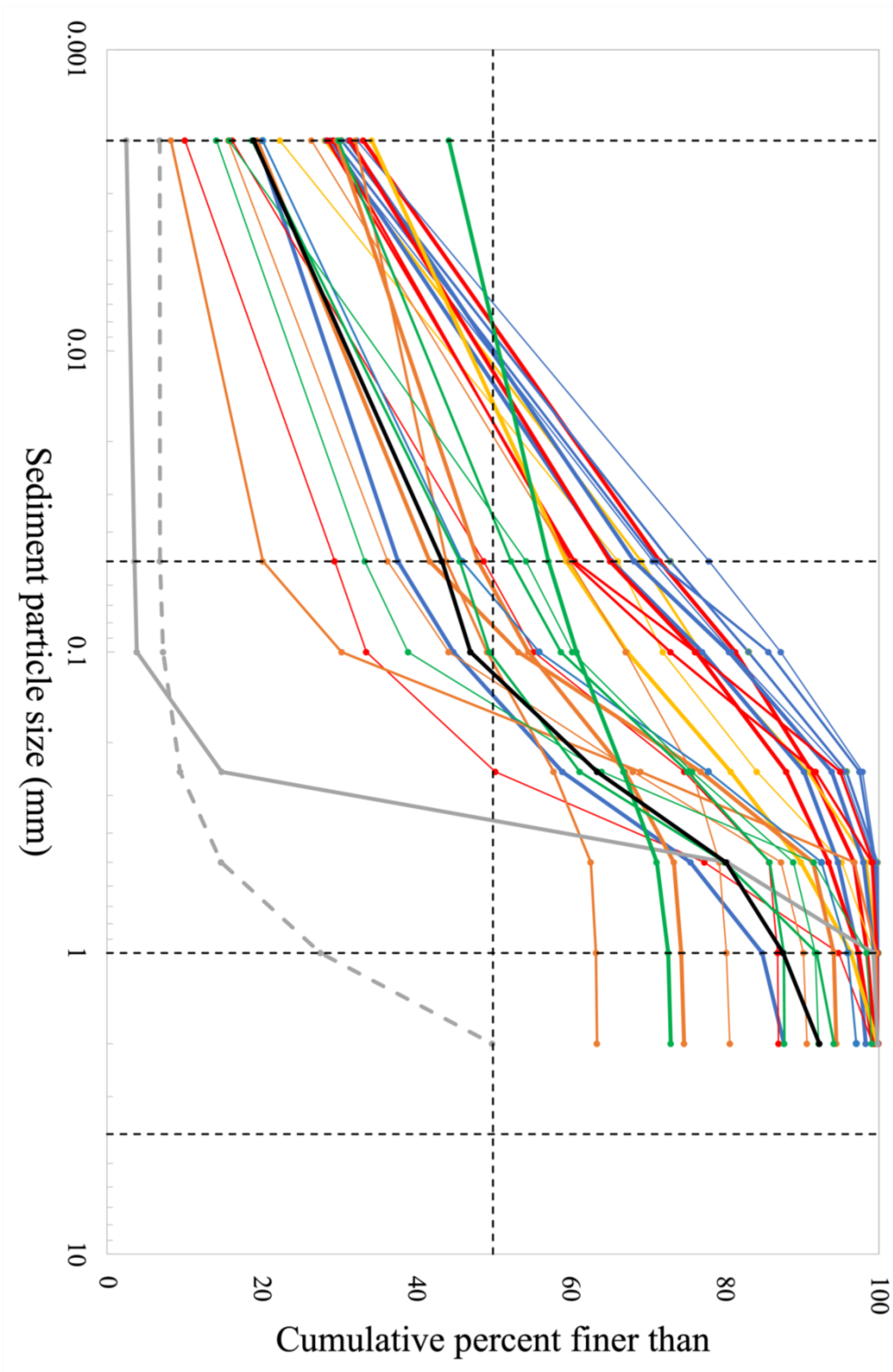


Figure 5. Cumulative percent finer grain size distribution plots for all samples from Smith Creek watershed, including all legacy sediment (Moore's Mill = orange, Seller's Mill = red, War Branch = green, Bruce's Mill = yellow, and Pine Forge = blue), buried hydric soil (black), surface deposit (grey) and coarser layer in bank (grey dashed). Thickness of plotted lines of legacy sediment are associated with locations from bank (thick lines = bottom of bank, thin lines = top of bank, and medium sizes lines = mid-bank samples). X-axis is plotted in log scale from clay sized particles to gravel.

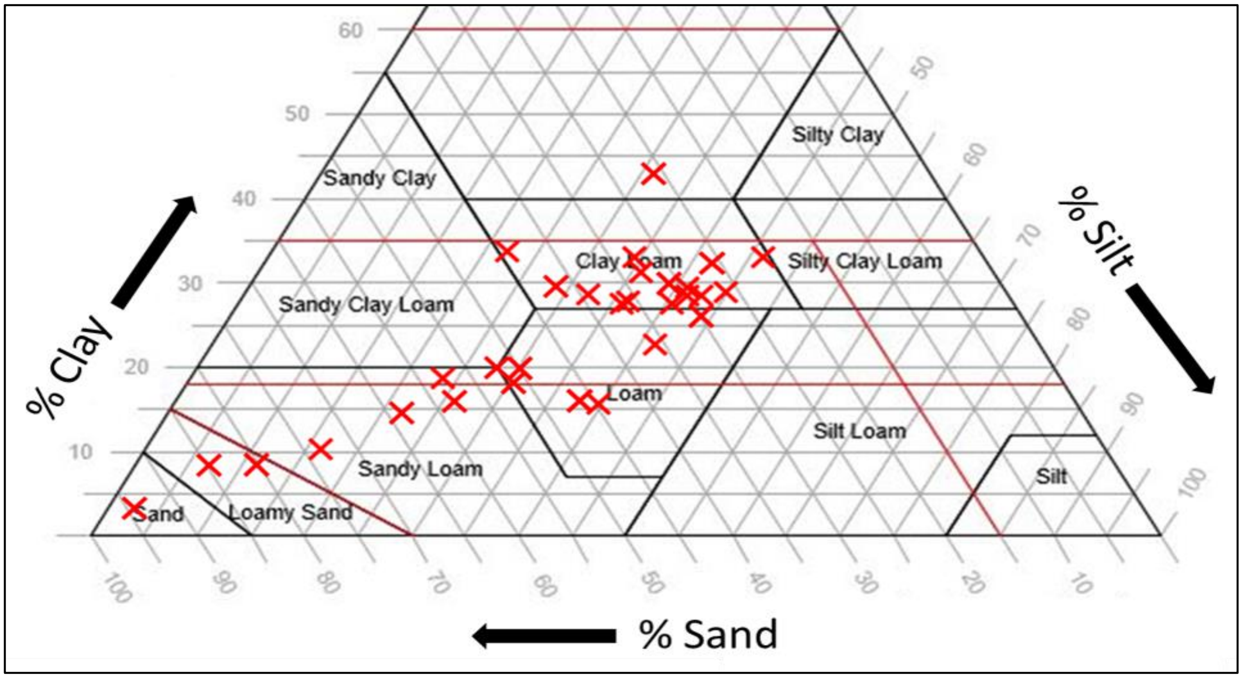


Figure 6. Soil classification pyramid illustrating the range and distribution of 27 legacy sediment samples across study sites for this project.

(20-100 lbs C/ton). Since legacy sediment is experiencing lateral retreat, individual averages from each legacy sediment sample site were used for estimating nutrient loads associated with specific erosion rates (See Appendix 2.4 for additional information).

With both 2011 lidar data and our generated UAV DEMs (2022), we calculated difference rasters for changes in elevation that occurred between 11 years at four different locations in the watershed (Moore's Mill, Seller's Mill, War Branch, and Bruce's Mill). Stream bank erosion rates ranged from ~0.01-0.04 tons/ft/yr (20-80 lbs/ft/yr) between the four sites. Along shorter stretches of stream (100-200 ft) we estimated bank erosion rates as high as ~0.07-0.11 tons/ft/yr (140-220 lbs/ft/yr). The War Branch tributary field site had the highest recorded erosion rates while displaying some of the lowest bank heights. Conversely, the highest banks were recorded at Moore's Mill, but they had the lowest erosion rates of our field sites. At a fifth location, Pine Forge near a USGS monitoring gage, two UAV surveys were conducted but canopy density was too thick to produce robust, reliable, data. Estimates for both erosion rates and terrace volume were generated using a bulk density value 1.07 g/cm^3 for legacy sediment.

B. Site Evaluations

1. Moore's Mill

This location on Smith Creek was selected for a UAV survey due to a lack of bank vegetation and thin canopy. The site is also near the previous Moore's Mill (1885) location, implying high probability of legacy sediment impoundments and eroding stream banks. Using lidar derived long profiles, we determined that the valley bottom is quite narrow but legacy sediment is present on both sides of the stream. Long profiles also showed that stream banks are vertical and often over six feet in height. From terrace mapping, we estimate ~40,000 tons of legacy sediment are present in the survey area with an average thickness of ~7 feet (Figure 4). From field inspection, we observed a wide, straight stream channel with legacy sediment banks between five and eight feet in height. Bank erosion was evident by undercut trees and eroded blocks of legacy sediment present near the edge of the stream. Several unfenced cow access points to the edge of the stream were also contributing to bank degradation at this site. No gravel bars are present, but eroded blocks of sediment sometimes direct small meanders in flow. The fields adjacent to both sides of the valley bottom are steep and the entire survey area is used for pasture up to the edge of the stream. Limestone bedrock outcrops are numerous throughout the stream and on the hillslopes.

A single UAV survey was completed at this location in March of 2022. We calculated an average bank erosion rate of ~0.02 tons/ft/yr (40 lbs/ft/yr) along 1,311 feet of stream (Figure 7). Near the upstream area of the survey section where a small meander is forming, bank erosion rates were as high as ~0.04 tons/ft/yr (80 lbs/ft/yr). Over the 11-year period, we estimate 286 +/- 118.8 tons (572,000 +/- 237,600 lbs) of bank sediment have been removed from the survey area and delivered downstream as fine sediment load. We also estimate ~590 lbs N and ~190 lbs P was transported downstream from bank erosion during this same period.

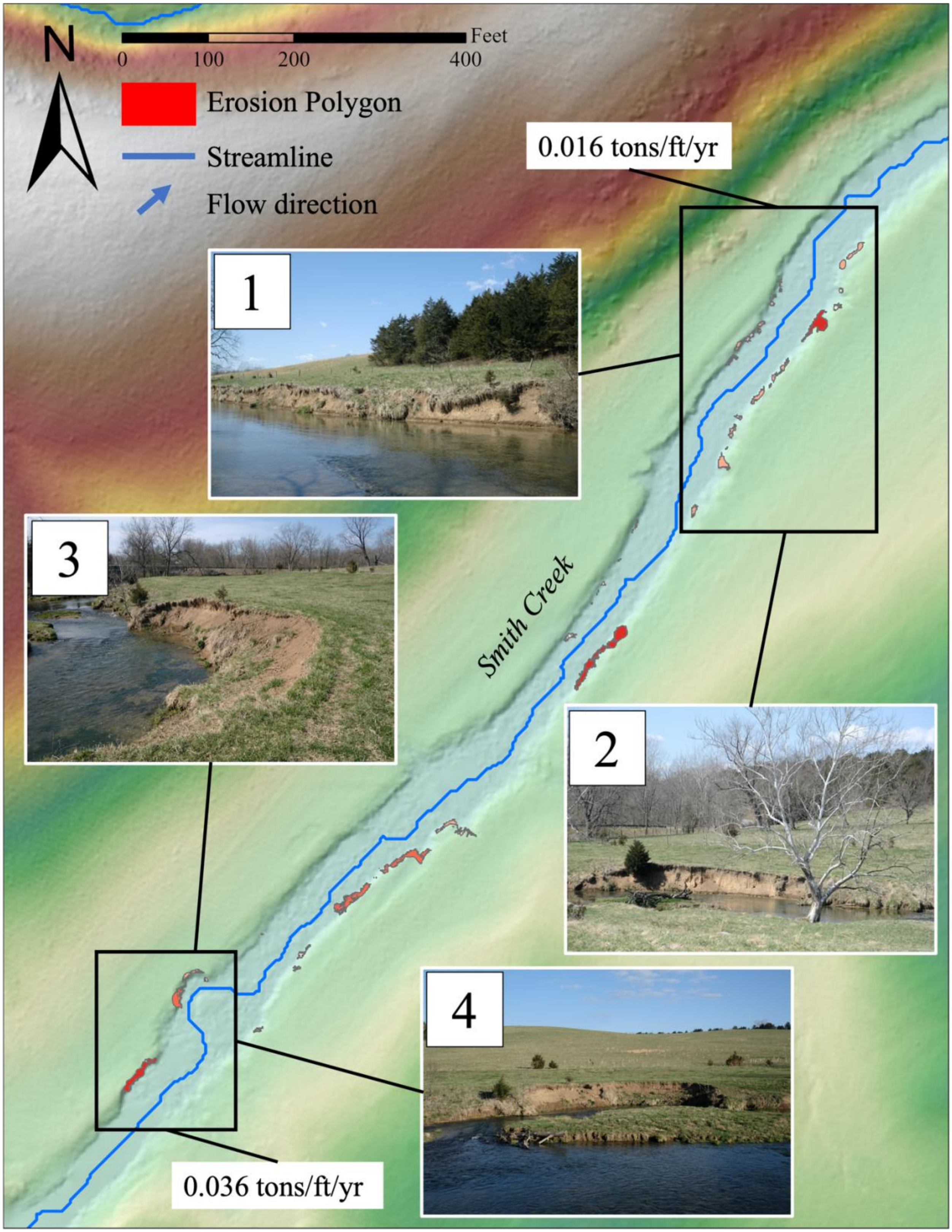


Figure 7. DEM differencing results from Moore's Mill site, see Appendix 3 for additional information about inset images and erosion polygons.

2. Seller's Mill

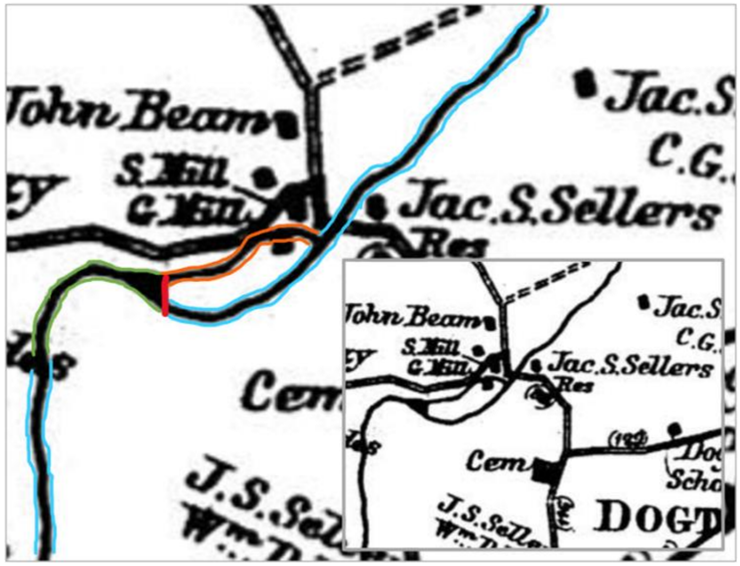


Figure 8. Capture from historical 1885 map of milldam (red), race (orange), and pond (green) associated with Jac S. Seller's Saw and Grist Mill. The blue path denotes the Smith Creek main channel. Inset image to the bottom right is same as larger image but without the custom, colored lines.

This location, first identified as the former, and current, Seller's Mill location (Figure 8) was recommended as a potential legacy sediment site by our NRCS and USGS colleagues. The millpond once powered a saw and grist mill before its final breaching in 1934. Current dam remnants are that of an inset dam, so presumably, the initial milldam was higher and stretched longer across the valley bottom. Both the mill building, and 950-foot mill race are well preserved downstream of the remaining inset dam remnants. From terrace mapping, we estimate ~40,000 tons of legacy sediment are present in the survey area, with an average thickness of ~7 feet (Figure 4). Most of the valley bottom consists of open pasture and the single fenced cattle crossing through the stream bounds the downstream (North) end of our survey. During field assessments we measured legacy sediment stream banks exhibiting striking verticality between seven and nine feet in height. Recent freeze-thaw cycles can be inferred from substantial amounts of loose sediment accumulating at the middle and base of banks (Figure 9). Other signs of bank retreat were gathered from fence sections falling into the stream, remnants of wire and posts embedded in the banks, and undercut trees. No notable gravel bars are present in this reach of Smith Creek.

Three UAV surveys were performed at Seller's Mill location, one occurring each March from 2020 to 2022. The survey area extended along 1,440 feet of stream, featuring a low to medium amount of canopy and minor bank vegetation. We calculated an average bank erosion rate of ~0.01 tons/ft/yr (20 lbs/ft/yr) for the stretch (Figure 10), with majority of the erosion occurring across from the dam remnants at a rate of ~0.07 tons/ft/yr (140 lbs/ft/yr). Between 2011 and 2022, we estimate 228.8 +/- 42.9 tons (457,600 +/- 85,800 lbs) of sediment have been expelled from the survey area and delivered downstream as fine sediment load. We also estimate ~570 lbs N and ~150 lbs P was transferred downstream from bank erosion.

Figure 9. Large amounts of unconsolidated sediment have accumulated along the bottom of banks from recent freeze-thaw. High flow events will quickly wash this sediment away.

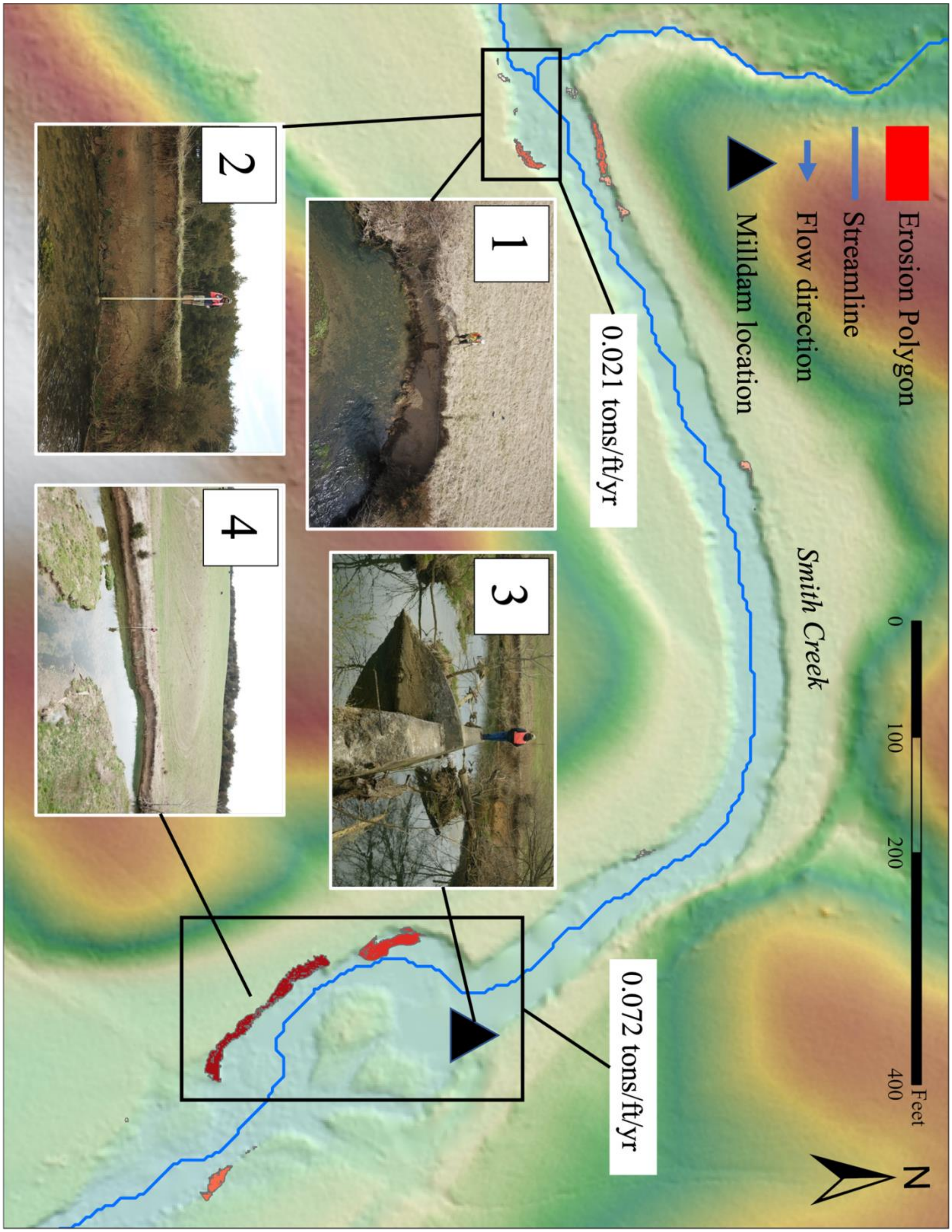


Figure 10. DEM differencing results from Seller's Mill site, see Appendix 3 for additional information about inset images and erosion polygons.

3. War Branch

Figure 11. Spring seep originating from edge of valley, many others were observed throughout the survey reach.

Our survey site on War Branch, a 3rd order tributary of Smith Creek, was pinpointed using a combination of aerial imagery and legacy sediment terrace characteristics. From aerial imagery and a preliminary site visit, we determined this location had few trees and banks with little vegetation. Using lidar derived long profiles we verified that legacy sediment is present on both sides of the stream and banks are vertical in nature. The site had a wide valley bottom exclusively used for pasture with several areas where cows accessed the unfenced stream. Numerous feeder springs and seeps were present near the edges of the valley (Figure 11). We also noted the presence of regularly placed stone formations protruding from banks near the downstream survey boundary, confirming likely post-settlement alteration of the original hydrology. From terrace mapping, we estimate ~30,000 tons of legacy sediment are present in the survey area, with an average thickness of ~4 feet (Figure 4). During field investigation, we measured stream banks between three and six in height. Most significant was the discovery of a layer of dark, organic-rich soil near the base of a five-foot eroding bank (Figure 12). Due to the layer's presence at the base of the bank and lying atop a gravel layer, we interpreted this as evidence of a wetland system that occupied the valley bottom prior to European settlement. Subsequent laboratory analysis revealed that the soil contained 13.4% organic matter, in contrast to the 2-3% range for other legacy sediment sampled in the watershed (See Appendix 2 for additional information). No gravel bars were identified but a likely pre-Holocene gravel layer was present under the sampled hydric soil.

The sole UAV survey at this site was conducted in March of 2022. We calculated an average bank erosion rate of ~0.04 tons/ft/yr (80 lbs/ft/yr) along 1,387 feet of stream (Figure 13). Near the upstream area of the parcel, erosion rates were as high as ~0.11 tons/ft/yr (220 lbs/ft/yr). Between 2011 and 2022, we estimate 544.5 +/- 80.3 tons (1,089,000 +/- 160,600 lbs) of sediment have been evacuated from the survey area and transported downstream as fine sediment load. We also estimate ~1,210 lbs N and ~310 lbs P was delivered downstream from bank erosion.

Figure 12. Dark, organic-rich soil found near water level, deposited below legacy sediment and above coarse basal gravel.

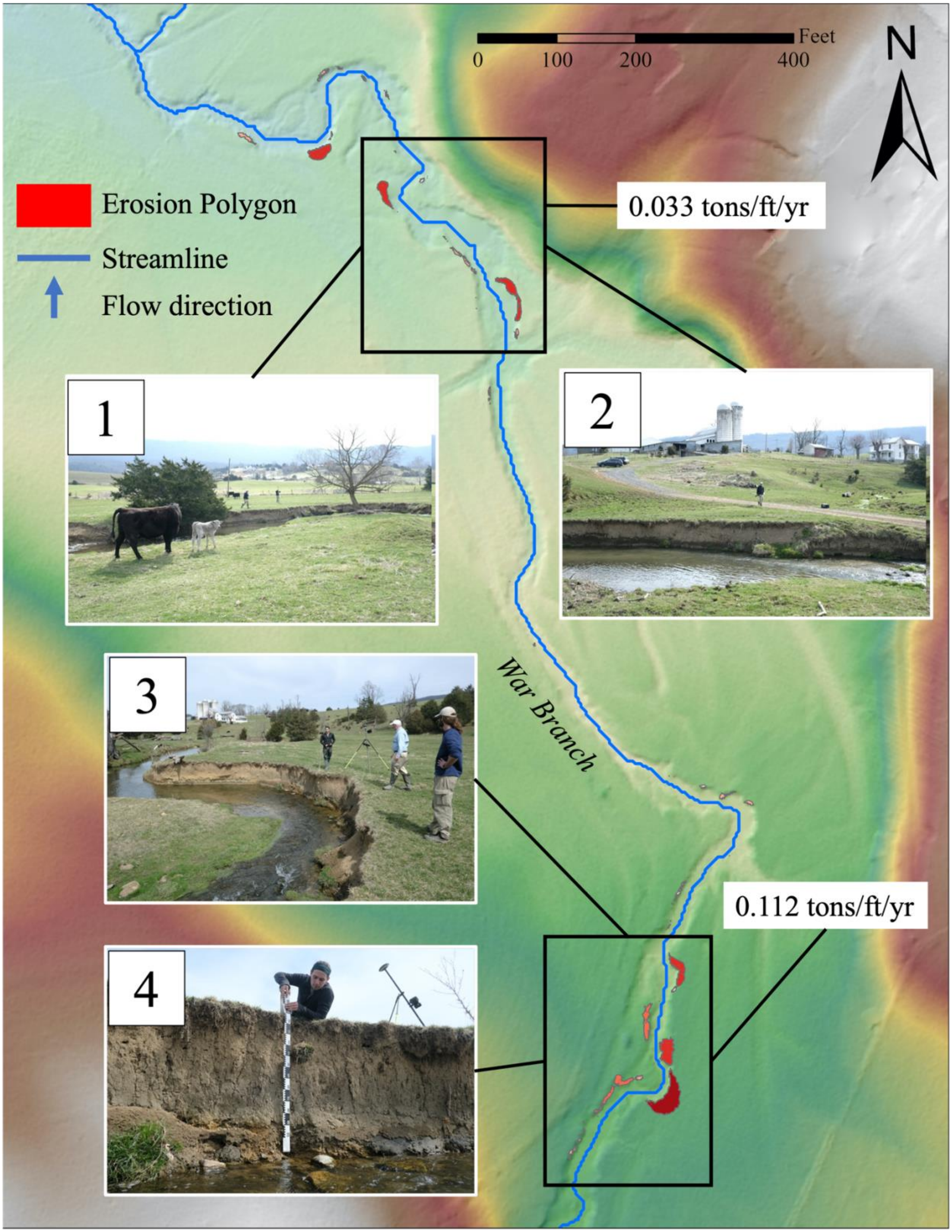


Figure 13. DEM differencing results from War Branch site, see Appendix 3 for additional information about inset images and erosion polygons.

4. Bruce's Mill

The most upstream site , originally identified as Carpenter's Mill and now called Bruce's Mill, was suggested by NRCS colleagues. It is just south of three former milldam locations (Figure 14). Using aerial imagery and lidar analysis, we selected this stream segment for UAV survey because of its thin canopy cover and wide sediment terraces. From subsequent terrace mapping, we estimate ~50,000 tons of legacy sediment are present in the survey area, with an average thickness of ~4 feet (Figure 4). We noted water quality monitoring equipment at two stream bank locations and a riparian planting throughout the survey area. We estimate the planting had occurred sometime in the early 2000s. Large boulders are present along the stream in the middle of the survey area, perhaps from previous erosion control attempts. Bank retreat could also be inferred from undercut trees and vertical stream banks. Legacy sediment is present on both sides of the stream at a maximum height of five feet. The lower bank heights are likely due to its distance upstream of the next known dam location. No notable gravel bars are present in the reach. Immediately downstream of our survey site, at a road bridge crossing near the closest known milldam location, we observed stream bank heights close to seven feet and signs of significant bank retreat. A second, relatively recent riparian planting was apparent on both sides of the stream on the legacy sediment terraces. It is likely that this area was where a mill pond formed behind one or more of the historic impoundments.

Annual UAV surveys were conducted in March 2020-2022. The survey area extended along 857 feet of stream, with low density in canopy cover and moderate amounts of thick grasses covering banks. We calculated an average bank erosion rate of ~0.01 tons/ft/yr (20 lbs/ft/yr) for this reach. (Figure 15). Between 2011 and 2022, we estimate 60.5 +/- 46.2 tons (121,000 +/- 92,400 lbs) of sediment have been expelled from the survey area and delivered downstream as fine sediment load. We also estimate ~150 lbs N and ~40 lbs P was transferred downstream from bank erosion.

Figure 14. Capture from historical 1875 map of three milldam locations, Bruce's Mill site is just upstream of third mill location from the top (all Carpenter's mills), each mill is depicted by a black star on the map. Flow is from bottom of image to the top (south to north).

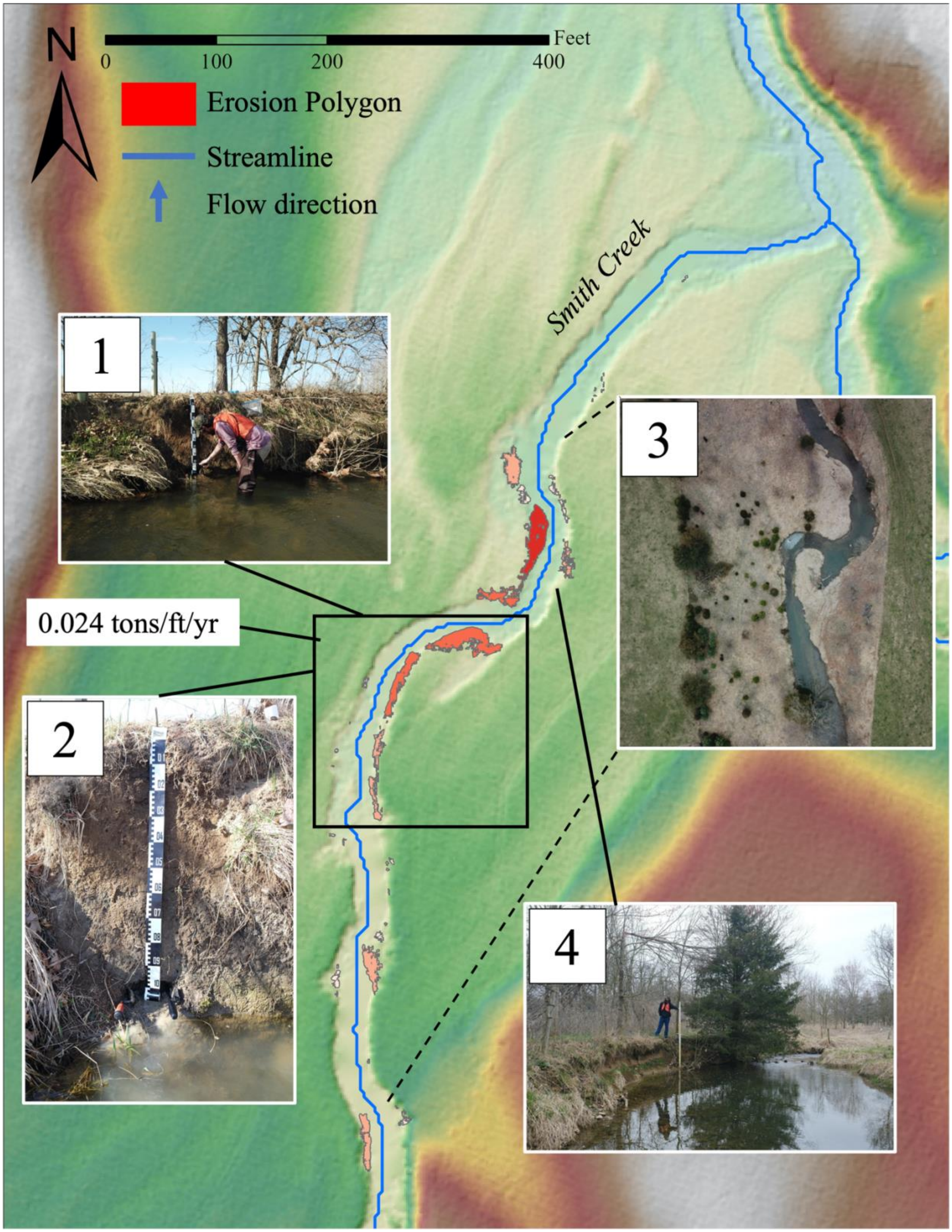


Figure 15. DEM differencing results from Bruce's Mill site, see Appendix 3 for additional information about inset images and erosion polygons.

5. Pine Forge

UAV surveys at the former Pine Forge dam on Smith Creek, where a current USGS gage station is active, were performed in March of 2020 and 202l. Neither survey was of sufficient quality to successfully perform our difference analysis, primarily because of the influence of dense canopy throughout the study reach that created large holes in our generated DEMs. Bank erosion into legacy sediment terraces is still evident at the site and the only substantial gravel bar at our field sites was observed here (Figure 16). Gravel bar material was visibly less coarse than basal gravel encountered elsewhere in the watershed. Legacy sediment banks were measured between five and seven feet in height on both sides of the stream (Figure 17). If DEM generation and differencing was successful, we believe significant bank erosion rate and volume would be detected. Nutrient analysis suggests that legacy sediment currently eroding from this site delivers a loading of 2.46 lbs N/ton and 0.64 lbs P/ton.

Figure 16. Gravel bar present across from likely rapidly eroding stream bank.

Figure 17. Legacy sediment bank measured at seven feet in height, showing signs of recent retreat and bank collapse.

V. Conclusions and Recommendations

Until recently, the environmental effects of historic dam activity and stream bank erosion of legacy sediment has not been fully recognized as a significant obstacle to meet water quality goals and the disconnect has often led to less effective and cost-efficient approaches to conservation management practice. This project provided an opportunity to develop a further understanding of legacy sediment; demonstrate a methodology for determining its presence in the Smith Creek watershed; and provide recommendations for future management consideration. Using historic milldam and terrace mapping, the project determined that legacy sediment is ubiquitous on almost all stretches of the Smith Creek mainstem and its major tributaries. Generally, a wide range of erosion rates were identified, with the highest rate measured at a Smith Creek tributary site with moderate bank heights. The latter results suggest that a successful application of legacy sediment removal may be best achieved by identifying and prioritizing smaller order streams for restoration. The identification of a buried hydric soil layer beneath legacy sediment is further indication that wetlands were present in watershed valley bottoms before European settlement.

The legacy sediment sampled was generally like that found in other watersheds of the Chesapeake Bay but contained higher concentrations of silt and fine sand, but less clay, perhaps reflecting the unique geologic composition of this physiographic province. Smaller concentrations of N, and particularly P, are likely associated with study locations utilized almost exclusively for grazing. The buried hydric soil contained 13.3% organic matter in contrast to the 1-3% range of legacy sediment samples. Loads of N and P are relatively consistent in legacy sediment throughout the watershed (2.2-2.5 lbs N/ton and 0.5-0.7 lbs P/ton), and on average, sediments decrease in N and P concentrations with depth from the terrace surface. Our estimated uncertainties using DEM methodology ranged from 19-76%, the higher range being from a site where minimal erosion was detected over a shorter period. Where large amounts of change are occurring, our error is much smaller (19-41%) and leads us to believe the methodology is well-suited for discerning where legacy sediment hotspots are in a watershed.

The UAV alternative to create a second DEM dataset was successful and supports the potential of repeat lidar data as a conservation management tool for BMP targeting and prioritization. The combination of data from this project and the recommended acquisition of a current lidar dataset can support more precise erosion hotspot identification in watershed streams. Identifying where legacy sediment erosion is occurring, and at what rate and volume, provides practitioners with the information to determine where and what conservation practices can be most effective. Our primary recommendation is that NRCS and Virginia partners should update its lidar to develop a powerful additional tool for conservation planning and implementation starting with an initial investment in the counties comprising the Smith Creek watershed. Legacy sediment is prevalent throughout the watershed and bank erosion has previously been identified as the largest contributing source. We predict that this is the case for many other Virginia watersheds and applying this approach to MS4 and Chesapeake Bay WIP requirements will enhance the Commonwealth's management strategy. Consideration of support and communication strategies regarding legacy sediment's impact and targeted funding of legacy sediment removal and restoration sites is encouraged. Future watershed restoration strategies will be more effective when legacy sediment removal is considered as a primary driver of pollution reduction and ecosystem service delivery. Development of science based and targeted pollution mitigation strategies that include legacy sediment sites will provide policy makers, practitioners, and managers with additional opportunities to reduce costs and increase successful conservation outcomes.

References:

D.J. Lake and Co., 1885. Rockingham and Shenandoah County Atlases, Virginia. Library of Congress – accessed at https://historicalmapworks.com.

Eaton, S.L., Tracey, A.L., and Sheets, R.M., 2015. The legacy of mill pond dams and sediment storage in the Smith Creek Watershed, Rockingham County, Virginia. GSA Southeastern Section – 64th Annual Meeting.

Gellis, A.C. and Gorman Sanisaca, L., 2018. Sediment fingerprinting to delineate sources of sediment in the agricultural and forested Smith Creek watershed, Virginia, USA. *JAWRA Journal of the American Water Resources Association*, *54*(6), pp.1197-1221.

Hotchkiss, Jedediah, 1875. Rockingham and Shenandoah County Maps, Virginia. Published by authority of U.S. Army, Library of Congress – accessed at https://loc.gov.

Merritts, D., Walter, R., Rahnis, M., Hartranft, J., Cox, S., Gellis, A., Potter, N., Hilgartner, W., Langland, M., Manion, L. and Lippincott, C., 2011. Anthropocene streams and base-level controls from historic dams in the unglaciated mid-Atlantic region, USA. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *369*(1938), pp.976-1009.

Merritts, D., Walter, R., Rahnis, M., Cox, S., Hartranft, J., Scheid, C., Potter, N., Jenschke, M., Reed, A., Matuszewski, D. and Kratz, L., 2013. The rise and fall of Mid-Atlantic streams: Millpond sedimentation, milldam breaching, channel incision, and stream bank erosion. *The challenges of dam removal and river restoration*, *21*, p.183.

VA NRCS, 2020. Smith Creek, Virginia's Chesapeake Bay Showcase Watershed, Smith Creek Factsheet – accessed at https://smithcreekwatershed.com/smith-creek-watershed-factsheet/.

Walter, R.C. and Merritts, D.J., 2008. Natural streams and the legacy of water-powered mills. *Science*, *319*(5861), pp.299-304.

Water Science Institute, 2018. Removing Legacy Impairments to Promote Ground and Surface Water Quality, NRCS Conservation Innovation Grant – accessed at https://www.waterscienceinstitute.org/funded-grants.

Water Science Institute, 2020. Legacy Sediment 2.0: Enhanced Mapping and Decision Support Tool, NRCS Conservation Innovation Grant – accessed at https://www.waterscienceinstitute.org/funded-grants.

Water Science Institute, 2020. WSI Data Guide: Using WSI data products for restoration decision-making – accessed at https://storymaps.arcgis.com/stories/9e3d307249284d64a8b7e40082c3a974.

Appendix 1

ID	Stream	Feature Label	Feature Type	Source Map	Status
1	Smith Creek	Mount Airy Mills	-	1885	breached in 1997
2	Smith Creek	Pine Forge	Forge	1885	breached
3	Smith Creek	Walter Newman	Saw & Grist Mill	1885	breached
4	Smith Creek	W.H. Snapp	Saw Mill	1885	breached
5	Smith Creek	Shirley	Saw & Grist Mill	1885	breached
6	Smith Creek	Craney Island Mills	Saw & Grist Mill	1885	breached
7	Smith Creek	Reuben Zirkle	Saw Mill	1885	breached
8	Smith Creek	Model Mills	Saw & Grist Mill	1885	breached
9	Smith Creek	R. Zirkle	Saw & Grist Mill	1885	breached
10	Smith Creek	Jac. S. Seller's	Saw & Grist Mill	1885	breached in 1934
11	Smith Creek	Stoney Point Mills	-	1885	breached
12	Smith Creek	Chas. H Nicholas	Saw & Grist Mill	1885	breached
13	Smith Creek	Carpenter's	-	1875	breached
14	Smith Creek	B.F. Armentrout	Grist Mill	1885	breached
15	Smith Creek	Carpenter's	-	1875	breached
16	Smith Creek	Christian Flook	Saw Mill	1885	breached
17	Smith Creek	Geo Yancey	Grist Mill	1885	breached
18	War Branch	Abrim Rosenberger	Saw & Grist Mill	1885	breached
19	War Branch	Phillips & Speck	Planning Mill	1885	breached
20	Mountain Run	Cyrus Rhodes	Saw & Grist Mill	1885	breached
21	Unnamed Tributary	Armentrout	Grist Mill	1885	breached

Historical milldam information compiled from this project and associated locations from Figure 3. Locations are listed from upstream to downstream starting from the first mill location on Smith Creek, Mount Airy Mills.

Appendix 2 (2.1-2.4)

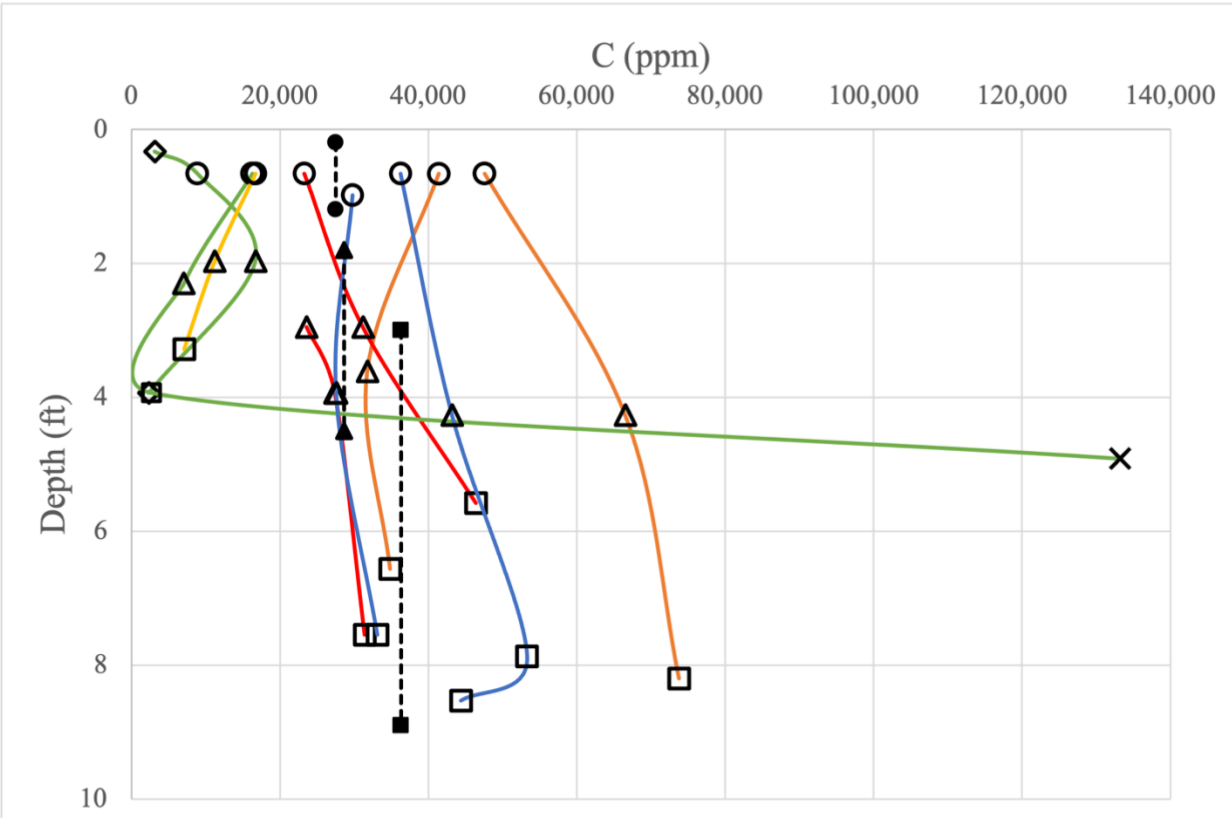
ID	Site	Position in bank	Depth (ft)	Soil Textural Class	% Clay	% Silt	% Fine Sand	% Medium Sand	% Coarse Sand	% Very Coarse Sand	% Gravel	D50 (mm)	Notes
1	Moore's Mill	Top	0.4-0.7	Sandy Loam	15.7	36.3	44.3	68.1	87.3	90.2	90.7	0.136	LS
2	Moore's Mill	Middle	3.3-3.6	Clay Loam	32.2	44.0	49.2	57.9	62.7	63.4	63.5	0.114	LS
3	Moore's Mill	Bottom	6.3-6.6	Clay Loam	29.8	48.1	54.6	67.2	73.5	74.4	74.8	0.065	LS
4	Moore's Mill	Top	0.4-0.7	Loam	26.5	60.0	67.2	75.8	79.3	80.3	80.7	0.035	LS
5	Moore's Mill	Middle	4.0-4.3	Loamy Sand	8.3	20.2	30.4	69.1	96.8	99.7	99.8	0.176	LS
6	Moore's Mill	Bottom	7.9-8.2	Loam	19.5	41.8	53.3	76.9	91.5	94.2	94.5	0.086	LS
7	Seller's Mill	Top	0.4-0.7	Loam	16.2	48.8	55.3	74.8	85.8	86.9	87	0.059	LS
8	Seller's Mill	Middle	2.7-3.0	Clay Loam	28.6	60.6	76.2	95	99.2	99.8	99.9	0.034	LS
9	Seller's Mill	Bottom	5.3-5.6	Clay Loam	31.5	65.2	76.3	88	93.5	97.4	99.2	0.028	LS
10	Seller's Mill	Middle	2.7-3.0	Sandy Loam	10.1	29.5	33.6	50.3	77.4	94.8	99.2	0.247	LS
11	Seller's Mill	Middle	3.6-3.9	Clay Loam	29.3	60.2	73	91.8	99.1	99.7	99.7	0.034	LS
12	Seller's Mill	Bottom	7.2-7.5	Clay Loam	33.2	71.6	81.4	91.3	96.8	98.5	99.5	0.023	LS
13	War Branch	Surface	0.0-0.3	Sand	2.5	3.6	3.9	14.9	80.4	99.3	99.9	0.354	surface
14	War Branch	Top	0.4-0.7	Sandy Loam	14.2	33.4	39.0	64.1	91.6	98.4	99.1	0.166	LS
15	War Branch	Middle	1.7-2.0	Clay Loam	30.0	52.4	58.8	75.2	85.9	87.7	87.8	0.045	LS
16	War Branch	Bottom	3.6-3.9	Loamy Sand	6.8	6.9	7.3	9.5	14.8	27.7	49.9	2.010	gravel lense
17	War Branch	Top	0.4-0.7	Loam	15.8	54.3	60.3	75.8	88.9	91.7	92.2	0.045	LS
18	War Branch	Middle	2.0-2.3	Loam	18.8	45.7	49.5	61.2	80.0	92.0	94.2	0.106	LS
19	War Branch	Bottom	3.6-3.9	Clay	44.3	57.2	60.8	66.9	71.2	72.7	73.0	0.023	LS
20	War Branch	Bottom	4.6-4.9	Sandy Loam	19.0	43.4	47.1	63.5	80.2	87.6	92.3	0.127	wetland soil
21	Bruce's Mill	Top	0.4-0.7	Loam	22.4	66.2	72	84.2	95.2	99.3	99.9	0.032	LS
22	Bruce's Mill	Middle	1.7-2.0	Clay Loam	28.2	69.2	76.9	90.8	98.4	99.7	99.9	0.028	LS
23	Bruce's Mill	Bottom	3.0-3.3	Clay Loam	34.3	59.5	67.4	80.8	89.9	96.4	99.8	0.032	LS
24	Pine Forge	Top	0.4-0.7	Clay Loam	28.4	70.7	80.9	95.3	99.5	99.7	99.8	0.027	LS
25	Pine Forge	Middle	4.0-4.3	Clay Loam	29.4	71.2	85.7	97.5	99.4	99.8	99.9	0.026	LS
26	Pine Forge	Bottom	7.6-7.9	Clay Loam	29	65.4	77.1	90.3	94.7	97.3	98.3	0.030	LS
27	Pine Forge	Bottom	8.2-8.5	Clay Loam	31.3	68.3	80.6	93.9	98	99.4	99.9	0.026	LS
28	Pine Forge	Top	0.7-1.0	Clay Loam	32.4	78	87.3	97.9	99.6	99.8	99.8	0.021	LS
29	Pine Forge	Middle	3.6-3.9	Clay Loam	30.4	73	83.1	95.8	99.8	99.9	99.9	0.024	LS
30	Pine Forge	Bottom	7.2-7.5	Sandy Loam	19.4	37.7	44.9	59	75.6	84.9	87.7	0.154	LS

Appendix 2.1. Percent finer than grain size distribution data and D50 values for all bank deposit sampled in Smith Creek watershed. Sample 13 is a surface layer deposit, 16 is a coarse gravel layer, and 20 is the buried hydric soil. LS = legacy sediment.

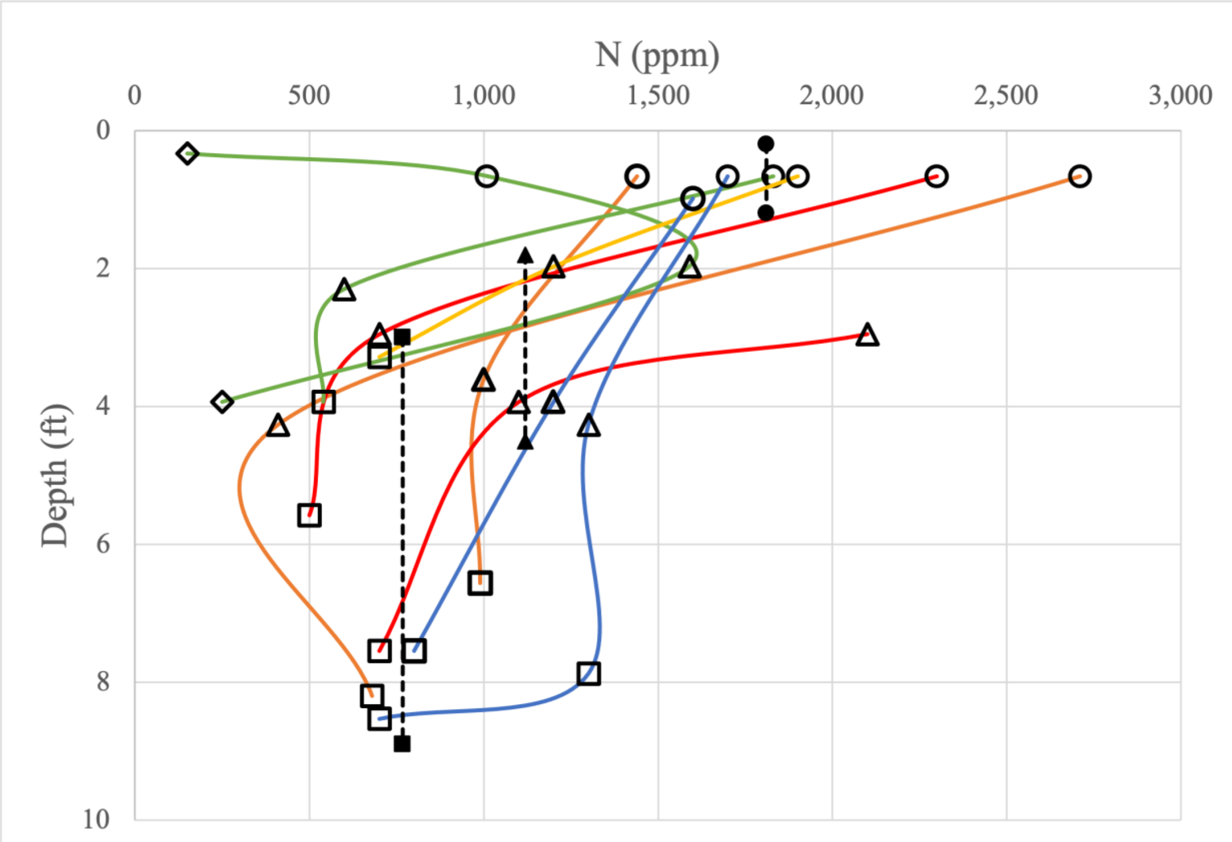
ID	Location	Position in bank	Depth (ft)	C (ppm)	C load (lbs/ton)	N (ppm)	N Load (lbs/ton)	P (ppm)	P Load (lbs/ton)	Organic Matter (%)	Notes
1	Moore's Mill	Top	0.4-0.7	41400	82.80	1440	2.88	397.78	0.80	-	LS
2	Moore's Mill	Middle	3.3-3.6	31760	63.52	1000	2.00	366.30	0.73	-	LS
3	Moore's Mill	Bottom	6.3-6.6	34840	69.68	990	1.98	272.22	0.54	-	LS
4	Moore's Mill	Top	0.4-0.7	47590	95.18	2710	5.42	557.61	1.12	-	LS
5	Moore's Mill	Middle	4.0-4.3	66540	133.08	410	0.82	169.43	0.34	-	LS
6	Moore's Mill	Bottom	7.9-8.2	73790	147.58	680	1.36	229.33	0.46	-	LS
7	Seller's Mill	Top	0.4-0.7	23300	46.60	2300	4.60	443.27	0.89	3.2	LS
8	Seller's Mill	Middle	2.7-3.0	31200	62.40	700	1.40	312.77	0.63	1.2	LS
9	Seller's Mill	Bottom	5.3-5.6	46400	92.80	500	1.00	243.26	0.49	1.0	LS
10	Seller's Mill	Middle	2.7-3.0	23600	47.20	2100	4.20	361.82	0.72	2.7	LS
11	Seller's Mill	Middle	3.6-3.9	27400	54.80	1100	2.20	405.54	0.81	1.7	LS
12	Seller's Mill	Bottom	7.2-7.5	31400	62.80	700	1.40	213.97	0.43	1.3	LS
13	War Branch	Surface	0.0-0.3	3120	6.24	150	0.30	106.56	0.21	-	surface
14	War Branch	Top	0.4-0.7	8890	17.78	1010	2.02	327.42	0.65	-	LS
15	War Branch	Middle	1.7-2.0	16710	33.42	1590	3.18	299.32	0.60	-	LS
16	War Branch	Bottom	3.6-3.9	2340	4.68	250	0.50	155.44	0.31	-	gravel lense
17	War Branch	Top	0.4-0.7	16280	32.56	1830	3.66	508.44	1.02	-	LS
18	War Branch	Middle	2.0-2.3	7060	14.12	600	1.20	181.50	0.36	-	LS
19	War Branch	Bottom	3.6-3.9	2720	5.44	540	1.08	105.09	0.21	-	LS
20	War Branch	Bottom	4.6-4.9	133200	266.40	-	-	-	-	-	wetland soil
21	Bruce's Mill	Top	0.4-0.7	16700	33.40	1900	3.80	542.58	1.09	2.9	LS
22	Bruce's Mill	Middle	1.7-2.0	11200	22.40	1200	2.40	355.06	0.71	2.1	LS
23	Bruce's Mill	Bottom	3.0-3.3	7100	14.20	700	1.40	182.60	0.37	1.6	LS
24	Pine Forge	Top	0.4-0.7	36300	72.60	1700	3.40	407.83	0.82	2.4	LS
25	Pine Forge	Middle	4.0-4.3	43200	86.40	1300	2.60	365.61	0.73	1.9	LS
26	Pine Forge	Bottom	7.6-7.9	53300	106.60	1300	2.60	279.97	0.56	2.3	LS
27	Pine Forge	Bottom	8.2-8.5	44400	88.80	700	1.40	246.76	0.49	1.1	LS
28	Pine Forge	Top	0.7-1.0	29800	59.60	1600	3.20	386.91	0.77	2.2	LS
29	Pine Forge	Middle	3.6-3.9	27600	55.20	1200	2.40	314.72	0.63	1.9	LS
30	Pine Forge	Bottom	7.2-7.5	33100	66.20	800	1.60	234.47	0.47	1.0	LS

Appendix 2.2. Measured total carbon (C), nitrogen (N), phosphorus (P), and organic matter concentrations from stream bank deposits in Smith Creek watershed. P concentrations were determined using a dry weight basis. Sample numbers are the same as those in Appendix 2.1. LS = legacy sediment.

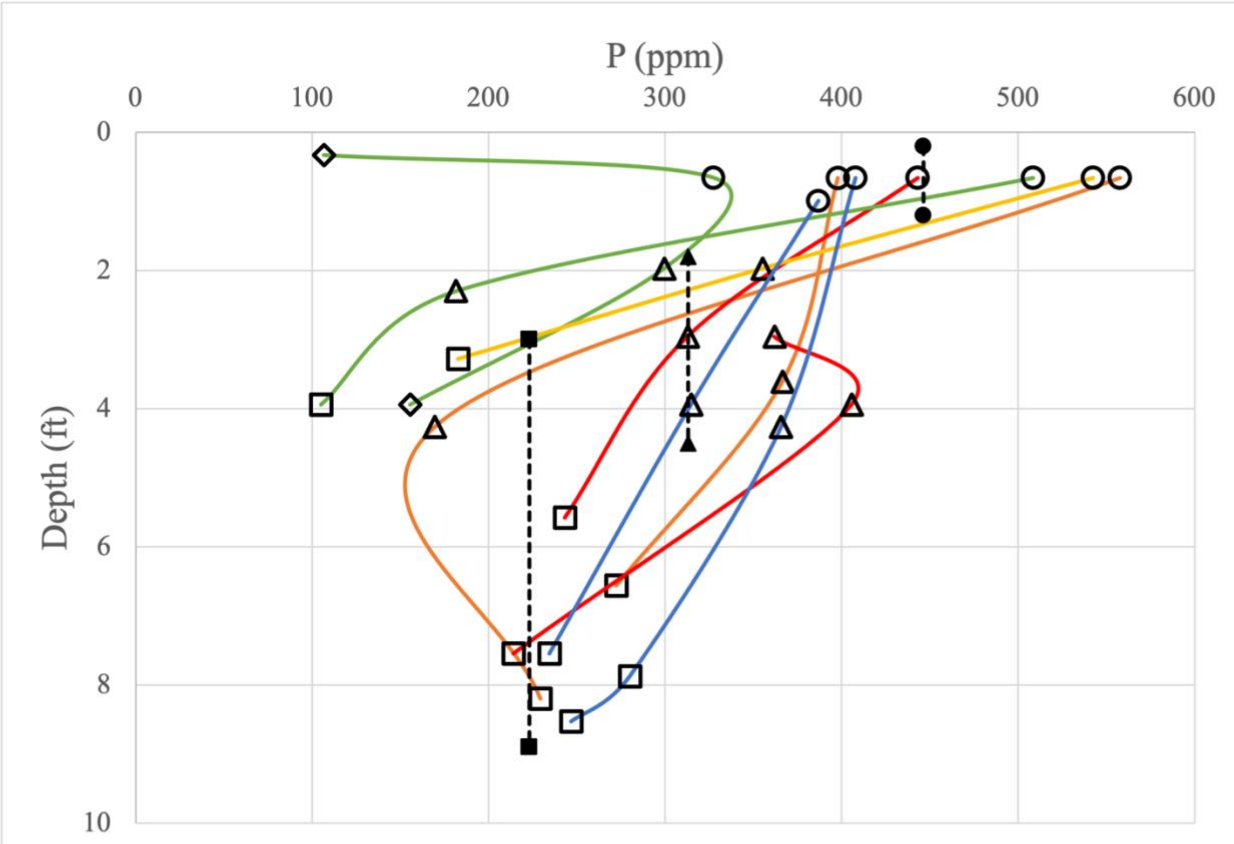
Appendix 2.3 (2.31-2.33)



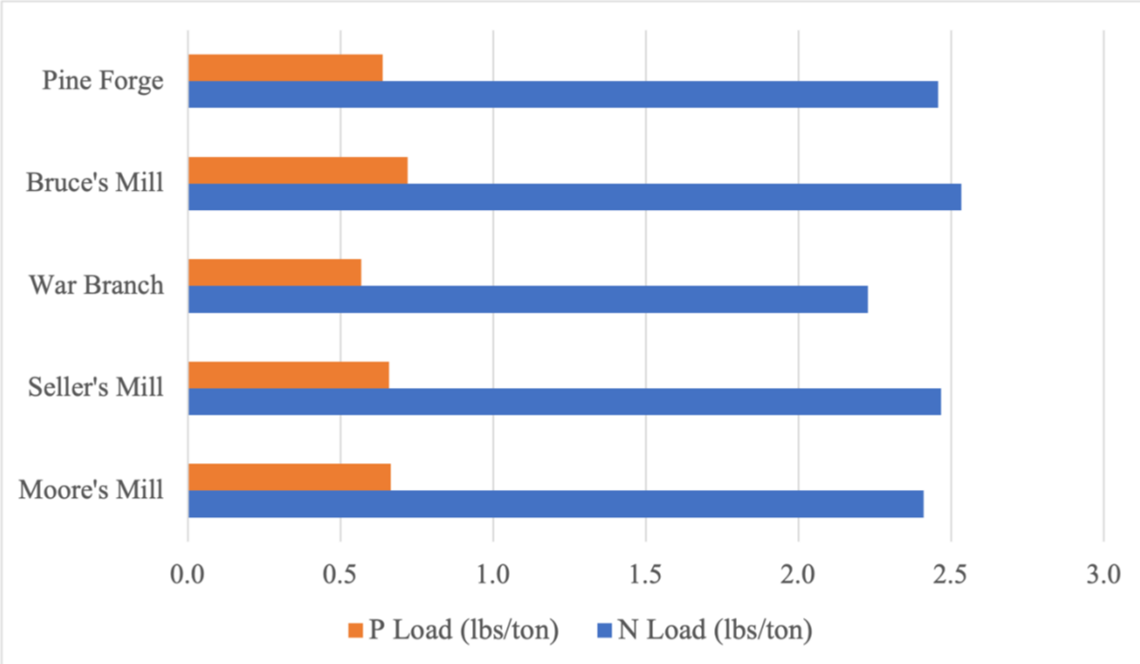
Appendix 2.31. Total carbon (C) measured in stream sediments with high, vertical banks along all sample sites. Locations are designated by profile line color (Moore's Mill = orange, Seller's Mill = red, War Branch = green, Bruce's Mill = yellow, and Pine Forge = blue), and position shape represent sample position in bank or samples other than legacy sediment (top of bank = circle, middle of bank = triangle, bottom of bank = square, buried wetland soil = black X, and coarser deposits = diamond). Dashed vertical lines capped with solid black shapes serve as bank position average nutrient concentration markers for legacy sediment samples (top = 27,600 ppm, middle = 28,600 ppm, and bottom = 36,300 ppm).

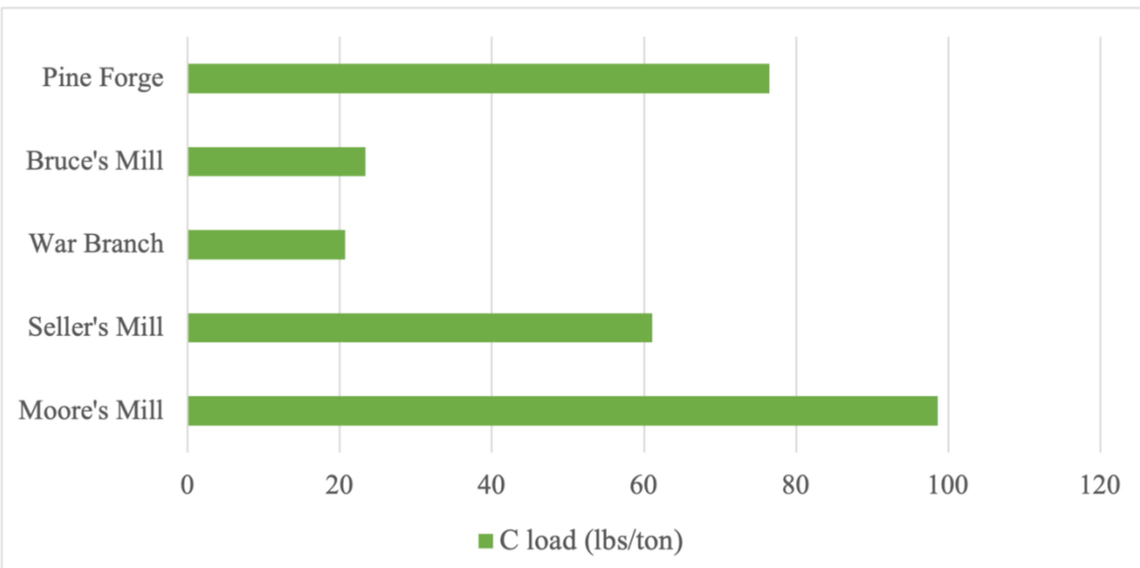


Appendix 2.32. Total nitrogen (N) measured in stream sediments with high, vertical banks along all sample sites. Locations are designated by profile line color (Moore's Mill = orange, Seller's Mill = red, War Branch = green, Bruce's Mill = yellow, and Pine Forge = blue), and position shape represent sample position in bank or samples other than legacy sediment (top of bank = circle, middle of bank = triangle, bottom of bank = square, and coarser deposits = diamond). Dashed vertical lines capped with solid black shapes serve as bank position average nutrient concentration markers for legacy sediment samples (top = 1,810 ppm, middle = 1,120 ppm, and bottom = 770 ppm).



Appendix 2.33. Total phosphorus (P) measured in stream sediments with high, vertical banks along all sample sites. Locations are designated by profile line color (Moore's Mill = orange, Seller's Mill = red, War Branch = green, Bruce's Mill = yellow, and Pine Forge = blue), and position shape represent sample position in bank or samples other than legacy sediment (top of bank = circle, middle of bank = triangle, bottom of bank = square, and coarser deposits = diamond). Dashed vertical lines capped with solid black shapes serve as bank position average nutrient concentration markers for legacy sediment samples (top = 450 ppm, middle = 310 ppm, and bottom = 220 ppm).





Appendix 2.4. Summary of average phosphorus (P), nitrogen (N), and carbon (C) loads, in pounds per ton (lbs/ton), for legacy sediment samples from each sample site.

Appendix 3

Figure Captions

1. Moore’s Mill (Figure 6)

    1) Retreating legacy sediment terrace where grasses are continuing to be undercut and fall into the stream.
    2) Legacy sediment bank undercutting small tree and large eroded blocks of sediment near edge of stream.
    3) Erosion into legacy sediment beginning to initiate a slight meander into this straight stretch of stream that will likely increase erosion in the next decades.
    4) Same area as (3), showing bar of legacy sediment in stream that is diminishing and influencing erosion into the stream bank itself.

2. Seller’s Mill (Figure 9)

    1) UAV capture of Sam Feibel measuring the thickness of legacy sediment at the upstream reach of our site analysis where major undercutting of the bank is occurring, likely influencing how much erosion can be captured from both UAV and lidar.
    2) Same location as (1), Logan Lewis measuring thickness of legacy sediment close to nine feet. A thin veneer of black soil is present near six feet above the water level.
    3) Logan Lewis observing breached inset milldam and rapid erosion into the previously impounded legacy sediment that is creating a large meander in the stream.
    4) UAV capture of rapidly eroding stream bank across from breached inset dam location, where banks are severely being undercut.

3. War Branch (Figure 12)

    1) Flat legacy sediment terrace stretching the width of valley bottom where cows are free to roam up to the edge of the stream.
    2) Eroding legacy sediment terrace located close to a cow crossing through stream, but crossing is not influencing bank erosion here.
    3) Joseph Sweeney, Logan Lewis, and Evan Lewis observing a bank that is rapidly eroding into the legacy sediment terrace. This was a location where stream bank samples were taken for additional lab analysis.
    4) Evan Lewis measuring the thickness of legacy sediment (~3.5 ft) at the edge of a rapidly eroding bank. A dark, hydric soil is present near the water surface and pre-Holocene basal gravel is present under the water level at the base of the bank.

4. Bruce's Mill (Figure 14)

   1) Sam Feibel measuring a four-foot-thick legacy sediment terrace and getting ready to take samples for additional lab analysis.
   2) Close-up of legacy sediment at (1) where samples were taken.
   3) UAV capture of much of the area flown for DEM creation and previous riparian buffer planting present on each side of the stream.
   4) Logan Lewis measuring a four-foot-thick bank of legacy sediment retreating into tree and rock wall.

Erosion Polygon Scale

0.01 - 0.28

0.28 – 1.11

1.11 – 2.86

2.86 – 6.11

6.11 – 13.54

Tons/yr