FRANKLIN & MARSHALL COLLEGE

Sediment and Nutrient Loads from Stream Corridor Erosion along Breached Millponds

Dorothy Merritts, Robert Walter, and Michael A. Rahnis

5/1/2010

Contents

1 Executive Summary 5

  1.1 President Obama's Executive Order regarding Chesapeake Bay watershed water quality 6

  1.2 Stream corridor and stream bank sediment sources from post-dam breach incised streams 6

  1.3 Stream bank erosion mechanisms 7

  1.4 Stream bank erosion rates and the concept of Sediment Production Unit (SPU) 9

  1.5 Modeling dam breaches and changing rates of sediment production 11

  1.6 Estimates of original and remaining volumes of sediment in millpond reservoirs 12

  1.7 Total nitrogen and phosphorus in stream banks 12

  1.8 Prognosis 13

2 Introduction and Background 14

  2.1 Objectives of this investigation 14

  2.2 Background to dams and reservoir sedimentation and erosion 14

    2.2.1 Milldams, sediment trapping, and trap efficiency 14

    2.2.2 Case Study: Trap efficiency of the 19th c. Eaton-Dikeman paper mill reservoir, Cumberland County, PA 16

    2.2.3 Conceptual model of post dam breach stream evolution: Incision and knickpoint migration 18

  2.3 Gravitational and hydraulic forces on stream banks 20

  2.4 Change in reservoir processes and rates of stream bank erosion after dam breaching 21

3 Characteristics and Mechanisms of Stream Bank Erosion 23

  3.1 Geomorphic processes of bank erosion 23

  3.2 Erodibility and critical shear strength of stream bank sediment 24

  3.3 Freeze-thaw, cohesive banks of silt and clay, and stream bank erosion rates 24

  3.4 Freeze-thaw cycling and the stream bank debris apron 27

4 Site Descriptions and Research Methods 28

  4.1 Site locations 28

  4.2 Research methods: Stream bank erosion rates 30

  4.3 Research methods: Measuring the concept of channel-normalized sediment production and its spatial and temporal variability 31

    4.3.1 The concept of a channel-normalized Sediment Production Unit (SPU) 31

    4.3.2 Converting volume of sediment eroded to mass (tons) 32

4.3.3 Spatial and temporal variability in stream corridor erosion rates 32
4.4 Quantifying nutrients stored in stream bank sediments 33
4.4.1 Field sampling and analytical methods 33
5 Data and Results 34
5.1 Stream bank erosion rates and dam breaching: Overview 34
5.2 Case studies for measurements of stream bank erosion rates 36
5.2.1 Hammer Creek—breached in 2001 36
5.2.2 Mountain Creek—breached in 1985 37
5.2.3 Conoy Creek—breached ca. 1972±10 yr 38
5.2.4 Valley Creek—breached ca. 1920 40
5.2.5 Big Spring Run 42
5.2.6 Little Conestoga Creek, West Branch, Denlingers Mill—breached ca. 1930±10 yr 43
5.2.7 Big Beaver Creek—breached in 1972 44
5.2.8 Penns Creek—breached in 1968 45
5.2.9 Gunpowder Falls, Hoffman Mill Pond—breached in 1932 46
5.2.10 White Clay Creek—breached prior to 1938 46
5.3 Total nitrogen and phosphorus in stream banks 47
6 Discussion of Results 47
6.1 Rates of bank erosion and sediment production curves 47
6.2 Modeling dam breaches and changing rates of sediment production 50
6.3 Implications for sediment and nutrient loads to streams from stream bank erosion of legacy sediment 52
6.4 Estimates of original and remaining volumes of sediment in millpond reservoirs 54
7 Conclusions 56
8 Works Cited 59
A. County Maps of Historical Dams 130
B. Methodologies 137
Estimating Change from Digital Orthophotos 137
Overview 137
Orthoimagery 137
Aerial Photography 137
Feature Digitization 138

        Feature Attribution 138
        Estimating Volume Change 138
    Stratigraphic Horizons and Local Datum Surfaces 139
        Overview 139
        Interpreting Legacy Sediment Features on Bare Earth Lidar 139
        Delineation of Terrace Surfaces with Lidar in ArcGIS 139
        Delineation of Water Surfaces in ArcGIS 140
        Calculation of Channel Volume 140
    Determining Bank Height Distribution 140
C. Production by Station 142
D. Production by Field Area 145

1 Executive Summary

This report provides evidence that a process given little attention to date—stream corridor erosion from breached millpond reservoirs—is a substantial source of suspended (i.e., fine grained) sediments and nutrients within the Chesapeake Bay watershed. Furthermore, the processes and rates of stream bank erosion documented here are not directly related to modern land use activity (e.g., storm water runoff from urban development), but rather to a series of land use activities that began as much as several centuries ago. These prior activities transformed valley bottom landscapes, first through reservoir sediment accumulation following milldam construction, then by stream bed incision and bank erosion following milldam breaching.

The mid-Atlantic region of the eastern US is characterized by numerous small (1st to 3rd order) streams upon which tens of thousands of mills, forges, and other industries relied for hydropower throughout the 17th to early 20th centuries (Walter and Merritts, 2008; see U. S. industrial censuses of 1840, 1870, and 1880). More than eight thousand milldams existed in Pennsylvania as of the late 19th century. Given the generally small size of the streams in this region, the typical dam height of 7 to 12 ft was sufficient to produce relatively high sediment trap efficiencies. Pennsylvania state inspection reports indicate that many reservoirs were substantially reduced in volume as a result of sedimentation by the early 20th century.

Assumptions and models regarding Chesapeake Bay water quality focus largely on modern land use—particularly agriculture and construction—as the dominant sources of high suspended sediment and nutrient loads in the majority of the region’s waterways. This work documents, however, that historic sediment and associated nutrients eroded from the stream corridor upstream of breached millponds are also an important component of the total load in modern streams.

Here we report on sediment production rates, nutrient contents, and erosion mechanisms of stream corridor sediments from the Piedmont and the Ridge and Valley physiographic provinces of the mid-Atlantic Chesapeake Bay Watershed. The focus of this report is on Pennsylvania, but one stream in the adjacent state of Maryland was investigated for comparison with Pennsylvania sites. Ten sites were selected from two counties (Chester and Lancaster) in the Piedmont lowland physiographic province of southeastern Pennsylvania, two counties (Cumberland and Centre) in the Ridge and Valley physiographic province of central Pennsylvania, and one county (Baltimore) in the Piedmont upland physiographic province of northern Maryland. These sites are considered representative of hundreds, and possibly thousands, of sites with similar conditions throughout Pennsylvania and Maryland. The Piedmont accounts for 23% of the Chesapeake Bay's watershed, and yet it is estimated to deliver >60% of the suspended load to the Bay (Gellis et al., 2004 and 2009). Our results show that stream corridor erosion, and particularly stream bank erosion within the corridor, is a major contributor to the suspended sediment and particulate-phosphorus loads carried by many streams in the Chesapeake Bay watershed, and that minor, but substantial, nitrogen loads are released by bank erosion as well.

1.1 President Obama's Executive Order regarding Chesapeake Bay watershed water quality

On May 12, 2009, President Obama issued an Executive Order that called for a new Federal Leadership Committee tasked with developing a "Strategy for Protecting and Restoring the Chesapeake Bay Watershed". The Preamble to the Executive Order noted that

> "Despite significant efforts by Federal, State, and local governments and other interested parties, water pollution in the Chesapeake Bay prevents the attainment of existing State water quality standards and the "fishable and swimmable" goals of the Clean Water Act. At the current level and scope of pollution control within the Chesapeake Bay's watershed, restoration of the Chesapeake Bay is not expected for many years. The pollutants that are largely responsible for pollution of the Chesapeake Bay are nutrients, in the form of nitrogen and phosphorus, and sediment.
>
> … the Administrator of the EPA (Administrator) shall, after consulting with appropriate State agencies, examine how to make full use of its authorities under the Clean Water Act to protect and restore the Chesapeake Bay and its tributary waters and, as appropriate, shall consider revising any guidance and regulations. The Administrator shall identify pollution control strategies and actions authorized by the EPA's existing authorities to restore the Chesapeake Bay that:
>
> (a) establish a clear path to meeting, as expeditiously as practicable, water quality and environmental restoration goals for the Chesapeake Bay;
> (b) are based on sound science and reflect adaptive management principles;
> (c) are performance oriented and publicly accountable;
> (d) apply innovative and cost-effective pollution control measures;
> (e) can be replicated in efforts to protect other bodies of water, where appropriate; and
> (f) build on the strengths and expertise of Federal, State, and local governments, the private sector, and citizen organizations."
>
> [From President Obama's Executive Order, May 12, 2009]

The results of the investigation for this report provide valuable information based on sound science regarding sources of sediment and nutrients from breached millponds that degrade water quality. As such, this work is timely and relevant for efforts "to establish a clear path to meeting, as expeditiously as practicable, water quality and environmental restoration goals for the Chesapeake Bay". These results also are important for ongoing development of "innovative and cost-effective pollution control measures".

1.2 Stream corridor and stream bank sediment sources from post-dam breach incised streams

When a dam is removed, the local base level for upstream reaches is lowered (c.f., Schumm et al, 1984; and Simon and Darby, 1997). As a result, channel depth and cross-sectional area increase at the site of dam breaching, leading to higher boundary shear stresses, bed degradation, and lowering of the water surface. As reservoir sediment dewaters, it continues to settle (become more compacted) for up to several years, as discussed for the Hammer Creek case study in this report. With continued incision and erosion of the bed, mass movement commonly occurs along incised channel banks near the dam because lateral support (confining pressure) is removed from wet reservoir sediment with high pore pressure.

Both bed scour from incision and subsequent bank erosion contribute to total erosion from the stream corridor. Bed scour is particularly important at the onset of dam breaching, which initiates a period of stream incision to the level of the breach. Some dams are breached fully, whereas others might only breach partly. Once a stream has scoured (i.e., incised) to the level of the breach, stream banks upstream of the breach retreat along an eroding edge. This latter process is referred to herein as stream bank erosion. Although both bed and bank erosion are examined in this report, it is the erosion of fine-grained sediment from banks that is of primary concern. Beds of streams examined in this study consist of pebbles, cobbles, and boulders, and this sediment is eroded and transported as bed load at a much slower rate than erosion and transport of fine-grained sediment (clay, silt, and sand) from banks. Both bed and bank erosion contribute to total erosion from the stream corridor, but the sediment stored in 18th-19th c. millponds generally is fine-grained (clay, silt, and sand), so bank erosion is largely a process of removing fine sediment.

In this report, our primary concern is to determine the rate of erosion of fine-grained sediment from banks of streams that are in various stages of post-dam breach conditions, and to assess how this rate changes with time. Few studies have tracked a reservoir over time for more than a year or two after dam breaching, so it is uncertain how rates of stream bank erosion vary over a period of decades to centuries following dam breaching. Although some bed scour and aggradation have occurred along some of the stream reaches examined here, this sediment is largely gravel and coarse sand that move as bed load, and is not the primary focus of this report. More work on the rates of erosion and transport of bed load from incised millponds is needed to more fully understand this contribution to sediment loads in streams. For the purposes of understanding sources of fine sediment to the Chesapeake Bay, the more important phenomenon is erosion of fine-grained millpond sediment from eroding stream banks.

1.3 Stream bank erosion mechanisms

For fine-grained sediment, the focus for this investigation of millpond sediment as a source of suspended sediment to streams, bank erosion occurs through three main types of processes (Hooke, 1979; Lawler, 1992, 1995; Lawler et al, 1997; Couper and Maddock, 2001; Wynn and Mostaghimi, 2006; and Wynn et al, 2008):

1) subaerial processes—freezing and thawing or wetting and drying of the surface soil, leading to weakening and erosion;
2) mass wasting—instability of bank material and failure via collapse, calving, toppling, or other mass failure; and
3) fluvial entrainment—detachment and entrainment of particles by hydraulic forces on stream banks from flowing water.

The combination of processes of freeze-thaw, wetting and drying, weakening of bank material, mass wasting, undercutting, bank collapse, and removal of material by stream flow causes banks to retreat laterally. At any one site, all three of these processes might occur and contribute to cumulative erosion with time.

Freeze-thaw has been well-documented as an erosive agent along stream banks, and was observed frequently during winter months of this investigation. The action of freeze-thaw directly results in bank erosion by the action of needle ice, as described by Wolman from his observations of erosion of fine sediment in a breached millpond along the banks of Watts Branch, Maryland (Wolman, 1959). Wolman showed that ~85% of observed erosion during a several year period occurred during the winter months, from December to March. Wolman (1959) observed that rises in water stage were more effective at removing bank material after cryogenic processes had increased its susceptibility to fluid erosion:

> "The variation observed between individual pins is not sufficient to destroy the obvious relation between lack of erosion in summer and marked erosion in winter. … The highest flood on record in this area occurred on July 20 [1956]. Despite the volume of flow and its stage, erosion around the pins was negligible compared to the erosion regularly observed during the preceding and following winters….The evidence gathered thus far indicates that lateral migration of Watts Branch by erosion of the banks takes place primarily during the winter." (Wolman, 1959, pp. 208 and 216)

Detailed monitoring of sites along the Ilston River, England, by Lawler (1986; 1993) and along Strouble Creek, Virginia, by Wynn et al (2008) established that freeze-thaw processes significantly lower the critical shear strength and increase the erodibility of cohesive stream bank sediment. In Lawler's study, nearly all bank erosion took place in the winter, from December to February (Lawler, 1986). The strongest control on average and maximum rates of bank erosion was frost action, and in particular the number of days for which minimum temperatures were below freezing (32 °F, or 0 °C). Air frost frequency, the variable most strongly associated with erosion rate, explained 94.2% of the variation in bank erosion rate in Lawler's study of the Ilston. Lawler (1986) determined that "bank erodibility increased during winter months due mainly to frost or cryergic activity" (p. 230), described as follows:

> "…the most important type of activity appeared to be development of needle ice along the lower half of the river bank. This is a form of segregated ice which grows externally to the ground surface as a collection of ice filaments oriented at right angles to the slope…. As growth proceeds, large amounts of sediment may become incorporated within the ice needles: analysis of Ilston samples revealed weights of extruded material to be more than 4 kg-m^{-2} for needles 50 mm long. During melting, some of this displaced sediment was transported downslope in a variety of ways, but most appeared to remain as a skin of friable, cohesionless material. This layer of prepared material was easily removed by a subsequent rise in river stage." (Lawler, 1986, p. 230)

During the course of this study, the authors noted that stream bank faces consisting predominantly of silt and clay develop an apron of loose sediment with low bulk density throughout the winter months.

This apron begins to accumulate with the earliest freeze-thaw events, which typically occur in November or December in southeastern Pennsylvania and northern Maryland, but even earlier in central, western, and northern Pennsylvania. With each period of thaw, the transformation of solid ice to water loosens fine sediment and moves it outward, perpendicular to the stream bank, where it drops and accumulates on the apron. During each of the winters of 2008 and 2009, air temperature dropped below freezing about 100 times.

The collective processes of subaerial erosion, mass wasting, and hydraulic entrainment are affected by variables such as local climatic factors (e.g., stream bank facing north), regional climate, degree and extent of stream channel incision after dam breaching, and the timing of storms and flood flow with respect to accumulation of loose debris in aprons after freeze-thaw or wetting-drying episodes. The nature of material in the banks plays a very important role as well. Cohesive silt and clay—with moderate to high critical shear stress when moist to dry, respectively—are particularly susceptible to freeze-thaw, wetting-drying, and mass failure.

Bank erosion is only one of several potential sources of sediment to streams. Other important sources include upland soil erosion from construction sites and agricultural lands. The key difference between these sources and that of bank erosion of historic sediment from a breached milldam is location and potential for sediment transport. Freeze-thaw, for example, produces disaggregated fine sediment that is dropped from the near-vertical stream bank to the toe of the bank, adjacent to the stream channel. Bank collapse and other types of failure drop masses of sediment of various sizes into the stream channel and along its margins. Fine sediment from these direct channel margin sources is more likely than any other sediment in a watershed to be transported as suspended sediment downstream.

1.4 Stream bank erosion rates and the concept of Sediment Production Unit (SPU)

At each of the ten study sites, at least one of four methods was used to estimate bank erosion rates over time periods that varied from one to 74 years in measurement period duration: bank edge retreat digitization; lidar estimate of volume eroded; repeat channel cross sections; and bank pins. The same units are used for all four methods of measuring sediment erosion. We refer to the erosion of sediment along the stream corridor, as measured in this report, as *channel-normalized sediment production*. Because of the inherent variability in bank height and stream length within a breached millpond reservoir, we normalize the amount of sediment eroded from the corridor by bank height and stream length and report sediment production in units of volume of eroded sediment (ft^3) per unit bank height (ft) per unit bank length (ft) per unit time (yr). The final units are ft^3/ft/ft/yr, which is essentially ft/yr, but it not simply a linear measurement at a point. It is a volumetric measurement based on bank height over a unit length of stream. This unit of measurement is given a new term here, the *sediment production unit*, or *SPU*, for the purposes of comparison of stream corridor erosion from different breached millponds.

The data for stream bank erosion rates are presented in two ways. First, the actual values for each site, station, method, and time period are provided for 79 measurements in a table in Appendix C. A given site, as at Big Spring Run, for example, has four cross sections and 16 sets of bank pins, resulting in 20 separate measurements. Bank edge digitization and lidar volume measurements represent greater lengths of stream, and these lengths are provided in Appendix C. Second, a synopsis for each site, method and time period is presented in a table in Appendix D.

Dam breach dates for the sites investigated in this report range from 1900 to 2001 AD, providing a record of about a century of fluvial response to incision and bank erosion. Stream bank erosion rates generally are highest for time periods shortly after the time of dam breaching. Whereas channel incision and knickpoint migration typically occur within several days to months of breaching, subsequent lateral channel migration and bank erosion can continue for centuries. The sediment production rates evaluated here encompass all of the processes of erosion of reservoir sediment over a period of years to approximately a century.

This compilation of data from ten breached millpond reservoirs reveals that stream bank sediment production rates are highest shortly after dam breaching and diminish with time, asymptotically approaching zero for at least a century. When part of a dam was removed at the Hammer Creek site in 2001, for example, rates of sediment production were as high as 19.7 ft^3/ft/ft/yr, or SPU, immediately afterward. Our field observations indicate that much of this erosion probably was associated with mass movement by bank collapse following wetting and drying of the banks as a result of short duration, high-flow events. Sediment production rates from bank erosion upstream of the Hammer Creek dam (channel cross section method) have decreased with time, from as high as 24.8 SPU during the interval of 2001-2003, to as low as ~1 SPU from 2006 to 2008.

Three of the four methods in this investigation were used at two different sites and enable a comparison of sediment production rates by method. These two sites are Conoy Creek and Mountain Creek, and the methods used are bank edge surveying, channel cross sections, and bank pins. For both sites, the largest range in values is obtained from bank pin measurements. Bank pins are the simplest of the techniques, as they can be measured frequently and readily, but they only provide estimates for the bank on which they are located. At both the Conoy and Mountain Creek sites, channel cross sections were done at the exact same locations as the bank pins, and these sections reveal net change for the entire width of the section, including both banks. The bank pins were located on one bank within each section. The cross section data generally yield a smaller, but overlapping, range in estimates with those of bank pins. For the bank edge surveying technique, which estimates erosion along the length of channel, the sediment production rates are within the range of bank pin measurements. At Conoy Creek, bank edge surveying yields a higher rate than the range of rates from cross sections, but at Mountain Creek bank edge surveying yields a lower rate. This is likely to reflect the fact that erosion rates vary along the length of a channel, so cross sections (and bank pins) will sometimes yield higher or lower estimates than the bank edge surveying technique.

From 40 to 100 years after dam breaching, the background rate of bank erosion determined in this report is about 0.6 to 1 ft^3/ft/ft/yr (SPU). Two possible causes of continued bank erosion long after dam breaching are bank collapse from wetting and drying after high-flow events and freeze-thaw during winter cold periods. All ten sites presented here have similar humid continental climatic conditions, with mean annual precipitation of about 40 inches/yr and mean annual temperature ranging from 49 to 59

°F. All sites have lowest temperatures from December through March, including temperatures that are below zero (freezing). Hydrographs throughout this region are similar as well, with low base flow during summer months and progressively higher base flow during winter months, reflecting the role of plants in water uptake during summer. We have observed needle ice in the stream banks at all sites during winter months.

High, vertical banks also contribute to bank erosion. All banks examined here are near vertical, a function of deep channel incision into easily eroded, fine-grained, cohesive sediment. Low stream flow relative to high banks results in constant undercutting, which leads to collapse during wetting-drying events. Near-vertical banks also are prone to freeze-thaw because they are exposed to lower air temperatures during the winter and night time. In addition, channel flow at the base of near vertical banks can sweep away material shed by collapse or freeze-thaw processes, resetting the bank for future erosion.

Given this suite of interacting bank erosion processes, it is possible that bank erosion will continue at a slowly diminishing rate long after dam breaching. Excluding the data from the most recently breached dam at Hammer Creek, all other sites have overlapping rates of bank erosion that generally range from zero (at a spot) to 3.4 ft^3/ft/ft/yr (SPU).

The range of estimates of sediment production presented here is similar to that obtained by Schenk and Hupp (2009) from their analysis of bank pins at five sites along the Little Conestoga Creek, a tributary to the Conestoga River, over a three-year period from July 2004 to June 2007. The Schenk and Hupp (2009) estimates of bank erosion are for a single bank, not the entire channel width, and are not normalized with respect to bank height, so they cannot be compared directly to our sediment production rate estimates. Furthermore, our estimates are based on examination of millpond reaches rather than spot locations. For the five sites monitored, Schenk and Hupp (2009) obtained estimates of bank erosion that range from ~0.1 to 0.5 ft/yr. Multiplying a mean bank height of 5.2 ft for the Little Conestoga Creek (determined with lidar) by bank erosion rates of 0.1 to 0.5 ft/yr results in estimated SPU values of 0.5 to 2.7 ft^3/ft/ft/yr. These estimates overlap the range of 0.6 to 1 ft^3/ft/ft/yr (SPU, or essentially ft/yr) reported here.

1.5 Modeling dam breaches and changing rates of sediment production

We simulate the breaching of 151 of 160 dams over a 300-year period, similar to the number of milldams in the Conestoga watershed of Lancaster County. The assumed annual probability of breaching is 1%, but greater values of annual probability are used for the years 1933, 1955, 1972, and 2004, when large storms occurred in the mid-Atlantic region. With time, fewer dams remain to be breached. However, dams that already have breached have added to the cumulative effect of greater channel network length producing sediment. Although sediment production from each individual breached reservoir diminishes with time, the cumulative amount of sediment produced from the growing number of breached reservoirs increases with time during the first century and remains high for at least two more centuries.

From 110 to 150 years after the start of the simulation, for model years 2010-2050, sediment production is about 4 million cubic-ft/yr, or ~162,500 tons per year (based on an average bank sediment bulk density value of 1.04 g/cm^3, or 65 lbs/ft^3). These model results are comparable to the annual average suspended sediment load measured at the USGS gage station at the mouth of the Conestoga River.

1.6 Estimates of original and remaining volumes of sediment in millpond reservoirs

Each millpond contains a volume and mass of historic sediment that is a function of dam height, valley gradient, and valley bottom topography underlying the millpond. A simple means of getting a rough estimate of reservoir sediment in a millpond is to estimate volume as a simple rectangular prism, using the product of pond length, width, and depth. We assume that at least 30% of this imaginary valley bottom prism is not available for storage due to variable topography beneath millpond sediment. For the ten millpond sites investigated in this report, the amount of sediment predicted to be stored in the millponds varies from ~25,000 to 368,000 tons (assuming a bulk density of ~65 lb/ft^3, or 1.04 g/cm^3).

We also estimate the total volume and mass of sediment eroded from the millpond along the incised stream corridor. As in the estimate of total reservoir sediment, we use the product of channel length, average width, and depth to get volume for a rectangular prism, and then convert to tons using an estimate of bulk density (1.04 g/cm^3). For the ten sites studied here, the estimate of volume of sediment (total) eroded from the stream corridor varies from ~5000 to 103,000 tons. Those sites where the dam breach occurred many decades ago generally have greater amounts of sediment eroded from the reservoir.

From the difference between these two estimates, it is possible to calculate the percent of reservoir sediment that remains. These estimates indicate that more than half of the reservoir sediment remains in all but two of the sites investigated here. For the Gunpowder Falls at the Hoffman milldam and Valley Creek at a dam near its mouth, only 8 and 40%, respectively, of the original reservoir sediment remains. Both dams breached in the early 20th c., and both have relatively narrow valleys, so these two factors appear to have resulted in relatively high proportions of sediment removal since breaching.

1.7 Total nitrogen and phosphorus in stream banks

Our analyses of stream bank sediments produce average nitrogen (N) concentrations of 1300 ± 450 ppm for 1 S.D. (n = 228). These results equate to a loading of 2.6 ± 0.9 lbs N/ton of eroded sediment. The average concentration of sorbed phosphorus (P) in stream banks is 600 ± 195 ppm for 1 S.D. (n = 390). These results equate to a loading of 1.2 ± 0.3 lbs P/ton of eroded sediment.

The concentration of stream bank P generally is lower and more consistent from site to site than N, which might reflect: (1) different physical and chemical properties of P and N; (2) historical land use activities that might have caused historical nutrient enrichments within the watershed; and (3) the transport mechanisms that redistributed these “legacy nutrients” and stored them in valley bottoms.

1.8 Prognosis

Clearly the amounts of sediment produced by stream channel erosion are large in absolute terms and, in relative terms, are likely to be similar to or greater than amounts from other major sources such as agriculture. Channel erosion is likely to continue to contribute significantly to sediment and nutrient loads over a centuries-long timeframe for four reasons:

1. dams were once regionally pervasive, and many have breached, but not all, leading to regional base-level fall;
2. dam breaching and incision have led to the formation of an entirely new regional eroding channel network;
3. production from breached reservoirs does not decline to zero over a century-long period of study; and
4. the sediment produced from the network consists largely of soil that was mobilized from the uplands and stored in the valley bottoms.

This report provides an assessment of the current trajectory, and likely future trajectory, of these incised channel networks. It is, however, important to recognize that, prior to disturbance, valley bottoms were not characterized by regionally pervasive eroding channel networks. Valley bottoms, rather, were characterized by regionally pervasive seeps, springs, and wetlands. Those features that were characterized by long-term stability, up until burial, are now being eroded. Strategies for reducing nutrient and sediment loads to the Chesapeake Bay must acknowledge this change in trajectory in order to have an impact.

2 Introduction and Background

2.1 Objectives of this investigation

The goal of this project is to quantify spatial and temporal variability in rates of erosion of fine-grained sediment from sediment-filled reservoirs with breached low-head milldams in Pennsylvania. The focus of this report is on Pennsylvania, but some counties and streams in the adjacent state of Maryland were investigated for comparison with Pennsylvania sites. This report assesses the relative contribution of erosion from the stream corridor to the load of suspended sediment for streams incised into millpond sediments. Incised streams erode sediment from both the bed and banks. Bed scour is particularly important at the onset of dam breaching, which initiates a period of stream incision to the level of the breach. Some dams are breached fully, whereas others might only breach partly. Once a stream has scoured (i.e., incised) to the level of the breach, stream banks upstream of the breach retreat along an eroding edge. This latter process is referred to herein as stream bank erosion. Although both bed and bank erosion are examined in this report, it is the erosion of fine-grained sediment from banks that is of primary concern. Beds of streams examined in this study consist of pebbles, cobbles, and boulders, and this sediment is eroded and transported as bed load at a much slower rate than erosion and transport of fine-grained sediment (clay, silt, and sand) from banks. Both bed and bank erosion contribute to total erosion from the stream corridor, but the sediment stored in 18th-19th c. millponds generally is fine-grained (clay, silt, and sand), so bank erosion is largely a process of removing fine sediment.

In addition to investigating rates of bank erosion upstream of breached milldams, the concentrations of two nutrients, phosphorous and nitrogen, were measured for stream bank sediments at multiple sites. These measurements are used to evaluate the role of stream bank erosion as a contributor to nutrient loading in streams.

2.2 Background to dams and reservoir sedimentation and erosion

2.2.1 Milldams, sediment trapping, and trap efficiency

The mid-Atlantic region of the eastern US is characterized by numerous small (1st to 3rd order) streams upon which tens of thousands of mills, forges, and other industries relied for hydropower throughout the 17th to early 20th centuries (Walter and Merritts, 2008; see U. S. industrial censuses of 1840, 1870, and 1880). More than eight thousand milldams existed in Pennsylvania. Our research of township-scale maps indicates that at least 1,200 milldams existed in Chester, Lancaster and York Counties (Figure 1), 153 in Cumberland County, 205 in Huntingdon County, and 186 in Centre County. These maps show the mills and dams that existed at the time of mapmaking. It is possible that other milldams existed prior to these maps but were no longer in use for milling, so they were not included by mapmakers. In addition, mills and milldams constructed after 1880 are not included in these maps.

Similarly to Pennsylvania, adjacent states in the mid-Atlantic region had ubiquitous milldams, with at least 211 in Baltimore and Montgomery Counties of Maryland, for example. County and district maps for Maryland are generally less detailed, or are of smaller scale, than historic Pennsylvania township maps, so it is possible that more dams existed in Maryland than are recorded on 19th c. maps. Dams for these six counties in Pennsylvania and two counties in Maryland are shown in Appendix A, and can be viewed at the following website: http://www.fandm.edu/x17479

Milldams commonly lined mid-Atlantic streams in series, forming chains of slackwater pools that enabled millers to maximize the potential energy of falling water (Figure 2). The South River in Virginia is representative of these streams. It was described by E. Folger Taylor, a water control specialist for DuPont, as characterized by "… a series of mill ponds. Dams from Serando to Port Republic were strategically located, often at 2 or 3 mile intervals" (Downs et al, 2004, p. 191).

Mid-Atlantic streams that were intensively milled from head to mouth include the Brandywine, Conestoga, Lehigh, Schuylkill, James, Potomac, Gwynns Falls, Gunpowder Falls, and Little Falls, but smaller and lesser-known streams were heavily milled as well. Valley Creek in southeastern Pennsylvania, for example, has a main stem length of only 12 miles, but had at least 10 milldams during the 18th and 19th centuries (discussed in Section 4.2.4). Even sites with high-flowing springs were dammed, as at Spring Mills on Penns Creek in Centre County, one of the streams examined in this report.

As a result of the deliberate, close spacing of milldams to maximize waterpower on streams as small as first order, the potential for trapping significant amounts of fine-grained sediment that was carried as suspended load was substantial throughout the mid-Atlantic region. The corollary is that the potential for releasing significant amounts of fine sediment after dam breaching is likewise substantial.

Previous work has shown that low-head dams (generally <25-ft high) built across small (1st to 3rd order) stream valleys have high sediment trap efficiencies of >40-80% (Brune, 1953; Gottschalk, 1964; Dendy and Champion, 1978; Petts, 1984; Evans et al, 2000a; and Doyle et al, 2003). A reservoir's trap efficiency (TE) is a measure of its ability to trap and retain sediment (Brune, 1953; and Verstraeten and Poesen, 2000). It is expressed as a ratio of incoming sediment that is retained by settling:

$$TE = S_{settled}/S_{inflow} \ [Eq. 1]$$

In this equation, $S_{settled}$ is the mass of sediment deposited within the reservoir and S_{inflow} is the mass of sediment entering the reservoir. This trap efficiency is dependent upon the amount of water inflow, the characteristics of the inflowing sediment, and the retention time of the water in the pond. Retention time is controlled by runoff characteristics and pond geometry (which are related to reservoir age).

Using data for 44 reservoirs, Brune (1953) identified a close correlation between the ratio of reservoir capacity to inflow (C/I ratio) and the trap efficiency. The greater the capacity of a reservoir relative to inflow of water, the higher its trap efficiency. A large reservoir on a small stream, for example, would have high sediment trap efficiency. A small reservoir on a large stream, in contrast, would have low sediment trap efficiency.

Dam height provides a measure of reservoir capacity, in that higher dams have larger reservoirs. From detailed historic records, we have calculated the average height of milldams in Lancaster County as ~7 to 12 ft (2 to 3.6 m), although some were as high as 30 ft (~9 m). U. S. Census records of milldams indicate that dams in other mid-Atlantic counties had similar heights. Given the generally small size of the streams in this region (see Figure 1, for example), this range in dam heights was sufficient to produce relatively high trap efficiencies. In the next section, we evaluate the reservoir capacity and trap efficiency of a milldam in south-central Pennsylvania.

2.2.2 Case Study: Trap efficiency of the 19th c. Eaton-Dikeman paper mill reservoir, Cumberland County, PA

Pennsylvania state dam inspection reports that date to as early as 1914 provide data that can be used to estimate trap efficiencies for a paper mill dam on Mountain Creek in Cumberland County (see Figure 2). Built in 1855, the dam was 700 ft in length and 13 ft high. By the early 20th c., the mill was known as the Eaton-Dikeman mill. The valley gradient is ~0.004, so we estimate backwater effects (reduced water velocity) that extended about 3,200 ft upstream. This is consistent with our observations of reservoir sediment that decreases in thickness from 13 to 2 feet from the dam to ~3,200 ft upstream of the dam. These dimensions result in an estimated reservoir capacity of ~170 acre-ft. State inspection reports in the 1980s estimated the original capacity as 140 acre-ft, and noted that the reservoir was completely filled with sediment by that time.

Inflow for the Eaton-Dikeman reservoir can be estimated from an upstream US Geological Survey stream gage station at Pine Grove Furnace, where the watershed area is 13.9 square miles. At this gage, average discharge is 19.7 cubic feet per second (data from 2006-2008), or ~14,260 acre-ft per year. The Eaton-Dikeman pond has an upstream drainage area of about 44.1 square miles, so we estimate a proportionally greater average discharge of 45,100 acre-ft per year. Hence, the capacity to inflow ratio is 0.003 to 0.004. The corresponding trap efficiency for these ratios for mixed grain sizes is 14% to 21% (Brune, 1953; Verstraeten and Poesen, 2000).

The earliest state inspection report of 1914 indicates that the reservoir capacity was 20 million gallons (61 acre-ft), but also notes that the reservoir was substantially reduced in volume as a result of sedimentation. If the original capacity was 170 acre-ft (our estimate), then the reservoir had accumulated ~110 acre-ft of sediment in less than 59 years and was 64 percent full. If the original capacity was 140 acre-ft (state inspection estimate from the 1980s), then the reservoir had accumulated ~80 acre-ft of sediment in less than 59 years and was 57 percent full. An excerpt from this report describes the reservoir as follows:

> “It was formerly considerably deeper than at present, but the large amount of silt and debris brought down and deposited during freshets has caused it to silt up, so that now it will average hardly 5 feet in depth. On the east, or railroad side, there is a considerable expanse of flats, overgrown with weeds and rushes, where the water is hardly more than 18 inches in depth, so that I think the above estimate of 20 million gallons is high rather than low.”

Several factors indicate that this reservoir probably had a sediment trap efficiency that was greater than 14% to 21%. The amount of time during which a reservoir fills with sediment depends not only upon the ratio of reservoir capacity and inflow of sediment, but also upon factors such as duration of time during which the pond surface does not reach the level of the spillway. When the water in a pond drops below the level of its spillway, retention time increases greatly and the trap efficiency approaches 100%. At Eaton-Dikeman, the engineer who wrote the 1914 report noted that the water in the pond did not reach the level of the spillway during his inspection in June of 1914. It is probable that this millpond, like others in this region, often was below the level of the spillway—even during relatively wet months—because water was removed from the pond via a head race in order to supply power to the mill. Mills typically were operated around the clock and rarely shut down. Flour and grist mills were especially busy during harvest season in late summer and fall.

In addition, stream flow values are so low during late summer to fall months in this region that it is likely that many millponds often did not reach the level of dams and spillways during low flow months, regardless of water taken out via races for milling. Gage data upstream at Pine Grove Furnace, as well as at gages throughout the region, consistently indicate high monthly streamflow from January to July, and low flow from August to December. Numerous historic accounts of milling and photographs of mill dams support the conclusion that water in millponds sometimes was below the level of the spillway. In addition, the presence of multiple thick mats of leaves in the lower half of the stack of sediment in the Eaton-Dikeman pond is consistent with rapid sedimentation and high trap efficiency during fall months. As a result of these various factors, it is not surprising that the Eaton-Dikeman pond was more than half filled with sediment by 1914. For low-flow months (August to December), we estimate capacity to inflow ratios as high as 0.048, and corresponding trap efficiencies of 77% to 86% (Verstraeten and Poesen, 2000).

Other factors affect reservoir sedimentation for ponds along streams that are heavily milled. An important attribute is the relatively close spacing of mills and reservoirs along streams, as noted above, and the concentration of sediment in the inflow of water. During floods, mill dams often breach, and this breaching releases large amounts of sediment to downstream dams. The Eaton-Dikeman dam breached at least five times in its history, in 1863, 1889 (the heavy storm of the Johnstown flood), 1909, 1915, and 1919. Each time, a 50-ft gap opened along a spillway at the eastern end associated with the headrace, and each time the pond was drained of water (information from state inspection reports). During at least one of these floods, in 1889, historic records and photographs in the Cumberland County Historical Society archives indicate that an upstream dam at Laurel Forge breached and sent large amounts of sediment downstream toward the Eaton-Dikeman reservoir.

Tailings, iron ore pits, clay mines, and washing ponds with small dams and berms along Mountain Creek provided immense amounts of clay, silt, sand, and gravel to downstream reaches. Historic photographs of these ore pits, tailings, and washing ponds are available at the Cumberland County Historical Society. We have identified large amounts of slag, charcoal, and kaolinite clay (the same type as mined upstream for bricks) in the sediment in the Eaton-Dikeman reservoir, and these findings confirm that the reservoir filled with sediment derived from upstream mining and forging activities. Horace Keefer, a 19th c. superintendent of the Pine Grove Furnace describes the ready availability of mine-related sediment to downstream transport in his description of the furnace operations:

> "The ore from this mine was run through washers to remove the clay and sand, the overflow from the washers was confined to a dam which frequently broke out, and the Mt. Holly Paper mills soon were to detect." (available at http://www.patc.us/history/archive/pine_grv.html)

2.2.3 Conceptual model of post dam breach stream evolution: Incision and knickpoint migration

When a dam is removed, the local base level for upstream reaches is lowered (c.f., Schumm et al, 1984; and Simon and Darby, 1997). As a result, channel depth and cross-sectional area increase at the site of dam breaching, leading to higher boundary shear stresses, bed degradation, and lowering of the water surface. As reservoir sediment dewaters, it continues to settle (become more compacted) for up to several years, as discussed below for the Hammer Creek case study in this report. With continued incision and erosion of the bed, mass movement commonly occurs along incised channel banks near the dam because lateral support (confining pressure) is removed from wet reservoir sediment with high pore pressure. Both bed scour from incision and subsequent bank erosion contribute to total erosion from the stream corridor.

The history of the IVEX milldam on the Chagrin River in northeast Ohio, built in 1842, illustrates the processes of reservoir sedimentation followed by erosion associated with dam breaching. The 7.4-m high (spillway level) earthen milldam breached during a 70-yr rainfall event on August 13, 1994, and the stream channel incised rapidly to within a meter of the bedrock surface below the reservoir sediment. The narrow breach released 23,700 to 31,300 m^3 of sediment, about 9 to 13% of the reservoir fill (Evans et al, 2000). The trapping efficiency of this reservoir was estimated to be 67% prior to failure, and the reservoir was filled to 86% of its capacity at the time of failure. The original amount of trapped fine-grained sediment was estimated to be 236,000 m^3. Sediment cores from the reservoir indicate that sedimentation had slowed by the 1960s, when the dam was ~120 yrs old (Evans et al, 2000a; Evans et al, 2000b). Another millpond exists immediately downstream, and the combined trapping efficiency of the two closely spaced dams was estimated to be 90%. During failure of the IVEX dam, much of the eroded sediment was trapped in the downstream reservoir, greatly diminishing its remaining pool capacity.

Failure occurred by seepage piping along the western end of the ~152-m long IVEX dam, near its juncture with a 33-m wide masonry spillway (Evans et al, 2000a; Evans et al, 2000b). As a consequence of the location of the breach, the newly incised Chagrin River channel became established along the western margin of the valley, against bedrock. The eastern margin of the incised channel, however, consists of fine-grained reservoir sediment that was easily eroded by the deepened stream channel. After the breach, investigators observed "significant slumping of the water-saturated reservoir sediments into the newly incised channel" (see Figure 9, Evans et al, 2000a), and lateral channel migration eastward into the unconsolidated reservoir sediment.

The authors of this report visited the IVEX reservoir about a decade after the breach, in 2005, and observed that the stream had continued to migrate laterally. Erosion of near-vertical banks of fine-grained sediment by the deeply incised stream clearly was an ongoing process some 11 years after dam failure.

Doyle et al (2003), building on the research of previous researchers that included Gilbert (1917), Howard (1982), Schumm et al (1984), and Simon and Darby (1997), developed a conceptual model for the evolution of a stream incised into a breached, sediment-filled reservoir (Figure 3). They tested this model by monitoring two dam removal sites in Wisconsin for a period of 1-2 years after dam removal (Doyle et al, 2003).

According to this conceptual model, a stream cuts into the unconsolidated sediment at the site of the breach immediately after dam breaching, forming a knickpoint, or head-cut, in the stream profile. Across this zone of increased grade, the stream has greater scouring capacity than upstream along the stream profile, where it remains perched in the reservoir sediment. This head-cut propagates up-valley through the reservoir sediment as the stream scours its bed. If the sediment is non-cohesive and fine-grained, the stream is able to cut into and transport sediment easily, so the knickpoint propagates rapidly.

After removal of the Rockdale milldam on the Koshkonong River, for example, Doyle et al (2003) documented that a head-cut migrated upstream at a rate of ~10 m/hour for 24 hours, but decelerated to an average rate of 40 m/month over the next 11 months (Figure 4). Downstream of the head-cut a deep, narrow channel had high boundary shear stresses (up to 20 to 30 N/m^2) capable of eroding bed and bank material. Upstream of the head-cut, however, low boundary shear stresses (less than 5 N/m^2) were insufficient to erode the bed or banks, and the reservoir sediment surface remained largely undisturbed (see Figures 9 and 12c in Doyle et al, 2003).[1]

Vertical incision generally ceases once the stream reaches the base of the dam and the bottom of the original valley, because the water slope decreases as the stream incises to this level and as upstream reaches become graded to this new local base level. Furthermore, the original substrate beneath historic reservoir sediment generally is more resistant to erosion, particularly if bedrock is shallow. Locally, however, the high banks of an incised stream can produce high boundary shear stresses that enable it to scour even deeper than the original valley bottom beneath the reservoir sediment. This scour is limited by grade controls along the bed, such as remnants of an original dam, resistant bedrock that floors the valley, or large boulders in talus and colluvial slopes along valley margins.

Streams that incise reservoir sediment often cut into what once were the margins of the valley and toes of slopes, because reservoirs fill to levels that are higher than the original valley bottom. This valley filling inundates and buries not only main stem valley bottoms, but also the toes of hillslopes and tributary confluences. As a result, incising streams in breached reservoirs often expose sediments that are of hillslope, rather than fluvial, origin, such as colluvium and talus along valley margins.

Coarse-grained deposits that existed prior to European settlement and milling are now buried beneath historic, fine-grained millpond deposits, and are being exhumed by channel incision and lateral bank erosion after dam breaching. These deposits are sources of gravel to incised channels with relatively high shear stresses (see discussion below). This gravel is moved as bed load, in contrast to fine-grained sediment (clay, silt, and very fine to medium sand) that is carried as suspended load.

---

[1] Doyle et al (2003a) used $\tau_{crit} = 8$ N/m^2 for fine (silt and clay), cohesive sediment (from Chow (1959) and $\tau_{crit} = 9$ N/m^2 for coarser sediment ($D_{50} = 12$ mm) based on τ^* of 0.047 (from Buffington and Montgomery, 1997)

2.3 Gravitational and hydraulic forces on stream banks

An incised stream with high banks of fine-grained sediment leads to bank instability in a breached reservoir. As sediment is dewatered, gravitational forces and rapidly changing pore pressures result in settling (compaction) and mass wasting. Hydraulic forces exerted by flowing water on bank-toe material help to maintain steep banks. As described by Simon et al (2000):

> "Gravitational forces acting on in situ bank material act in concert with hydraulic forces at the bank toe to determine rates of bank erosion. The interaction of these forces control streambank mechanics. Hydraulic forces exerted by flowing water on in situ bank-toe material and failed cohesive material at the bank toe are often sufficient to entrain materials at relatively frequent flows and to maintain steep lower-bank profiles. Seepage forces exerted on in situ bank material by groundwater, downward infiltration of rainwater and lateral seepage of stream flow into and out of the bank are critical in determining bank strength.… A stable bank can be transformed into an unstable bank during periods of prolonged rainfall through:
>
> 1) increase in soil bulk unit (specific weight),
>
> 2) decrease or complete loss of matric suction, and, therefore, apparent cohesion,
>
> 3) generation of positive pore-water pressures, and, therefore, reduction or loss of frictional strength,
>
> 4) entrainment of in situ and failed material at the bank toe, and
>
> 5) loss of confining pressure during recession of stormflow hydrographs.
>
> Relatively small frequent flows during the winter have the ability to erode failed bank materials, maintain oversteepened, unstable bank surfaces and promote prolonged periods of bank retreat, channel migration and high yields of fine-grained sediment." (from Simon et al, 2000)

Mass wasting (e.g., bank slumping and collapse) is particularly common immediately after dam breaching. It was observed and described, for example, after breaching of the Rockdale dam in Wisconsin (Doyle et al, 2003) and of the IVEX dam in Ohio (Evans et al, 2000a). The authors of this report have observed rotational slumping, calving, and other types of mass wasting failures after periods of prolonged or intense rainfall at most of the study sites described here (Figure 5). All of these processes contribute to the overall erosion of stream banks.

Cantelli et al (2004, 2007) simulated reservoir filling and breaching in a laboratory flume and observed processes of mass wasting and bank erosion in the wake of knickpoint propagation, similar to the features described by Doyle et al (2003), Evans et al (2000), and in this report. Videos of Cantelli's flume model can be downloaded at: https://repository.nced.umn.edu/browse.php?dataset_id=28

Still photos from Cantelli et al's (2004) laboratory videos shown in Figure 6 illustrate the mass movement of bank material in response to dam breaching, knickpoint propagation, and channel incision. Cantelli et al (2004) observed that a brief period of channel narrowing was associated with mass movement until the stream channel was able to remove the failed material, after which time bank widening ensued. This phenomenon of initial narrowing followed by widening can be seen in Figure 6.

2.4 Change in reservoir processes and rates of stream bank erosion after dam breaching

It is reasonable to assume that a reservoir with a high trap efficiency will have little to no stream bed scour or erosion from exposed banks prior to dam breaching[2], and that stream bed and bank erosion after dam breaching will be much higher than when the dam remained intact. As observed in the two breached milldams studied in Wisconsin by Doyle et al (2003), the reservoirs were sediment sinks when the dams were in place, but became sediment sources after the dams breached.

It is probable that rates of stream bed scour, bank erosion, and mass wasting are highest immediately after a dam breaches and at sites closest to the dam. Downstream of a recently formed knickpoint, banks are high, and bank sediments that are still dewatering (i.e., saturated to partly saturated) have high pore pressures responding to a rapidly steepening hydraulic gradient. During this time, much bank erosion near (upstream of) the dam might be the result of gravitational forces and will occur as mass movement, including rotational slumping and planar calving.

As previous researchers have shown and as discussed above, shear stresses upstream of a knickpoint are much lower than those downstream of a knickpoint that is propagating through a breached reservoir. Shear stress is proportional to flow depth and water slope. As the channel bed adjusts to the base-level drop near the breach, upstream migration of the head-cut initiates a propagating wave of channel adjustment and bank instability, so that the hydraulic geometry of the channel throughout the reservoir changes with time. Immediately after dam breaching or arrival of the head-cut, channel width is low and depth is high, resulting in a low width to depth ratio (see Figure 9, Doyle et al, 2000). Flow depth affects shear stress, τ, which is the product of fluid and water density, flow depth, and water slope:

$$\tau = \gamma RS \ [Eq. 2]$$

where γ is the specific weight of water (9800 N/m^3), S is the energy slope, and R is hydraulic radius, calculated as A (channel area) divided by P (wetted perimeter). With time after passage of the head-cut, and with increasing width of the corridor of the stream incised into the sediment-filled reservoir, it is likely that the bed shear stress will decrease for a given flow event. A 10-year storm, for example, would

---

[2] The authors note a few exceptions. One exception occurs where a stream has cut between a dam and the valley wall, rather than breaching the dam, and has been able to carve a channel that is lower than the dam crest or spillway level. In addition, many older milldams were breached partly or fully during their life spans, sometimes repeatedly. Some milldams were repaired to lower heights than the original dam, but in many cases newer dams were set within channels that were incised into older breached reservoirs. The channels upstream of these inset dams have stream bank heights that are dependent upon the original reservoir fill thickness relative to the height of the newer dam. An example is the inset dam built on Valley Creek at Valley Forge in the late 1930s, after removal of part of a 20-ft high, 19th c. dam in 1920. In this case, the inset dam is located ~1,200 ft upstream of the removed dam. The inset dam is lower than the original, so its backwater effects do not extend as far upstream as that of the older dam. As a result, banks of exposed, older reservoir sediment exist upstream of younger (more recently deposited) sediment trapped at a lower level by this newer dam's backwater effects (see photo in Figure 34d).

lead to a higher stage (and hydraulic radius) and shear stress in an incised channel immediately after dam breaching than it would after several decades of post-dam breach bank erosion and channel widening, when the stream corridor width to depth ratio has increased.

Pizzuto and O'Neal (2009) tested the hypothesis that dam breaching leads to higher rates of stream bank erosion. They examined eight millpond reaches along 30 km of the South River, a tributary to the Potomac River in Virginia, in the Blue Ridge and the Valley and Ridge physiographic provinces, and assessed rates of bank erosion from 1937 to 2005. All but one of the milldams—which date to the 18th and early 19th centuries—were breached in the 1950s, and the last was breached by 1976. Stream bank sediment was mostly silt and clay with some sand and gravel, and average bank height was 1.5 m. Similar to the mean height of milldams throughout the mid-Atlantic region, average dam heights in the Pizzuto and O'Neal study were 2 to 3 m. Studying changing bank lines on aerial photos, they found a statistically significant, strong correlation between accelerated rates of bank erosion and dam breach conditions, with normalized estimates of mean bank erosion rates increasing by more than a factor of 3 in the first two decades after dam breaching. Median values of bank erosion for the monitoring sites showed an even more pronounced increase, by a factor of 6, after dam breaching.

Pizzuto and O'Neal (2009) concluded that "the demise of milldams has been an important influence on fluvial processes in the region", and accelerated erosion could not be explained by climatic factors (e.g., storm intensity or frequency of freeze-thaw cycles) or by changes in the density of riparian trees along stream banks.

In this report, our primary concern is to determine the rate of erosion of sediment from banks of streams that are in various stages of post-dam breach conditions, and to assess how this rate changes with time. Few studies have tracked a reservoir over time for more than a year or two after dam breaching, so it is uncertain how rates of stream bank erosion vary over a period of decades to centuries following dam breaching. With time, it is likely that vegetation grows on what once were pond fill surfaces, as can be demonstrated by examining historic air and ground photos of former millponds. Such photos show stands of trees on former pond surfaces that become established after dam breaching (Figure 7). Even as the pond surface becomes vegetated, however, an incised channel migrates laterally and erodes sediment from the reservoir.

We posit several scenarios for the relation between stream bank erosion and time since dam breach. It is possible that erosion rates are constant with time or diminish gradually until the majority of reservoir sediment is eroded (Figure 8). It is more likely, however, that the rate decelerates with time. Recall that 9 to 13% of the reservoir sediment of the IVEX dam was eroded during and immediately after dam breaching in 1994, and that a laterally migrating stream channel has continued to erode reservoir sediment since then. As noted above, rates are high just after breaching because of rapid incision, mass movement fostered by pore pressure changes in saturated sediment as it dewaters, and low width to depth ratios that lead to high boundary shear stresses. Doyle et al (2003) reported a decline in average monthly rate of sediment removal from two millponds in southern Wisconsin, as shown in Table 1:

Site	Percent volume of sediment removed first 8 or 10 months after dam removal	Percent volume of sediment removed from 8 to 11 or 10 to 13 months after dam removal
LaValle Dam, Baraboo River	7.3%/10 months = 0.7% per month (average)	0.5%/10-13 months = 0.2% per month (average)
Rockdale Dam, Koshkonong River	13.9%/8 months = 1.7% per month (average)	1.6%/8-11 months = 0.5% per month (average)

Table 1. The rate of erosion of sediment, or sediment production rate, from a reservoir after dam breaching is greatest immediately after dam breaching, and diminishes thereafter. (Calculations made with data from Table 1 in Doyle et al, 2003.)

An important question is how rates of bank erosion change over a period of decades to centuries subsequent to dam breaching. Once the stream geometry is established and adjusted for upstream runoff conditions, it is possible that a lower rate of stream bank erosion will continue for decades or perhaps even centuries until most or all reservoir sediment is gone. In this case, the long-term trend might appear as a negative power function (see Figure 8). It also is likely, however, that sporadic, stochastic events, such as high-magnitude floods, or tree falls that lead to localized scour, could cause short-term deviations in this long-term signal.

A primary objective of the research presented here is to evaluate this long-term trend and to determine how rates and processes of bank erosion change with time after dam breaching. In this report, we present data that enable us to quantify the trend in long-term removal of fine-grained sediment from the stream corridor in breached millpond reservoirs. In the discussion section, we compare this observed trend to the scenarios posited here.

3 Characteristics and Mechanisms of Stream Bank Erosion

3.1 Geomorphic processes of bank erosion

Stream bank erosion is the detachment and removal of particles from the surface of the bank. For fine-grained sediment, as is the focus for this investigation of millpond sediment, bank erosion occurs through three main types of processes (Hooke, 1979; Lawler, 1992, 1995; Lawler et al, 1997; Couper and Maddock, 2001; Wynn and Mostaghimi, 2006; and Wynn et al, 2008):

4) subaerial processes—freezing and thawing or wetting and drying of the surface soil, leading to weakening and erosion (Couper and Maddock, 2001);
5) mass wasting—instability of bank material and failure via collapse, calving, toppling, or other mass failure; and
6) fluvial entrainment—detachment and entrainment of particles by hydraulic forces on stream banks from flowing water.

The combination of processes of freeze-thaw, wetting and drying, weakening of bank material, mass wasting, undercutting, bank collapse, and removal of material by stream flow causes banks to retreat laterally. At any one site, all three of these processes might occur and contribute to cumulative erosion with time. Wetting and drying and freeze-thaw are more likely to occur, however, under certain climatic conditions. Freeze-thaw, for example, is more frequent at higher elevations and latitudes, and wetting-drying is more common where precipitation is highly seasonal or where streams are incised and hydrographs are strongly peaked (i.e., flashy) due to the high channel banks. Mass wasting is promoted by scour and undercutting, which depends in part on the nature of material at the base of the bank. A non-cohesive sandy or gravelly layer at the base of a bank consisting of cohesive silt and clay, for example, is prone to undercutting and collapse of the cohesive material by mass failure. Fluvial entrainment is directly proportional to shear stress of flowing water, which is proportional to flow depth and water surface slope (see Eq. 2).

3.2 Erodibility and critical shear strength of stream bank sediment

The critical shear strength of stream bank material is equal to the critical shear stress, τ_c (in Pa, or N/m^2) at the threshold of entrainment by bank erosion. Stream bank erodibility, k_d (in m^3/N-s), is the rate per unit area at which mass (sediment) is removed from the bank once it begins to erode. The lateral erosion rate of a stream bank, E_r, (in m/s) is proportional to its erodibility and the amount of available excess shear stress (in Pa, or N/m^2), the latter of which is the difference between the shear stress of the flowing water in the stream, τ, and the critical shear stress needed to entrain material from the bank (Arulanandan et al, 1980; Osman and Thorne, 1988; Darby and Thorne, 1996; Langendoen and Simon, 2000; and Hanson and Cook, 2004), as follows:

$$E_r = k_d(\tau - \tau_c)\ [Eq. 3]$$

3.3 Freeze-thaw, cohesive banks of silt and clay, and stream bank erosion rates

Freeze-thaw has been well-documented as an erosive agent along stream banks. The action of freeze-thaw directly results in bank erosion by the action of needle ice, as described by Wolman from his observations of erosion of fine sediment in a breached millpond along the banks of Watts Branch, Maryland, in December, 1955[3]:

> "Particles are heaved out from the bank by ice crystals and upon melting of the crystals the sediment drops into the stream....During intensely cold periods slabs of sediment perhaps one foot square containing thin ice lenses have been observed. The action of frost appears to be one of preparation of a veneer of sediment for erosion as well as increased retention of moisture in the soil." (Wolman, 1959, p. 215)

Wolman's observation that the freeze-thaw process disaggregates stream bank material and increases its susceptibility to erosion was confirmed in several subsequent studies. Detailed monitoring of sites along the Ilston River, England, by Lawler (1986; 1993) and along Strouble Creek, Virginia, by Wynn et al (2008) established that freeze-thaw processes significantly lower the critical shear strength and increase the erodibility, k_d, of cohesive stream bank sediment (Figure 9).

---

[3] For this investigation, we sampled the material in the stream banks of Watts Branch, MD, at the approximate location of Wolman's (1959) study of stream bank erosion. The grain size was 90% silt and clay and 10% fine sand. Overall, grain size coarsened from bottom to top, with most of the fine sand in the upper 30 cm of the 1.5-m high stream bank.

Bank erosion processes are highly dependent upon the nature of the bank material. In all three of the studies cited above (Watts Branch, Strouble Creek, and the Ilston River), the banks varied from one to two meters in height and consisted primarily of silt and clay. Furthermore, this sediment is likely to be historic and the result of slackwater sedimentation in all three cases (see discussion below). Cohesive sediment (e.g., silty clay) commonly forms vertical banks from which slabs have been observed to slake and calve into the stream. Undercutting and bank collapse can reset the slopes of the banks as the stream erodes material from the toe, or base, of the bank. Much less cohesive sand and gravel, on the other hand, form banks that are closer to the angle of repose, generally 35 to 40 degrees.

Lawler (1986) installed and monitored 230 erosion pins along stream banks consisting of cohesive silt and clay at two meander bends on the Ilston River in South Wales over a two-year period (1977 to 1979), and his statistical analysis of the data indicated a strong seasonality to stream bank erosion.[4] Hydrological and meteorological (stream flow, temperature, and soil moisture) variables were measured in the watershed during the monitoring period, and changes in these variables and short-term rates of bank erosion were examined. Three stream gages bracketed the two meander bends sites.

In Lawler's study, nearly all bank erosion took place in the winter, from December to February. The strongest control on average and maximum rates of bank erosion was frost action, and in particular the number of days for which minimum temperatures were below freezing (32 °F, or 0 °C). Lawler (1986) determined that "bank erodibility increased during winter months due mainly to frost or cryergic activity" (p. 230), described as follows:

> "…the most important type of activity appeared to be development of needle ice along the lower half of the river bank. This is a form of segregated ice which grows externally to the ground surface as a collection of ice filaments oriented at right angles to the slope…. As growth proceeds, large amounts of sediment may become incorporated within the ice needles: analysis of Ilston samples revealed weights of extruded material to be more than 4 kg-m^{-2} for needles 50 mm long. During melting, some of this displaced sediment was transported downslope in a variety of ways, but most appeared to remain as a skin of friable, cohesionless material. This layer of prepared material was easily removed by a subsequent rise in river stage. If the stream level failed to rise above the limit of prepared material, an erosional notch was created which marked the maximum stage attained. If, however, river level rose above the vertical extent of previous needle ice growth, then a notch tended to be created at the upper limit of the ice-needle zone and not at the level of peak stage achieved. These further observations suggested that significant bank erosion and morphological change was accomplished by fluid forces only when the bank material had first been conditioned by cryergic activity." (Lawler, 1986, p. 230)

---

[4] It is of interest to note that the Ilston River had several water-powered mills with dams during its history, and a meander bend site studied by Lawler (1986) is the Parkmill Ilston (PI) meander. Lawler (1986) notes that bank height increases from 1.1 to 1.5 meters from the upstream meander bend in a downstream direction to the Parkmill meander, and bank sediment consists of 21 to 83% silt and clay overlying a thin band of coarse basal gravels. This is very similar to the stratigraphy of Piedmont millpond streams of the mid-Atlantic region described in Walter and Merritts (2008). It is possible that the Lawler study was done on a stream with millpond sediments quite similar to those examined in this report.

Lawler's investigation revealed a sequence of processes that enables banks to be eroded significant amounts even with relatively minor rises in discharge and stage. During the summer and fall, periods of quiescence occur with little erosion, regardless of stage (depth) of water and fluvial shear stress. During the cold winter months, these periods are followed by bank material disaggregation as a result of freeze-thaw and fluvial entrainment during subsequent rises in stage (Figure 10).

Stepwise multiple regression analysis yielded equations that can be used to predict bank erosion based on climatic (temperature) data (Lawler, 1993). This statistical analysis revealed that both mean and maximum stream bank erosion rate correlate most strongly with five indices of air frost:

1) Number of days of air frost (as % of period length). Air frost = minimum temperature ≤ 0.0 °C;
2) Number of days of air frost in erosion period;
3) Total duration of air temperatures ≤ 0.0 °C (as % of period length);
4) Number of air 'freeze-thaw' cycles (as % of period length); and
5) Number of days with minimum temperature ≤ -1.0 °C.

Air frost frequency, the variable most strongly associated with erosion rate, explained 94.2% of the variation in bank erosion rate in Lawler's study of the Ilston. The correlation is linear (Figure 11):

$$E = 4.53 + 6.07 \times A \; (for\ n, number\ of\ observations, = 22;\ r^2 = 0.971), or$$
$$E = 1.16 + 6.92 \times A \; (for\ n, number\ of\ observations, = 21; r^2 = 0.945)\ [Eq. 4].$$

The percentage of days with air frost (<0.0 °C), the independent variable A, corresponds more strongly with erosion rate (E) than the other 16 meteorological and hydrologic variables examined by Lawler (1986). In the n = 21 case, the period of highest erosion was excluded.

Strong seasonality in bank erosion was noted much earlier than the Lawler work during a study along Watts Branch, Maryland (Wolman, 1959). Wolman's study, also on stream banks consisting primarily of cohesive silt,[5] showed that ~85% of observed erosion during a several year period occurred during the winter months, from December to March (Figure 12). Bank pins (metal bars), surveyed channel cross sections, and two base lines parallel to the retreating bank edge were used to document bank erosion over a period of several years.

Wolman (1959) observed that rises in water stage were more effective at removing bank material after cryogenic processes had increased its susceptibility to fluid erosion, as described in the following excerpt:

> "A thickness of as much as 0.4 feet of sediment was eroded from the bank at specific points in a period of several hours during which a bankfull flow attacked banks which had previously been thoroughly wetted. … Little or no erosion was observed during the summer despite the occurrence of the highest flood on record in July, 1956. Second in erosion effectiveness were

---

[5] The reach of Watts Branch studied by Wolman (1959) was immediately upstream of a breached mill dam from a former 19th c. (and possibly earlier) grist mill (see Supporting Online material in Walter and Merritts, 2008).

> cold periods during which wet banks, frost action, and low rises in stage combined to produce 0.6 feet of erosion in six weeks during the winter of 1955-56." (Wolman, 1959, p. 204)
>
> "Despite variation in the amount of erosion around individual [bank] pins, the amount of erosion at each pin between successive measurement on each line and the rates and times of erosion on the two lines are in general agreement. The variation observed between individual pins is not sufficient to destroy the obvious relation between lack of erosion in summer and marked erosion in winter. … The highest flood on record in this area occurred on July 20 [1956]. Despite the volume of flow and its stage, erosion around the pins was negligible compared to the erosion regularly observed during the preceding and following winters." (Wolman, 1959, p. 208)
>
> "The evidence gathered thus far indicates that lateral migration of Watts Branch by erosion of the banks takes place primarily during the winter." (Wolman, 1959, p. 216)

From this work, Wolman made one of his most well-known, fundamental conclusions regarding geomorphic processes:

> "Inasmuch as such [flashy] summer floods constitute the rare and "catastrophic" events on small drainage basins in this region, present observations suggest that the cumulative effect of more moderate climatic conditions on this process of erosion exceeds the effect of rarer events of much greater magnitude." (Wolman, 1959, p. 204)

This important finding has been referred to as the "magnitude-frequency" problem, referring to the phenomenon of low-magnitude, high frequency events doing more geomorphic work (e.g., erosion) than high-magnitude, low frequency events.

3.4 Freeze-thaw cycling and the stream bank debris apron

During the course of this study, the authors noted that stream bank faces consisting predominantly of silt and clay develop an apron of loose sediment with low bulk density throughout the winter months (Figure 13). This apron begins to accumulate with the earliest freeze-thaw events, which typically occur in November or December in southeastern Pennsylvania and northern Maryland, but even earlier in central, western, and northern Pennsylvania. The apron of fine sediment accumulates on the face of the stream bank as long as the process of freeze-thaw continues, and it thickens with time. During the coldest months of January and February, when temperatures sometimes remain below freezing, the apron is frozen for days to weeks at a time. When sampling this material, we had to use a chisel. With each period of thaw, the transformation of solid ice to water loosens fine sediment and moves it outward, perpendicular to the stream bank, where it drops and accumulates on the apron. A similar apron of weakened sediment produced by freeze-thaw cycling was described by Wynn et al (2008) and is shown in Figure 10a of that paper.

4 Site Descriptions and Research Methods

4.1 Site locations

Rates of stream bank erosion are highly variable in space and time for the various reasons discussed above. The collective processes of subaerial erosion, mass wasting, and hydraulic entrainment are affected by variables such as local climatic factors (e.g., stream bank facing north), regional climate, degree and extent of stream channel incision after dam breaching, and the timing of storms and flood flow with respect to accumulation of loose debris in aprons after freeze-thaw or wetting-drying episodes.

The nature of material in the banks plays a very important role as well. Cohesive silt and clay—with moderate to high critical shear stress when moist to dry, respectively—are particularly susceptible to freeze-thaw, wetting-drying, and mass failure. In contrast, non-cohesive material such as sand—with a low to moderate critical shear stress—is more prone to erosion by hydraulic forces (c.f., Julian and Torres, 2006). Vegetation on banks also plays a role, with tree roots and grasses adding various degrees of cohesive strength to banks. On the other hand, fallen trees can block flow and trap sediment within incised channels, leading to localized scour and accelerated bank erosion around the obstruction.

Given this variability, we realized at the start of this project that one approach to defining stream bank erosion rates would be simply to characterize the range of rates of bank erosion at multiple sites, whereas another would be to identify the primary processes that control bank erosion rates for typical reservoir sediment in central and southeastern Pennsylvania, the primary study region. The first would be an empirical approach, somewhat of a blind, random analysis. The second is designed to determine the actual mechanisms of erosion and the factors that control the rates for these mechanisms. The second approach was selected for this study. In particular, we decided at the outset to select sites for which the date of dam failure is constrained to within ~10-15 years, so as to evaluate the role of time since breach channel incision as a factor in stream bank erosion rates.

Ten sites were selected from two counties (Chester and Lancaster) in the Piedmont lowland physiographic province of southeastern Pennsylvania, two counties (Cumberland and Centre) in the Ridge and Valley physiographic province of central Pennsylvania, and one county (Baltimore) in the Piedmont upland physiographic province of northern Maryland. These sites are illustrated in Figure 14.

One of the variables examined with respect to stream bank erosion rate is time since dam breach, and study sites were selected with this important variable in mind so as to measure erosion rates that span up to a century since dam breach date. For Big Beaver Creek, Big Spring Run, Conoy Creek, West Branch Little Conestoga, and White Clay Creek, the breach date was estimated based on analysis of historic air photos. The dams could be seen clearly on early photos, but not on later photos. A local, long-term resident at Big Beaver Creek confirmed our estimate of 1972 for the breach date, for example, and showed us a picture of the dam taken just after it breached.

In addition, Pennsylvania state inspection reports and photos often indicate when dams were and were not breached, and this information was particularly useful in determining breach dates for Conoy Creek and the West Branch Little Conestoga sites. At West Branch Little Conestoga Creek, for example, the dam at the study site was in place during a 1916 inspection report, but not in a 1938 air photo. We estimate 1930 as the breach date, but the time of breach could be 22 years earlier or 8 years later. At White Clay Creek, the dam appeared to be breached, although minimally, in a 1937 air photo. We are not certain of the breach date for this dam, but know from historic maps that it probably was in place in the late 1800s to provide water power to a mill downstream. We estimate a date of 1900 for its breaching, but this estimate could be ~37 years too old or 20 years too recent. At Big Spring Run, the dam downstream of the study site supplied water to a mill in the 1800s, and a local long-term resident confirmed it was present circa 1890-1900. It was gone by about 1916, we determined, because a local farmer straightened and relocated the channel in 1916, as it was incising and eroding into the property near his spring and house. The present farmer (H. Keener) showed us a photo of this incision taken about 1890-1900. In addition, another farmer upstream provided us with photos of a newly incising stream channel taken about 1930. The dam downstream of these sites appears breached on the earliest historic air photos (late 1930s).

At Big Beaver Creek, Conoy Creek, and Hammer Creek, dams were inset within older millponds that had breached sometime in the late 19th to early 20th centuries. Small wedges of sediment accumulated behind these newer dams, and these wedges were set within older packets of historic sediment from the higher dams. These packets can be discerned clearly in the banks of the modern incised streams now that these inset dams have breached. The younger packets of sediment commonly are more gravelly, as the incised streams were carrying gravel before the more recent damming with the inset structures. The older 19th c millpond sediment was mostly silt, clay, and fine sand. In addition, the younger wedges of sediment contain early 20th century artifacts, such as narrow tube tractor tires, glass medicine bottles, and leather shoes with hand-pounded nails.

Multiple dams existed along the length of Valley Creek examined here, and one inset dam (early 20th c) was built within an older (18th to 19th c) incised millpond about 1,200 ft upstream of the breached dam. This inset dam is much lower than the original dam and still exists, continuing to trap sediment in its reservoir. We focus on the incision and bank erosion in the older millpond, and evaluate rates of bank erosion both upstream and downstream of the inset dam. This reach was investigated from 2003 to 2006 by Fraley (2006), Fraley et al (2007), and Fraley et al (2009). Data from these previous works and our investigation of the timing of dam building and breaching are used herein to evaluate rates of bank erosion of millpond sediments.

Although some bed scour and aggradation have occurred along some of the stream reaches examined here, this sediment is largely gravel and coarse sand that move as bed load, and is not the primary focus of this report. More work on the rates of erosion and transport of bed load from incised millponds is needed to more fully understand this contribution to sediment loads in streams. For the purposes of understanding sources of fine sediment to the Chesapeake Bay, the more important phenomenon is erosion of fine-grained millpond sediment from eroding stream banks.

4.2 Research methods: Stream bank erosion rates

At each of the ten study sites, at least one of four methods was used to estimate bank erosion rates over time periods that varied from one to 74 years in duration (Table 2). At one site, Mountain Creek, all four approaches were used, and results from the different methods can be compared with one another. At another site, Conoy Creek, three methods were used and are compared. At three sites, two methods are used, and at the remaining five sites only one method is used. The four methods of measurement are described briefly as follows, and further details can be found in Appendix B:

1) Bank edge digitization—stream bank edges were digitized on digital orthophotos (orthorectified) acquired on different dates, then compared with GPS surveying of bank edges done by the report authors (or Fraley, 2006, and Fraley et al., 2009, in the case of Valley Creek);
2) Lidar volume—elevation data from airborne laser swath mapping using light-detection and ranging (lidar) were used to estimate volume of sediment removed along the stream channel corridor from the original millpond reservoir since the time of dam breaching (lidar is not yet available for eastern PA, and could not be used for Lancaster or Chester Counties, with exception of sites within the Little Conestoga watershed, for which USGS lidar is available;
3) Cross sections—stream channels were surveyed perpendicular to stream flow and endpoints were monumented with markers; repeat surveys enabled the calculation of removal of sediment during intervals between surveys; and
4) Bank pins—metal rods (rebar) were inserted into stream bank faces at multiple locations and the extent of the rod exposed at different times was measured to estimate a linear bank erosion rate.

		Period of measurement, by methodology			
Site	**Breach year**	**Bank edge digitization**	**Lidar volume**	**Cross section**	**Bank pin**
Big Beaver Creek, Lancaster County, PA	1972	2001-2005 2005-2009			
Big Spring Run, Lancaster County, PA	1916			2004-2009	2008-2009
Conoy Creek, Lancaster County, PA	1972	2001-2005		2006-2008	2006-2008
Gunpowder Falls, Baltimore County, MD	1932		1932-2005		
Hammer Creek, Lancaster County, PA	2001			2001-2008	
Little Conestoga Creek, W Br, Lancaster County, PA	1930	2006-2009 (fenceline)	1930-2004		
Mountain Creek, Cumberland County, PA	1985	2003-2007	1985-2007	2008-2009	2008-2009
Penns Creek, Centre County, PA	1968		1968-2006		
Valley Creek, Chester County, PA	1920	2004-2005		2004-2005	
White Clay Creek, Chester County, PA	1900				2008-2009

Table 2. Ten study sites described in this report, and the methods used to estimate stream bank erosion rates for each site. The number listed with each site is the estimated or known time of dam breach and table values represent the longest period of measurement (see text).

4.3 Research methods: Measuring the concept of channel-normalized sediment production and its spatial and temporal variability

4.3.1 The concept of a channel-normalized Sediment Production Unit (SPU)

We refer to the erosion of sediment along the stream corridor, as measured in this report, as *channel-normalized sediment production*. Bank height varies along the stream length, rising downstream toward breached dams and dropping markedly immediately downstream of such dams. Channel corridor width varies from one millpond reach to another as a result of time since dam breach. Incised channel corridors generally widen with time after dam breaching as a result of lateral stream erosion. Lower depositional surfaces—primarily bars—form within these corridors, and these landforms can be eroded as well as the channel migrates laterally. Channel length within a breached millpond reservoir can vary with time as a result of channel meandering through fine-grained historic sediment. Highly sinuous streams have more bank length exposed to wetting and drying, freeze-thaw, and stream erosion than straighter stream channels.

Because of this inherent variability in bank height, stream length, and stream corridor width within a breached millpond reservoir, we normalize the amount of sediment eroded from the corridor by bank height and stream length and report sediment production in units of volume of eroded sediment (ft^3) per unit bank height (ft) per unit bank length (ft) per unit time (yr). The final units are ft^3/ft/ft/yr, or SPU (sediment production units), which is essentially ft/yr, but it not simply a linear measurement at a point. It is a volumetric measurement based on bank height over a unit length of stream.

The same units are used for all four methods of measuring sediment erosion. For the one-dimensional bank pin method, we measure lateral retreat at a point and convert this value to volume by multiplying lateral retreat and bank height (ft) for one unit length of stream (ft). This value is then presented as cubic feet of sediment per foot of bank height per foot of stream length. For two-dimensional channel cross sections, we measure net area removed in square feet and multiply by one unit of stream length to get cubic feet, which then is presented as cubic feet per foot of bank height per foot of stream length. For two-dimensional plan view digital orthophotos, we measure net area of bank retreat and multiply this area by bank height to get volume of eroded sediment. This estimate, in cubic feet, is then presented as cubic feet per foot of bank height per foot of stream length over which the aerial change was measured.

Finally, from lidar we calculate the volume of the channel corridor incised within the historic sediment-filled reservoir, assuming that the fill formed a continuous subplanar surface just prior to dam breaching. We then normalize this volume with respect to average bank height for the entire length of reach over which the volume change was measured. This estimate of erosion is a measure of how much sediment (of all sizes) is gone since dam breaching occurred, and is not a measure of a contemporary, short-term erosion rate.

The following example illustrates the concept of a sediment production unit for a given stream corridor using the four methods described here. Consider a stream reach of 100 ft with bank heights of 8 ft. One of the two banks is eroding at a rate of 1 ft/yr, and the other is not eroding. Three methods—bank pins, bank edge digitization, and repeat channel cross sections, could be used to quantify the rate of bank retreat. Over the 100 ft length of channel, for 8-ft high banks, this rate of bank erosion would produce 800 ft^3 of sediment per yr, or 8 ft^3/ft/ft/yr, or 8 SPU. If both banks were eroding at 1 ft/yr, the sediment production would be 1600 ft^3 of sediment per yr, or 16 ft^3/ft/ft/yr, or 16 SPU. If the banks were 4 ft high instead of 8 ft, then for a bank retreat rate of 1 ft/yr the rate of sediment eroded would be 4 ft^3/ft/ft/yr, or 4 SPU. Repeat channel cross sections one year apart would reveal that 4 ft^2 of bank had eroded (for a 4-ft high bank retreating at 1 ft/yr), yielding 4 SPU. If lidar were used to determine the approximate amount of sediment eroded since dam breach, and if this amount were 3200 ft^3 over a period of 4 years, then the rate of sediment production would be 3200 ft^3/100 ft length/8 ft height/4 yrs, or 1 ft^3/ft/ft/yr, or 1 SPU.

4.3.2 Converting volume of sediment eroded to mass (tons)

A volumetric estimate of eroded sediment from a bank or stream corridor can be converted to mass by multiplying volume and bulk density, the latter of which is mass/bulk volume. Bulk density measures the mass of solid within a total volume that includes both solid and open space (e.g. pores). This is the appropriate density to use for unconsolidated sediment in a stream bank or gravel bar. We have measured the bulk density of bank and bar material for dozens of sites in the Piedmont and Ridge and Valley provinces of Pennsylvania and Maryland, and have found that it varies from ~56.2 to 87.4 lb/ft^3, or 0.9 to 1.4 g/cm^3. Here we use a range in estimates of bulk density of 1.04 ± 0.3 g/cm^3, or 0.74 to 1.34 g/cm^3 (46.2 to 83.7 $lb/ft^{3)}$. This range can be compared with estimates of sediment volume from bank erosion in Schenk and Hupp (2008), who use a bulk density value of 1.04 g/cm^3. For example, 1 ft^3 of sediment has a mass of 0.0283 to 0.042 tons (short tons) given this range in estimates of bulk density.

4.3.3 Spatial and temporal variability in stream corridor erosion rates

For a given length of stream in a breached millpond reservoir, some of the stream banks are exposed and eroding, whereas others are protected by lower, inset depositional landforms that form as the opposite bank retreats. Some parts of stream channels are straight whereas others are highly sinuous, and this plan-view curvature produces spatial variability in rates of bank erosion. Due to these and other factors, the entire length of stream is unlikely to be eroding at the same rate. As discussed in the next section, bank pin and cross section measurements reveal this variability.

Because of spatial variability in stream corridor erosion rates, it is necessary to use an average of many bank pin and channel cross section measurements, or to use a method that measures bank erosion over a larger part of the eroding stream. In this study, estimates of aerial erosion from digital orthophotos and volumetric erosion from lidar data provide data along relatively great lengths of streams so as to account for spatial variability in rates of stream corridor erosion.

Temporal variability also is captured in the different methods of measuring bank erosion rates. A measure of the volume removed along a channel corridor 50 years after a dam breach yields a long-term, 50-year average rate of erosion. However, bank pins installed 48 years after dam breaching and measured for two years would yield a post dam-breach, short-term average rate from years 48 to 50. If bank pins or channel cross sections are monitored over a lengthy period, it is possible to compare short-term rates from different intervals within the longer measurement period, and to compare these short term estimates to the long-term average rates. Similarly, digital orthophotos from different years can be compared with one another, as well as with survey data for bank edge and other features for different years. As with bank pin and channel cross section data, the different years can be compared to assess variability in bank erosion rates over different time intervals and with time after dam breaching. This temporal variability is discussed at length in subsequent sections.

As noted above, inset depositional landforms form over time as sinuous streams erode banks of fine-grained sediment in incised millponds after dam breaching. These depositional landforms generally are sand and gravel bars. We have done preliminary analyses of their grain size at Mountain Creek in the Eaton-Dikeman reservoir, and at Big Spring Run. At both sites, the bars consist largely of medium to coarse sand and gravel whereas the banks consist largely of clay, silt, and fine sand. However, at Big Spring Run some parts of the bars have greater amounts of fine sand, silt and clay. The amount is highly variable spatially, with close to zero percent silt and clay in parts of some bars and about 40% at others. Although more work needs to be done to determine the amount of fine sediment that is trapped in these depositional features, it is certain that the banks consist of >90% clay and silt at Big Spring, and the bars are generally much coarser grained. In addition, at both Mountain Creek and Big Spring our analysis of the plan-view stream channel pattern over time from digital orthophotos indicates that the bars migrate downstream as the meander pattern shifts. The upstream ends of bars are eroded as downstream ends prograde by deposition. In essence, the bars themselves are both depositional and erosional features, whereas the banks are only erosional features.

In essence, the bars forming within the incised stream corridor are both depositional and erosional features, whereas the banks are mostly erosional features once a dam has breached and a stream channel has incised deeply into the reservoir sediment.

4.4 Quantifying nutrients stored in stream bank sediments

4.4.1 Field sampling and analytical methods

For this study, most stream banks were sampled in 10 cm increments, from the top of the bank to below the water line, in order to determine variations in concentration as a function of sediment depth and sediment characteristics (e.g., color, particle size, mineralogy, organic matter). For example, a 2-m-high stream bank would yield 20 samples. Approximately 500 g of sediment was collected per interval. Each sample was stored and transported to our laboratory in a clean, sealed plastic bag (e.g., ZipLoc). Field moist samples were air dried for ca. 10 days before analyses. Initially, we compared the results of field moist samples (transported on ice and analyzed within 24 hours) to air dried samples and found no statistical difference between them for total N, total P, nitrate, orthophosphate, and trace metals. We concluded that air-drying is the best method because: (1) it yields results comparable to field most methods; (2) dry samples are more easily crushed, sieved, and homogenized (making repeat measurements more consistent); and (3) the measured concentrations are “dry mass” values, and therefore directly comparable to standard soil and sediment geochemical reporting procedures (i.e., field moist measurements must be corrected to their dry mass equivalent, which adds an additional source of error to an analysis).

In general, post-settlement legacy sediments, which comprise the thickest portion of most stream banks, are light to reddish brown in color, and classified as silt or silt loams (usually between 70-90 % silt and clay). The typical legacy sediment is mostly quartz (even the silt and clay-sized particles), with rare kaolinite (determined by x-ray diffraction), has organic carbon content less than 3%, and a bulk density of roughly 1.3 +/- 0.1 g/cm^3.

The pre-settlement sediments are dark gray or black, and classified as loams, usually with more very fine sand than in the post-settlement deposits. The particles are mixture of organic matter (seeds, nuts, twigs, etc.) and inorganic matter (quartz). The low chroma, its proximity to the groundwater table and stream surface (which yields saturated conditions), and the abundance of seeds of wetland plants indicates that this sediment is a buried hydric (wetland) soil. The < 2 mm fraction of these hydric soils yields organic carbon contents of 3 to 9 %. The hydric soils have a bulk density of 0.9 +/- 0.1 g/cm^3.

Inorganic particle densities for both the pre- and post-settlement sediments are ~ 2.6 g/cm^3 (determined via a gas pynctnometer), reflecting the predominance of residual quartz in these samples. High iron and aluminum contents sediments suggest the presence of Fe- and Al oxides and/or oxyhydroxides, probably as colloids. Quartz is one of the most resistant minerals on Earth, and kaolinite and Fe-Al oxides are common terminal-stage weather products in soils in the region. The predominance of quartz and terminal-stage weather products indicates that the sediments were derived from the erosion of geologically ancient, highly weathered landscapes.

Nutrient contents of stream bank sediments were measured using three analytical instruments: (1) Inductively Coupled Plasma (ICP) Optical Emission Spectrometry for total sorbed phosphorus; (2) Flow Injection Analysis (FIA) for total sorbed phosphorus; and (3) Elemental Combustion Analysis (ECA) for nitrogen and carbon. The EPA 3051 Method, a microwave partial digestion technique, provided solutions that were analyzed for P by ICP and FIA. The microwave procedure was designed to mimic the release of trace elements that are sorbed onto clay-sized particles, which can be become available for plant uptake under optimum E_h/pH conditions (especially from Fe-oxides).

Reference standards were analyzed as unknowns and subsequently used to assess quality assurance and quality control parameters related to our analytical procedures. The analyses of standard reference materials measured in our laboratory fell within the range of certified analyses, verifying that the data presented here for N and P contents of stream bank sediments are robust and accurate.

5 Data and Results

5.1 Stream bank erosion rates and dam breaching: Overview

The data for stream bank erosion rates are presented in two ways. First, the actual values for each site, station, method, and time period are provided for 79 measurements in a table in Appendix C. A given site, as at Big Spring Run, for example, has four cross sections and 16 sets of bank pins, resulting in 20 separate measurements. Although each measurement represents only a short length of stream reach, collectively the sites span about 0.5 km of stream length. Bank edge digitization and lidar volume measurements represent greater lengths of stream, and these lengths are provided in Appendix C. Second, a synopsis for each site, method and time period is presented in a table in Appendix D.

Stream bank erosion rates generally are highest for time periods shortly after the time of dam breaching. At Hammer Creek, for example, part of the dam was removed in 2001, and average rates of sediment production were as high as 19.7 SPU immediately afterward. Much of this erosion was associated with mass movement (e.g., bank collapse; Figure 15).

Another factor that affects rate of bank erosion is distance upstream of the breached dam. This variable affects erosion rates in three ways. First, the wedge of historic sediment that accumulates in a reservoir is thickest near the dam. As a result, stream banks are highest at sites nearer the breached dam, and lowest upstream toward the end of the reservoir. Higher stream banks might be associated with greater rates of erosion, for example, because they are more prone to mass movement and larger failure masses as a result of undercutting at the bank toe.

Second, the finest sediment in a reservoir generally accumulates nearest the dam, where the original pool was deepest and water velocity slowest. Our grain size analyses at several millpond sites indicate that stream banks near dams have greater amounts of silt and clay than do those upstream within the breached reservoir, where reservoir sediment more commonly contains sand and sometimes fine gravel. Silt and clay are more cohesive than sand and gravel, and as a consequence more prone to weakening by freeze-thaw and wetting-drying cycles. Reservoirs of sand might flush rapidly by hydraulic forces, but reservoirs of silt and clay might flush more slowly as a result of subaerial and mass movement processes.

If two dams with these two different types of material in their reservoirs breached 100 years ago, for example, the reservoir of sand might have very little sediment left and bank erosion rates might be low at this time. The reservoir of cohesive silt and clay, however, might still contain near-vertical banks that retreat annually as a result of freeze-thaw and wetting-drying cycles. At present, 100 years post-dam breach, bank erosion rates at such a site might be higher than those of the sandy reservoir, even though less material has been eroded during the entire interval. In other words, the flushing time is longer for the silt-clay reservoir, and the rates of erosion many decades after dam breaching remain relatively high in comparison to the sandier reservoir sediment.

Finally, it is more likely that higher hydraulic shear stresses are generated in the downstream reaches of reservoirs, where banks are higher and water depth can become greater without going overbank, than in the upper reaches where the thickness of millpond sediment is less and banks are lower. This factor probably plays a particularly important role during the years immediately after dam breaching, when the freshly incised channel has a small width-depth ratio. As lateral bank erosion occurs and the stream corridor is widened, flow depth generally decreases for a given amount of runoff.

These comments must be considered with respect to the type of sediment eroded from a watershed. If the local bedrock is silty limestone, for example, and little coarse-grained sediment is produced on hillslopes, then the reservoirs in the valley bottom are not likely to contain coarse sediment in the historic reservoir fill, regardless of proximity to a dam. The bedrock at the majority of sites described here is silty limestone or schist, the former of which weathers to silt and the latter of which weathers to sand, silt, and clay. The exceptions are Hammer Creek and Conoy Creek, both of which are underlain by conglomerate, sandstone, and shale.

Although the historic sediment generally consists of sand, silt, and clay in all reservoirs examined in this study, nearly all valley bottoms in the Piedmont and the Ridge and Valley physiographic provinces of Pennsylvania and Maryland are mantled with coarse material that is buried beneath the historic sediment. This prehistoric sediment commonly consists of gravel, cobbles, and even boulders, and is both a long-term denudational lag from deep, prolonged weathering over geologic time, and a result of episodic freeze-thaw and frost weathering during cyclical full-glacial episodes. This region has been affected repeatedly by permafrost activity during full-glacial periods, when a continental ice sheet extended south from the Arctic and reached nearly half-way into the state of Pennsylvania. Between the coarse gravelly sediment and the fine-grained historic sediment a thin organic-rich soil commonly exists across valley bottoms in 1st, 2nd, and 3rd-order valleys of the mid-Atlantic piedmont. As discussed by Walter and Merritts (2008) and Voli et al (2009), this organic soil typically is a hydric soil that accumulated in wet meadows and other types of valley bottom wetlands during the past ~10,000 years, a time of interglacial warmth.

5.2 Case studies for measurements of stream bank erosion rates

5.2.1 Hammer Creek—breached in 2001

The Hammer Creek study site is the ~5-ft high Pump Station dam, which was removed in 2001. Hammer Creek was named during the Colonial period for the constant hammering of iron at forges and mills along the stream. In this report, “mill dam” is used to refer to all types of water-power dams, including for forges, grist mills, paper mills, etc. The headwaters of Hammer Creek was within the vast holdings of the original Coleman family iron works, and was used intensively for water power for iron mining, forges, and associated activities. The Pump Station dam was built for the purposes of water supply in the early 20th c. within the incised stream channel of Hammer Creek. This incised channel on Hammer Creek had formed upstream of an older milldam that is shown on 19th c maps. The early 20th c dam, referred to here as an inset dam because it was set within older reservoir sediment, reached the top of the historic sediment. The reservoir formed by this dam is shown in an historic air photo from 1940 in Figure 16. At the lower left in this photo can be seen a small tributary entering Hammer Creek from the west; this tributary had an iron gate that was used to control its water flow into Hammer Creek. A digital orthophoto from 1993 shows the stream 53 years later, just 8 years before dam removal (Figure 17). By that time, sedimentation had narrowed the stream channel substantially. A digital orthophoto from 2005 illustrates Hammer Creek about 3.5 years after dam removal (Figure 18).

Three cross sections upstream of the Pump Station dam (XS-3, 4, and 5) were surveyed prior to and after dam removal by DEP scientists Jeff Hartranft and Scott Cox, and a fourth cross section (XS-6) farther upstream was added by Chris Scheid (Franklin and Marshall College graduate, 2008) in 2006 (Figure 19a). All of these sections are within the historic valley sediment formed by the combined effects of the older Colonial-era dam that was downstream and the early 20th c. Pump Station dam. These cross sections yield rates of lateral bank erosion that have decreased with time, from as high as 24.8 ft/yr in

2001-2003 (at XS-4) to ~1 ft/yr in 2006-2008. This decrease in sediment production rate is shown in Figure 19b.

From dam breaching in 2001, up until October 2008, there was a change in cross-sectional area at XS-4 of 180 ft^2, representing material that was removed by erosion. Likewise, cross-sections at XS-5 showed a change of 131 ft^2 that resulted from channel enlargement by erosion. The two cross-sections, XS-4 and XS-5, are 170 ft apart. Multiplying the average area eroded from the cross-sections by the channel length between the cross sections suggests that 26,400 ft^3 of material, representing approximately 860±250 tons of mostly fine-grained sediment, was removed in seven years over a channel length of just 170 ft (~0.72 tons/linear ft/yr).

The repeat channel cross section surveys reveal that the entire stack of historic sediment settled and subsided after the dam was breached, as a result of dewatering of the sediment-filled reservoir. This process appears to continue, even as of the 2008 surveys. Note in Figure 19a that the initial response to dam removal was incision, whereas the subsequent response was lateral bank erosion.

5.2.2 Mountain Creek—breached in 1985

The Mountain Creek study site extends from the 13-ft high Eaton-Dikeman paper mill dam, which was removed in 1985, to the upstream end of the reservoir, a distance of about 3,300 ft. The original dam was built in 1855, although field evidence indicates that an older dam might have existed in the vicinity (within 30 feet upstream) of this structure. Pennsylvania state dam inspection reports indicate that the reservoir was substantially filled with sediment by 1914 (see discussion above). The reservoir formed by this dam is shown in an historic air photo from 1968 in Figure 20. This photo reveals a deltaic lobe of sediment crossing the valley from southeast to northwest near the dam. Bathymetric surveying by Dickinson College students in 1976 revealed that the greatest water depth near the dam was ~40 inches, and that the majority of the reservoir had water depths less than one foot.

A 50-ft breach in the dam was made in 1984 when the Eaton-Dikeman mill owners chose to drill a well for groundwater to supply the mill rather than to continue to repair the aging dam. Digital orthoimages from 2003 and 2006 illustrate Mountain Creek 18 and 21 years after dam removal (Figure 21, 22).

With Jeff Hartranft and Scott Cox of DEP, and Noel Potter of Dickinson College, we established and have done repeat surveying at, four cross sections upstream of the dam (XS-1, 2, 3, and 4). Cross sections XS-1 and XS-2 were installed in December 2007 to January 2008, and cross sections XS-3 and XS-4 were installed in August 2008. At each of these sites we also installed sets of vertical pins (4-ft rebar) to monitor bank erosion, with 3 pins at each site. We also surveyed channel breaklines in 2008 and 2009 with a Trimble GeoXH GPS unit. These breaklines are compared with digital orthoimages from 2003 and 2006 (Figure 21, 22). The cross section surveys, bank pin measurements, and GPS breakline surveys were part of the thesis work of Matt Jenschke of Franklin and Marshall College.

The bank pin measurements reveal that more lateral bank erosion occurs in the winter than in other seasons (Figure 23). This phenomenon was observed in the 1950s by Wolman at Watts Branch in Maryland (Wolman, 1959), and by Lawler in his studies of stream banks in England (c.f. Lawler, 1987, and other references discussed above). We observed freeze-thaw processes and needle ice in the stream banks of the Eaton-Dikeman reservoir in the winter of 2008-2009.

The four cross sections yield rates of lateral bank erosion that varied from 2.0 to 3.8 ft/yr from 2008 to 2009. The GPS breakline surveys done in 2008 and 2009 are compared with digital orthophotos in 2003 and 2006, and yield a rate of lateral bank erosion of 1.0 ft/yr for the 2003-2006 time period. We estimate that the amount of sediment removed from the reach of stream between cross sections XS-1 and XS-4 (a distance of 1200 ft) between 2003 and 2006 was 54,500 cubic ft, or 1,770±510 tons (~1.5 tons/linear ft/yr). Using lidar topography for this site, we estimate that 1,350,000 cubic ft of sediment was eroded over a distance of 3880 ft since dam breaching in 1985, which is equivalent to 43,800±12,500 tons of sediment, or ~11 tons/linear ft/yr. Note that this is a long-term average production rate if sediment were eroded at a constant rate since the time of dam breaching. It is likely that the rate was actually much higher during the years immediately after breaching, and has diminished with time.

Our particle size analyses (using a sedigraph and laser particle analyser) of the stream bank sediment indicates that it consists of ~10-20% clay and 80-90% silt and fine to medium sand with minor fine gravel at cross sections XS-1 and XS-2. The minor fine gravel is slag in the uppermost 4 ft of reservoir sediment. This slag is most likely from the Pine Grove and Laurel Forge iron workings, which are located 7.2 miles upstream. It is likely that most of the 46,500 tons of sediment that was eroded from 1985 to 2007 was fine sediment.

5.2.3 Conoy Creek—breached ca. 1972±10 yr

The Conoy Creek study site is upstream of a ~4-ft high dam that was built in 1930 to supply water for garden plots at the Masonic Village. This dam was similar to the structure built on Hammer Creek (discussed above) in that it was built within a stream channel that had incised into older reservoir sediment. The older reservoir sediment appears to have been the result of a paper milldam in the same location that is shown on mid-19th century maps. Water-powered mills existed along Conoy Creek as early as the 1740s according to historical documents. The stream was particularly important for industrial activities associated with the iron mining in the Elizabethtown area.

A Pennsylvania state dam inspection report from July 1, 1931, describes the dam as follows:

> "On December 18, 1930 a permit was issued to the Masonic Homes of Pennsylvania for the construction of a dam across Conoy Creek, near Elizabethtown. The plans provided for a gravity type concrete structure.
>
> "The writer made an examination of the dam on June 25, 1931, and found that a timber structure had been built about 3 feet high with two rows of 2-inch planks along the upstream face and a sloping deck on the downstream side. It was not possible to determine the nature of the construction underneath the planks. The dam has a length of 18 feet and at each end there are masonry walls built to the height of the channel banks…. The construction appears to be satisfactory…"

The next inspection report in the state files is dated October 22, 1959, and is based on an examination from October 20 of the same year. In this report, the inspector notes that the reservoir upstream of the dam is “silted up” with no remaining capacity, and describes the stream banks around the wing walls as eroded:

> "Flood waters have washed away the right wall for the wasteway channel and the parts of the banks. A hole in the bank has formed on the left side and flood waters will probably waste away left wall.… Dam appears to be abandoned."

Photos that accompany the report illustrate this channel erosion between the masonry wall and the valley margin in its early stages of development (Figure 24). These photos also illustrate how the crest of the dam is ~2 feet below the level of the valley flat that formed as a result of sedimentation from the older mill dam.

A 1940 air photo shows the intact dam set within the valley flat (the older millpond fill surface), and it appears to have substantial sediment within the channel that was blocked by the 1930 dam (Figure 25). A 1971 air photo also shows the dam as intact, although erosion can be seen along the left (southeastern) bank between the masonry wall and the valley margin, and some water appears to be passing through this eroded area (Figure 26). Air photos from the late 1970s and 1980s indicate that the channel had completely bypassed the dam along this margin, effectively causing a dam breach without breaching the actual structure. We estimate the timing of complete dam bypass as 1972, the year that Hurricane Agnes caused severe flooding in the region and damaged many old dams. Because the erosion occurred along the eastern valley margin in bedrock, the bypass channel developed at a slightly higher elevation than the center of the original valley floor to the northwest. The channel grade control at this elevation determined the level of incision of the upstream channel, which cut down through the sediment that had filled in the channel that had been dammed by the inset 1930 structure. This sediment was generally coarser grained (sand and gravel with some silt) than the older valley fill, which is largely silt and clay. The inset fill formed a prominent bench along the valley that is about 1 to 2 feet lower than the larger valley flat.

Digital orthoimages acquired since the 1990s illustrate a channel with significant meander migration and bank erosion at multiple locations, in marked contrast to the limited channel migration and bank erosion prior to 1971 (Figure 27). The recent digital orthoimages are of sufficient resolution to measure bank erosion over a period of several years or greater. Terrace edge and water edge breaklines, surveyed in 2008, helped distinguish terrace surfaces from bar surfaces (Figure 28), and improved image interpretation and change classification. Using surveyed breaklines in conjunction with orthoimages from 2001 and 2005, we identified and classified changed areas (Figure 29). We observed both deposition and erosion of bars (mostly sand and gravel), and erosion of the terrace (mostly silt and clay), during this time. The average net rate of lateral erosion of the bank from 2001 to 2005 along the 1,788 ft of channel length measured was 1.5 ft/yr (see Appendix D).

Four cross sections and associated sets of bank pins were installed upstream of the Conoy Creek dam (XS-1, 2, 3, and 4, from upstream to downstream) by LandStudies, Inc., in 2006 (see Figure 27 for locations). All four of these cross sections were located within the historic valley sediment that had accumulated as a result of the combined effects of the older Colonial-era dam as well as the 1930 water supply dam. We resurveyed these cross sections several times between February 2005 and July 2008, but use only the total change during that time period to estimate an average rate of bank erosion. Part of this bank erosion monitoring effort was a thesis project by Franklin and Marshall College student Colette Buchanon. The four cross sections yield rates of lateral bank erosion that ranged from 0.17 to 1.21 ft/yr in 2006-2008. The second lowest rate of 0.47 ft/yr is for XS-4, which was located along the southeastern valley margin near the bypass that had eroded behind the masonry wall of the dam, and a large amount of rubble, including of masonry and concrete, existed in the channel bed, probably as a result of the collapse of the older dam structure. This cross section did not experience the deeper incision and scour that occurred farther upstream at the other three cross sections, which were not limited by the grade control of the bed or the blocks of rock and rubble in the bed. This clear difference in bank erosion between cross section XS-4 and the other three can be seen in the repeat channel cross sections surveys shown in Figure 30.

We measured the bank pins four times for two sets of pins, and five times for the two other sets (see Appendix C for bank pin data). The bank pins yielded rates of lateral bank erosion that ranged from 0.36 to 1.99 ft/yr during the period of 2006 to 2008. The pins at XS-4, immediately upstream of the dam and located along the southeastern valley margin, yielded the lowest rate of bank erosion. Very little historic sediment was located on the left bank, where the pins were established, because that site was the original edge of the Colonial mill pond, where the reservoir sediment lapped on to the valley margin. All other pins were established within historic sediment.

In sum, the rates of bank erosion estimated for Conoy Creek were as follows:

- 0.36 to 1.99 ft/yr during 2006-2008 (bank pins);
- 0.17 to 1.21 ft/yr during 2006-2008 (cross sections);
- and 1.53 ft/yr during 2001-2005 (digital orthoimages).

We estimate that, for 1,788 feet of stream length, greater than 60,000 cubic feet was removed over the period from 2001-2005. This amounts to approximately 1,950±560 tons of sediment eroded during that four year period, or approximately 0.27 tons/linear ft/yr.

5.2.4 Valley Creek—breached ca. 1920

Valley Creek in southeastern Pennsylvania is a typical mid-Atlantic Piedmont mill stream in that it had a long history of milling that included forges, paper mills, grist mills, slitting mills, and textile (wool and cotton) mills (Figure 31). The stream is about 12 miles in length and drains into the Schuylkill River. At least 10 dams and associated mills existed along Valley Creek in the 18th and 19th centuries, and at least one inset dam was built in the 1920s (Figures 32-35). Today, remnants of these older breached dams are exposed in the stream banks of Valley Creek, and extensive deposits of laminated, fine-grained millpond sediment can be traced upstream from breached dams (Figure 36). These sediments occur as wedges that are thickest near the breached dams and thin upstream toward what once were the upper ends of millponds.

The Valley Creek study reach described in this report encompasses a distance of about 12,000 ft along the lowermost part of the main stem of the creek within Valley Forge National Historical Park (Figure 37-38). This reach was investigated from 2003 to 2006 by Fraley (2006), Fraley et al (2007), and Fraley et al (2009). Data from these previous works are used herein to report bank erosion of millpond sediments. The Fraley (2006) publication is a Master's thesis from the University of Maryland, and the Fraley et al (2007) publication is a report on this work to the National Park Service. Here, we refer to this body of work with reference to the journal article published by Fraley et al (2009), but additional details on the work can be found in the earlier publications.

In June and July of 2004, Fraley et al (2009) installed and surveyed three channel cross sections within each of 12 reaches of the lowermost 12,000 ft of Valley Creek, for a total of 36 cross sections. These sections were resurveyed after major storm events and at the end of the study period from April to June of 2005. The area of change was calculated by comparing the repeat surveys, in the same method as described in this report for channel cross section analyses (see 3.2 Research Methods: Bank Erosion Rates). In addition, ten of 38 locations where significant bank instability was observed were monitored by resurveying the bank tops and bottoms throughout the study period. The method used by Fraley et al (2009) to measure change for these ten areas are similar to our approach using bank edge digitization from digital orthoimages and repeat GPS surveying. Fraley et al (2009) calculated the area of bank retreat and divided by the length of bank surveyed in order to determine average lateral distance of bank retreat. They combined this estimate with average bank height to get net volume of sediment eroded from the stream bank. This method is similar to that used in this report (see section 3.2).

Fraley et al (2009) sieved samples of stream bank sediment from each of the ten locations with significant bank instability in order to determine particle size distribution (see Table 3 in Fraley et al, 2009). With two exceptions, the stream banks consisted of 80 to 100% sand, silt, and clay. The two exceptions were 65 and 24% sand, silt, and clay. With three exceptions of these ten samples, the stream banks consisted of 59 to 90% silt and clay. In other words, stream banks at seven of the 10 sample sites consisted of 59% or more silt and clay.

The results of calculations of volume of eroded stream bank for each of the 12 reaches assessed are presented in Table 4 of Fraley et al (2009). We used these estimates and the values of average bank height and stream length for each reach, as presented in Fraley et al (2009) and Fraley (2006), to calculate channel-normalized sediment production in ft^3/ft/ft/yr, or SPU (see discussion above in section 3.3). We plot these estimates along a long profile of Valley Creek obtained from a total station survey by Fraley et al (2009; see Figure 2 in Fraley et al). In Figure 39, the estimates are presented in metric units, because the original figure from Fraley et al (2009) is in metric units. Equivalent measurements in ft^3/ft/ft/yr are presented in Appendix C. Upstream of the 17-ft high dam that was breached in the 1920s the channel-normalized sediment production rates diminish from 1.78 to 0.13 SPU over a distance of approximately 10,000 ft. This length of Valley Creek is the approximate extent of the millpond that was formed by the 17-ft high dam that was built in 1789 and breached in the 1920s. Our field observations indicate that the pond was filled to the brim with historic sediment, and historic photos of the dam, millpond, and breached dam support these observations (see Figures 32-35).

5.2.5 Big Spring Run

The Big Spring Run study reach encompasses a distance of about 1800 ft along the main stem of the creek. A dam 1.1 miles downstream of the study site supplied water to a mill in the 1800s, and a local long-term resident confirmed it was present circa 1890-1900. We determined that the dam was gone by about 1916 (see discussion above). The dam appears breached on the earliest historic air photos (late 1930s), and air photos from 1940, 1957, and 2005 (digital orthoimage) reveal that the stream has been incised and migrating laterally during this time period (Figure 40, 41).

Using a total geodetic station, surveyors from LandStudies, Inc., established twelve cross sections along the study reach in 2004 and resurveyed the cross sections in 2006 (see Figure 41 for section locations). With Allen Gellis of the USGS we resurveyed these cross sections and added 2 more cross sections near the original twelve in 2008. We installed twelve sets of pins (2-ft and 4-ft rebar) to monitor bank erosion in 2008, with three pins aligned vertically on the bank at each site (see Figure 41 for pin locations). Allen Gellis (USGS) also installed four sets of pins in 2008, with 4 pins aligned vertically on the bank at each site. The cross section surveys and bank pin measurements were part of the thesis work of Andrea Shilling of Franklin and Marshall College in 2009-2010. Students from the Fall geomorphology classes at Franklin and Marshall College in 2008 and 2009 assisted in installing and monitoring the bank pins. Only four sets of cross sections, representative of the trends for the others, are discussed in this report. A detailed report just on Big Spring Run—which is part of a focused investigation on suspended sediment and nutrients by Franklin and Marshall College, the USGS, the EPA, and other groups—will be produced in 2010. That report will contain data on all of the cross sections and bank pins, as well as analyses of sediment and nutrient loads from stream gages and nutrient concentrations from groundwater wells.

Our particle size analyses of bank material from the vicinity of XS-5 using both a Micromeritics sedigraph and a Micromeritics laser particle size analyzer on duplicate samples indicates that banks consist of nearly 100% silt and clay. Our mineralogical analysis of the clay-sized fraction indicates that the clay-sized sediment is quartz, not clay minerals. This fact is important because clay minerals have much higher cohesion, and hence critical shear strength, than clay-sized quartz.

Similarly to bank pin measurements at the Eaton-Dikeman dam breach site on Mountain Creek, those from the sixteen sets of pins at Big Spring Run reveal that more lateral bank erosion occurs in the winter than in other seasons. As noted above, this phenomenon was observed in the 1950s by Wolman at Watts Branch in Maryland (Wolman, 1959), and by Lawler in his studies of stream banks in England (c.f. Lawler, 1987, and other references discussed above). We observed freeze-thaw processes and needle ice in the stream banks of Big Spring Run in the winters of 2008-2009 and 2009-2010, and documented the growth of an apron of debris from freeze-thaw processes during these winters (Figure 42).

In addition to the role of freeze-thaw in bank erosion, we noted that bank slumping and calving are frequent and typically occur immediately after a rise and fall in stage (Figure 42). Other workers have noted that high stages cause banks to be wetted, and the rapid drop in pore pressure in wet banks after a high stage event is highly conducive to failure in banks composed of large amounts of silt and clay. For Big Spring, we documented that such failure occurred throughout the year, but was especially notable in the Fall during long-duration events that wetted the banks over a period of days. Julian and Torres

(2006) noted the importance of flow duration in reducing the critical shear strength of stream banks that consist of more than 20% silt and clay. Julian and Torres (2006) proposed that for stream banks consisting of more than 40% silt and clay, flow duration is more important than flow depth in bank erosion. During the summer months we observed that the stream banks became very dry and fractured (Figure 43). This drying is associated with vegetation growth that removes water from the pore spaces of the fine-grained banks. Summer drying and fracturing prime the banks for failure during the fall, when the decline in vegetation activity and the increased frequency of storms in the mid-Atlantic region increase bank moisture content.

The four cross sections presented here (XS-3, XS-4, XS-5, and XS-11) yield rates of lateral bank erosion that varied from 0.13 at XS-3A to 0.88 SPU at XS-11A from 2004 to 2009 (Figure 44; see Appendix C for cross section data). We measured the bank pins multiple times during 2008 and 2009 (see Appendix C for bank pin data). With exception of four sets of bank pins that were buried slightly during this time interval (producing negative values for measured change), the pin data yielded rates of lateral bank erosion that ranged from 0.16 to 2.1 ft/yr during the period of 2008 to 2009. The equivalent rates of channel-normalized sediment production are 0.13 to 2.13 SPU.

5.2.6 Little Conestoga Creek, West Branch, Denlingers Mill—breached ca. 1930±10 yr

The West Branch Little Conestoga Creek study site extends along a stream distance of ~8100 ft upstream of the 20-ft high Denlingers mill dam that breached some time between 1919 (state inspection report with photos) and 1940 (Figure 45). The 1940 air photo clearly shows an incised stream with high banks that appear to diminish in height upstream toward the next mill dam (upper left corner of Figure 45). Both the lidar data from 2005 and our field mapping indicate that the wedge of sediment in the milldam reservoir tapers from 20 feet in thickness at the dam to about 5 feet in thickness at the upstream end of the reservoir. Grain size analysis of ~4-inch intervals of the reservoir sediment sampled from top to bottom of the wedge at 4 sites (labeled sites 2, 4, 5, and 6, from upstream to downstream on Figure 46) indicate that the sediment fines downstream, as expected for a slackwater reservoir. At sites 5 and 6, the majority of the sediment column is silt and clay, whereas at sites 2 and 4 the sediment consists of silt with fine to medium sand, and some gravel occurs in the sediment stack at site 2, the most upstream site.

Sediment production rates were obtained with two different methods. Lidar acquired by the USGS in 2005 was used to estimate the volume of material removed from the millpond reservoir by channel erosion for the 8,100-foot reach upstream of the dam (Figure 47). This method yields a sediment production rate of 0.72 SPU. Note that this lidar approach to estimating sediment production yields a long-term average rate. In other words, the rate just after dam breaching might have been very high, and rates might have decreased with time. The lidar method yields an average rate since the start of sediment erosion after dam breaching.

Indistinguishable from this estimate of sediment production is a rate determined from a series of measurements of 16 posts along a straight corral fence from 2006 to 2009. The endpoints of the fence line are shown with white triangles in Figure 46. Over the 5-year monitoring period, the left stream bank edge retreated increasingly closer to the corral fence until, in 2008, some of the posts began to collapse and fall toward the steep bank face. This method is akin to that used by Wolman at Watts Branch in 1955-57 and referred to by him as a baseline method (Wolman, 1959). With exception of one post for which little bank retreat has occurred, the retreat rates at all other posts ranged from 0.13 to 2.13 ft/yr from 2006 to 2009, with a mean value of 0.69 ft/yr. The sediment production rate for the time period of 2004 to 2009 from this baseline approach is 0.7 SPU. It is possible that the long-term average rate of erosion is similar to the short-term estimate measured >60-70 years after dam breaching because rates of sediment production from a breached reservoir are high immediately after breaching and decline rapidly thereafter, so that the long-term average is similar to the rate after many years.

The sediment production rate at the fence line, which is close to the dam, is based on a mean bank height of 13.8 ft, whereas the production rate along the ~8,100 feet of stream length based on lidar is calculated with a mean bank height of 7.6 feet. This latter estimate is an average based on bank heights measured with the lidar data.

During five years of field work at this site, we have noted multiple large block failures along the banks. In places, the banks have retreated to the bedrock valley margins, exposing large blocks of bedrock on talus slopes that underlay the historic millpond sediment. Toward the valley center the deep incision has exposed numerous outcrops of buried wetland soils that can be traced along the length of the valley for thousands of feet and can be found on both sides of the valley bottom. Note on Figure 46 (2005 digital orthophoto) that the stream corridor upstream of the Denlingers mill dam became heavily forested between 1940 and 2005. Many of the trees growing on the surface of the reservoir sediment have fallen into the stream as the banks retreat, leading to large debris jams and scour features.

For the 8,100 feet of stream length and 74 year period, 3.3 million cubic feet of material was removed from Little Conestoga Creek West Branch upstream of the Denlinger's Mill dam. This amounts to 107,000±31,000 tons of sediment evacuated to create the modern-day channel (~0.2 tons/linear ft/yr). Note that this is a long-term average production rate if sediment were eroded at a constant rate since the time of dam breaching. It is likely that the rate was actually much higher during the years immediately after breaching, and has diminished with time.

5.2.7 Big Beaver Creek—breached in 1972

The Big Beaver Creek study site extends along a stream distance of ~2,530 ft and encompasses part of the wedge of sediment from the Shultz grist mill dam, which is about 2,000 ft downstream from the study reach. The Shultz grist mill dam appears breached in 1938 air photos, and vertical stream banks appear to be eroding upstream of the dam, with exception of the area upstream of an ~3 to 4-ft high inset dam that was placed ~3,000 ft upstream of the Shultz mill dam (Figure 48). In the 1938 air photo, steep banks and a wide channel can be seen downstream of this dam, but upstream of the inset dam the high banks disappear and the channel is much more narrow. The inset dam was breached in 1972 during Hurricane Agnes, according to a local long-time resident, and this date was confirmed by our examination of air photos from time periods prior to and after 1972. Aerial photos and local residents confirm that after the 1972 breach, incision and channel bank erosion became pronounced upstream of the breached inset dam.

Significant amounts of stream channel migration and bank erosion occurred between 1972 and 2009, and large, coarse-grained gravel bars formed in the wake of eroding stream banks, as can be seen on digital orthophotos from 2001 and 2005 (Figure 49-51). Our examination of these bars in the field indicates that they consist almost entirely of cobbles, gravel, and coarse sand. We interpret these features and processes as an indication that the inset dam provided a grade (or base-level) control structure that minimized bank erosion upstream of the inset dam prior to its breaching, but after Hurricane Agnes the channel incised into the reservoir fill and began to migrate rapidly.

We surveyed terrace, bank, and water edge breaklines in April 2009 (Figure 49), and compared these features to 2001 and 2005 digital orthophotos in order to digitize and classify changed areas for the intervals 2001-2005 and 2005-2009 (Figures 50, 51). Our mapping includes areas of fill terrace (millpond sediment) erosion, channel bar deposition, and channel bar erosion.

The sediment production rate determined from bank digitization and comparison with digital orthophotos was 2.39 SPU from 2001 to 2005, and 1.54 SPU from 2005 to 2009, for the 850 ft upstream of the inset dam breached in 1972. We also calculated these values separately for the areas both downstream and upstream of the inset dam, but were not able to distinguish a significant difference between the two areas. The area downstream of the inset dam has been eroding for a longer time period, since at least as early as 1938 based on the evidence of bank erosion in the 1938 air photo (see Figure 48). If the downstream Shultz grist mill dam breached in 1930, for example, then bank erosion had been occurring for 42 years at the time of Hurricane Agnes. As discussed below, however, bank erosion and sediment production rates are markedly higher during the first 10 years after dam breaching than in later years, and after several decades the rates are nearly indistinguishable. It seems, therefore, that the rates of bank erosion upstream and downstream of the inset dam are similar to one another at this time, at least in the reach studied here.

Although we have no short-term data from bank pins or other measurements, our field observations indicate that seasonal freeze-thaw is very important at Big Beaver Creek. We observed an apron of freeze-thaw debris on April 2, 2009, at the same localities where no such aprons existed on November 30, 2008 (see Figure 13).

Over a stream length of 890 feet, erosional processes removed 66,000 cubic feet of material, amounting to approximately 2,140 ± 620 tons, during the period 2001-2005 (~0.60 tons/linear ft/yr). For the period 2005-2009, erosional processes removed approximately 27,000 cubic feet of material, amounting to approximately 880 ± 260 tons (~0.24 tons/linear ft/yr).

5.2.8 Penns Creek—breached in 1968

The Penns Creek study site extends along a stream distance of ~7,960 ft upstream of the 5-ft high (plus additional 1-ft high flashboards) Spring Milling Company mill dam in the town of Spring Mills, which breached in 1968 (state inspection report with photos). A 1938 air photo shows this dam while still intact, and Penns Creek upstream of the dam has the typical characteristics of an impounded stream and slackwater, including a pond surface that widens in the downstream direction and an absence of riffles (Figure 52). A 2006 digital orthophoto shows that the stream had become incised with pronounced riffles along the channel bed (Figure 53). Lidar acquired by the Pennsylvania State Topographic and Geologic Survey in 2006 was used to estimate the volume of material removed from the millpond reservoir by channel erosion for the 7,960-foot reach upstream of the dam (Figure 54). This method yields a sediment production rate of 1.2 SPU. Note that this lidar approach to estimating sediment production yields a long-term average rate. In other words, the rate just after dam breaching might have been very high, and rates might have decreased with time. The lidar method yields an average rate since the start of sediment erosion after dam breaching.

Along a large meander bend just downstream of this breached dam and upstream of a breached saw mill dam (see Figure 55) we used bank edge digitization from the 2006 digital orthophotos and GPS bank edge surveying completed in 2009 to determine rates of bank retreat. These values were as high as several feet per year on the right bank of the meander bend.

For the 7,950 feet of stream length examined, greater than 2.2 million cubic feet of material—amounting to nearly 72,900 ± 21,000 tons—has been removed over a period 38 years (~0.24 tons/linear ft/yr). Note that this is a long-term average production rate if sediment were eroded at a constant rate since the time of dam breaching. It is likely that the rate was actually much higher during the years immediately after breaching, and has diminished with time.

5.2.9 Gunpowder Falls, Hoffman Mill Pond—breached in 1932

The Gunpowder Falls study site extends along a stream distance of ~3,980 feet upstream of the 20-ft high Hoffman paper mill dam which breached in 1932 (Slawson, 2004). A 2005 digital orthophoto and lidar show the stream to be incised with high banks (Figures 56, 57). Lidar, acquired by Baltimore County in 2005, was used to estimate the volume of material removed from the millpond reservoir by channel erosion for the 3,980-foot reach upstream of the dam. This method yields a sediment production rate of 0.97 SPU for an average bank height of 11.3 feet. Note that this lidar approach to estimating sediment production yields a long-term average rate. In other words, the rate just after dam breaching might have been very high, and rates might have decreased with time. The lidar method yields an average rate since the start of sediment erosion after dam breaching.

For the 3,980 feet of stream examined, approximately 3.2 million cubic feet of material amounting to greater than 103,000±3,000 tons, has been removed over 73 years (~0.35 tons/linear ft/yr). Note that this is a long-term average production rate if sediment were eroded at a constant rate since the time of dam breaching. It is likely that the rate was actually much higher during the years immediately after breaching, and has diminished with time.

5.2.10 White Clay Creek—breached prior to 1938

The White Clay Creek study site extends along a stream distance of ~1,100 feet upstream of a small dam which appears to have been breached by the time of a 1937 air photo (Figure 58). A 2005 digital orthophoto shows that the stream is incised for about 1,100 feet upstream of the dam and that forest growth along the riparian corridor was extensive between 1937 and 2005 (Figure 59). A small inset dam exists at the top of the photo in 2005, although it cannot be observed through the tree cover. This small dam was breached at the time of our first investigation in 2007. Up to 4 feet of laminated silt and clay (millpond sediment) exposed in the banks along the study reach overlie a very dark organic-rich wetland soil from which we have extracted hundreds of wetland seeds (primarily tussock and other sedges) and acquired radiocarbon dates that range from ~2,000 to 600 yrs BP.

Six sets of bank pins (3 at each site) were monitored from August 2008 to September 2009 yielded sediment production rates that ranged from 0.08 to 0.72 SPU. The average bank height for these sites is 3 feet. The rate at one site was low, 0.08 SPU, and the others ranged from 0.36 to 0.72 SPU.

5.3 Total nitrogen and phosphorus in stream banks

Our analyses of stream bank sediments produce average nitrogen (N) concentrations of 1300 ± 450 ppm for 1 S.D. (n = 228). These results equate to a loading of 2.6 ± 0.9 lbs N/ton of eroded sediment. The average concentration of sorbed phosphorus (P) in stream banks is 600 ± 195 ppm for 1 S.D. (n = 390). These results equate to a loading of 1.2 ± 0.3 lbs P/ton of eroded sediment.

The concentration of stream bank P generally is lower and more consistent from site to site than N, which might reflect: (1) different physical and chemical properties of P and N; (2) historical land use activities that might have caused historical nutrient enrichments within the watershed; and (3) the transport mechanisms that redistributed these "legacy nutrients" and stored them in valley bottoms.

6 Discussion of Results

6.1 Rates of bank erosion and sediment production curves

Data from the ten sites investigated in this report are examined as a group in order to evaluate the long-term trend of sediment production from a former sediment-filled millpond reservoir in response to dam breaching. As described in this report, sediment production is the channel-normalized volume of sediment produced per foot of channel height per foot of channel length per year. Sediment produced is the net volume of sediment removed from the active channel corridor. This sediment production results from channel incision at the dam breach, upstream knickpoint migration, subsequent lateral channel migration by bank erosion, and bed scour. As shown here for Hammer Creek and by previous workers for other dam breach sites, channel incision and knickpoint migration occur rapidly, typically within several days to months of breaching (e.g., Evans et al, 2000a; Doyle et al, 2003; Major et al, 2008; and O'Connor et al, 2008). As shown in this investigation, subsequent lateral channel migration and bank erosion can continue for centuries, whereas bed scour and aggradation typically are minimal.

The sediment production rates evaluated here (see Appendices C and D) encompass all of the processes of erosion of reservoir sediment over a period of years to approximately a century. Dam breach dates for the sites investigated in this report range from 1900 to 2001 AD, providing a record of about a century of fluvial response to incision and bank erosion (Figure 60). This compilation of data from ten breached millpond reservoirs reveals that stream bank sediment production rates are highest shortly after dam breaching and diminish with time, asymptotically approaching zero for at least a century.

The long-term deceleration in rate of sediment production from bank erosion shown in Figure 60 is similar to the hypothetical power function decay curve shown in Figure 8. When part of the inset dam was removed at the Hammer Creek site in 2001, for example, rates of bank erosion were as high as 19.7 SPU immediately afterward. Much of this erosion probably was associated with mass movement by bank collapse following wetting and drying of the banks as a result of short-lived, high-flow events (e.g., see Figure 15). Sediment production rates from bank erosion upstream of the Hammer Creek dam (channel cross section method) have decreased with time, from as high as 24.8 SPU during the interval of 2001-2003, to as low as ~1 SPU from 2006 to 2008 (see also Figure 18).

Three of the four methods in this investigation were used at two different sites and enable a comparison of sediment production rates by method. These two sites are Conoy Creek and Mountain Creek, and the methods used are bank edge surveying, channel cross sections, and bank pins. For both sites, the largest range in values is obtained from bank pin measurements. Bank pins are the simplest of the techniques, as they can be measured frequently and readily, but they only provide estimates for the bank on which they are located. At both the Conoy and Mountain Creek sites, channel cross sections were done at the exact same locations as the bank pins, and these sections reveal net change for the entire width of the section, including both banks. The bank pins were located on one bank within each section. The cross section data generally yield a smaller, but overlapping, range in estimates with those of bank pins. For the bank edge surveying technique, which estimates erosion along the length of channel, the sediment production rates are within the range of bank pin measurements. At Conoy Creek, bank edge surveying yields a higher rate than the range of rates from cross sections, but at Mountain Creek bank edge surveying yields a lower rate. This is likely to reflect the fact that erosion rates vary along the length of a channel, so cross sections (and bank pins) will sometimes yield higher or lower estimates than the bank edge surveying technique.

Superimposed on the dominant signal of decreasing rates of bank erosion after dam breaching is a relatively large spatial variability in measurements of short-term sediment production from bank erosion at any given site, regardless of measuring technique (see Figure 60a). One cause of this spatial variabililty might be distance from the breached dam. For the Valley Creek site, for example, we present data from Fraley et al (2009) for the stream banks upstream of a 17-ft high dam that was breached in 1920. This dam is located at a distance of ~1300 ft (400 m) on the long profile in Figure 39, and one-year erosion rates (from 2004-2005) were measured for a distance of ~10,000 ft (3,050 m) upstream of this dam (reaches 4 through 12 of Fraley et al, 2009; see Appendix D for data for each reach). Sediment production rates are as high as 1.78 SPU near the breached dam, but diminish progressively upstream to 0.13 SPU, an order of magnitude decrease over a distance of about two miles. This decrease in bank erosion rates could be a function of bank height, which diminishes upstream as the wedge of reservoir sediment thins. However, another factor could be the affect of a local base level control from an inset dam that was built within the breached reservoir ~1,200 ft (360 m) upstream of the older breached dam in the late 1920s (see Section 4.2.4 and Figures 34 and 39). Fraley et al (2009) determined that deposition occurs in the slackwater area along the channel bed upstream of this inset dam. This inset dam and associated upstream net deposition, rather than net scour, along the channel bed might be the cause of the reduced rates of bank erosion along this length of Valley Creek.

At other sites sediment production rate does not decrease upstream of the dam in as predictable a manner. At Mountain Creek, for example, the left bank of the cross section nearest the Eaton-Dikeman dam (XS-1) is located along the bedrock valley wall, which consists of quartzite bedrock and coarse colluvium at the foot of South Mountain. This bank erodes very little in comparison to the right bank, which consists of about 12 ft of historic sediment. At the next two cross sections upstream, both left and right banks consist of historic sediment, and at the fourth cross-section upstream of the dam the right bank consists of fine-grained millpond sediment banked against colluvium from the valley margin. These three cross sections yield similar rates of bank erosion that are higher than XS-1 nearest the dam.

In addition to the role of composition of bank material is the importance of processes of bank erosion. On Mountain Creek, the stream bank both up and downstream XS-1 has collapsed as a result of large mass failure events in the past several years. The stream channel has been deflected about these masses and it is very likely that the promontory formed by the bank at XS-1 will also fail in the near future. Such stochastic events have significant impact on rates of erosion measured over a period of years. We continue to survey the cross sections at the sites presented here, and it is likely that the short-term rates determined so far will shift as the measurement interval is lengthened.

Two possible causes of continued bank erosion long after dam breaching are bank collapse from wetting and drying after high-flow events and freeze-thaw during winter cold periods. All ten sites presented here have similar humid continental climatic conditions, with mean annual precipitation of about 40 inches/yr and mean annual temperature ranging from 49 to 59 °F. All sites have lowest temperatures from December through March, including temperatures that are below zero (freezing). Hydrographs throughout this region are similar as well, with low base flow during summer months and progressively higher base flow during winter months, reflecting the role of plants in water uptake during summer. We have observed needle ice in the stream banks at all sites during winter months.

Recall that Wynn et al (2008) demonstrated for similar banks in Virginia that critical shear strength of banks is lowest and bank erodibility highest during winter months as a result of freeze thaw. Wynn et al (2008) also found that critical shear strength is low and bank erodibility high during fall months as a result of later summer and fall storms that wet the banks. We have observed pronounced fracturing of dry banks, with fractures sub-parallel to bank faces, and propose that storm-induced wetting and drying of banks at the end of the summer leads to pronounced bank collapse along these pre-existing fracture planes. We observe this process frequently at multiple sites, but it is hard to quantify its importance relative to freeze-thaw. Both processes clearly play important roles in the erosion of millpond sediment.

Of importance is the fact that all banks examined here are near vertical, a function of deep channel incision into easily eroded, fine-grained, cohesive sediment. Low stream flow relative to high banks results in constant undercutting, which leads to collapse during wetting-drying events. Near-vertical banks also are prone to freeze-thaw because they are exposed to lower air temperatures during the winter and night time. In addition, channel flow at the base of near vertical banks can sweep away material shed by collapse or freeze-thaw processes, resetting the bank for future erosion.

Given this sequence of interacting processes, it is possible that bank erosion will continue at a relatively constant rate long after dam breaching. This might be the cause of the long deceleration in bank erosion rates shown in Figure 60. Excluding the data from the most recently breached dam at Hammer Creek, all other sites have overlapping rates of bank erosion that generally range from zero (at a spot) to 3.4 SPU. From 40 to 100 years after dam breaching, the background rate of sediment production determined in this report is about 0.6 to 1 SPU.

This range of values is similar to that obtained by Schenk and Hupp (2009) from their analysis of bank pins at five sites along the Little Conestoga Creek, a tributary to the Conestoga River, over a three-year period from July 2004 to June 2007. The Schenk and Hupp (2009) estimates of bank erosion are for a single bank, not the entire channel width, so they cannot be compared directly to all of our sediment production rate estimates. To first order, however, it is likely that the Schenk and Hupp (2009) values would be about half the estimate of channel-normalized sediment production for the entire stream corridor. Schenk and Hupp obtained estimates of bank erosion that range from ~0.1 to 0.5 ft/yr. Doubling these values results in 0.2 to 1 ft/yr, which overlaps the range of 0.6 to 1 SPU (essentially ft/yr) reported here.

6.2 Modeling dam breaches and changing rates of sediment production

Assuming that each millpond reservoir flushes sediment at a rate that decays with time after breach date, as in the power function presented in Figure 60b, it is possible to simulate sediment production from a channel network that forms when members of a population of dams throughout a watershed breach randomly over time. We constructed a computer program to track the age of each dam within the population of dams after its breach. Each new dam breach generates a channel that adds length rapidly at first and then less rapidly with time, up to a maximum of 10,000 feet ($l_a = 2500 \times a^{0.4}, where\ a = age$). This distance of channel incision includes that which can develop along the main stem or along both the main stem and adjacent tributaries that incise in response to the base-level drop on the incising main stem. A sediment production rate is applied to this network of new stream channel length from the power function determined for time since dam breach (age) shown in Figure 60b:

$$P_a = 14.82 \times a^{-0.698}\ [Eq. 5]$$

where:

$$a = age, or\ time\ elapsed\ post\ dam\ breach$$

As each aging dam breaches in the computer simulation, the power function is used to calculate a simulated sediment production rate with time.

In addition to channel length, sediment production is a function of bank height. To determine a reasonable estimate for bank height, we sampled lidar elevation data from the terrace (or top of bank) above the water surface at 20-meter intervals along the main stem of Little Conestoga Cree k and the West Branch of Little Conestoga Creek (Figure 61). The histogram of bank height versus frequency of occurrence created from this sampling indicates that mean bank height is 5.2 ft. We use this value in the simulation.

In essence, a dam breach leads to channel formation and a rate of sediment production that decays with time after dam breaching. The rate of sediment production is determined from the power function in

Figure 60, and applied to the channel length of up to 10,000 ft for a bank height of 5.2 ft. The product of sediment production rate, channel length, and bank height is an estimate of volume of sediment produced with time, in cubic-feet per yr.

The production from a channel network associated with a single breach at a given age, $P_{b,a}$, is calculated as follows:

$$P_{b,a} = P_a \times l_a \times h \, [Eq. 6]$$

where:

$$P_a = unit\ productinon\ at\ a\ given\ age, a$$
$$l_a = channel\ length\ at\ a\ give\ age, a$$
$$h = terrace\ height$$

The production from the channel network associated with the population of breached dams at a given time is calculated as follows:

$$P_t = \sum_{b=1}^{n} P_{b,a} [Eq. 7]$$

In the simplest model run, we simulate the simultaneous breaching of 160 dams in the year 1900 (Figure 62). The channel network length increases rapidly, peaking within about 30 years after dam breaching. All of the breached reservoirs produce sediment and this rate of production declines with time, rapidly at first and more slowly thereafter. Immediately after dam breaching, 30 million cubic-feet of sediment per year is produced. A century after these dams breached, sediment production is about 5 million cubic-feet per year. After 300 years, sediment production is about 2.5 million cubic-feet per year.

A more realistic scenario simulates a population of dams that breach randomly over a period of time (Figure 63). Here, we simulate the breaching of 151 of 160 dams over a 300-year period. The annual probability of breaching is 1%, but greater values of annual probability are used for the years 1933, 1955, 1972, and 2004, when large storms occurred in the mid-Atlantic region. With time, fewer dams remain to be breached. However, dams that already have breached have added to the cumulative effect of greater channel network length producing sediment. Although sediment production from each individual breached reservoir diminishes with time, the cumulative amount of sediment produced from the growing number of breached reservoirs increases with time during the first century and remains high for at least two more centuries. About 300 years after the start of the simulation, sediment production is 3 million cubic-ft/yr, or ~97,000 tons per year (based on average bank sediment bulk density value of 1.04 g/cm^3, or 65 lbs/ft^3, from Schenk and Hupp, 2009).

The model results illustrate several points about sediment production from an evolving channel network formed by dam breaching:

1) sediment loads increase over time as the number of breached dams increases
2) sediment loads are likely to remain high for two reasons:

a) not all dams are breached at the same time, so new channel continues to be added
b) even though unit production declines rapidly at first, it becomes asymptotic and establishes a nearly constant background level
c) the sediment production is applied to abnormally high banks over long lengths of channel (which are generated from low-head dam breach at typical gradients of 0.002); in other words, sediment available for erosion is nearly unlimited within the time period of the simulation.

These processes and rates are characteristic of the current evolutionary trajectory of dam-impacted streams and are not characteristic of the pre-settlement wetland condition that existed throughout the mid-Atlantic region (Walter and Merritts, 2008; Voli et al, 2009; and Merritts et al, in preparation). Prior to European settlement, widespread land-clearing, and mill damming for water power, spring-fed mid-Atlantic streams were characterized by very low energy processes and widespread formation of wet meadows and other wetland ecosystems. The springs and wetlands were submerged and then buried under vast amounts of historic sediment as a result of mill damming.

6.3 Implications for sediment and nutrient loads to streams from stream bank erosion of legacy sediment

Here we evaluate the sediment production data and modeling results in terms of implications for sediment and nutrient loading to streams from stream bank erosion. We use the Conestoga watershed for this analysis. The Conestoga River drainage area is about 474 square miles above a USGS stream gage station that monitors suspended sediment load near the river mouth. Stream length in the watershed is about 638 miles, as measured from USGS National Hydrography Dataset. The long-term average load of suspended sediment at the gage is ~184,000 tons/year, or 390 tons/square mile. We compare these values to the estimates from our model simulation for sediment loading from breached mill dams.

In our simulation (Figure 63), 151 of 160 dams breached between 1900 and 2200, but the majority were breached by 2020. Township-scale maps from the 19th c. indicate that about 150-160 milldams existed throughout the Conestoga watershed. Total length of channels affected by dam breaching is 284 miles, or 45% of the length of channels in the Conestoga watershed. Recall that the mean bank height used in the simulation is for two tributaries in the Conestoga watershed. In the simulation, total sediment production from the years 2000 to 2200 declines from 6 million ft^3/yr (year 2000) to 3 million ft^3/yr (year 2200), or 195,000 to 97,000 tons/yr (based on average bank sediment bulk density value of 1.04 g/cm^3, or 65 lbs/ft^3). These model results for 2000 are comparable to the annual average load measured at the USGS gage station at the mouth of the Conestoga River.

This comparison between actual measured values of suspended sediment and loads predicted from a simulation of breached dams suggests that a large portion of suspended sediment in the Conestoga River could be from bank erosion. Nevertheless, several sources of uncertainty must be considered:

1) suspended load estimates at gage stations are based on assumptions about sediment load during low flow and integration of data throughout hydrograph records for high flow; these estimates have some error and uncertainty;

2) some of the sediment from bank erosion might be trapped and stored before reaching the mouth of the Conestoga River, and some of this stored sediment is remobilized with time (e.g., as bars themselves are eroded), so the estimate of sediment production from bank erosion might be higher than the amount measured at a gage station; and
3) perhaps less than 45% of the channel length of the Conestoga River experiences bank erosion.

Based on our field mapping and observations, it is likely that at least 45% of the stream banks along the Conestoga River and its tributaries experience bank erosion. Furthermore, our ongoing work at several sites indicates that some fine sediment is trapped in some parts of the stream corridor in bars of gravel and sand. Schenk and Hupp (2009) noted some accumulation of fine sediment at clay pads that they installed to monitor deposition at the five sites where they studied bank erosion. We note from analysis of lidar data that deposition is more likely to occur downstream of breached dams, where bank heights are lower than upstream of dams, particularly where such spots are upstream of bridges and other base-level control structures or constrictions (as at site 4 in Schenk and Hupp, 2009). It also is more likely to occur where roads cross stream channels and cause backwater effects, as for example where the Little Conestoga Creek is crossed by Harrisburg Pike (Figure 64).

It is very unlikely that the incised channel corridor that typifies the majority of the Conestoga watershed has sufficient storage space for as much sediment as is eroded from historic reservoir sediment stored along its high banks. Schenk and Hupp (2009) determined that 5,634 megagrams (6,210 tons) of sediment is eroded from 28 kilometers (17.4 miles) of the Little Conestoga watershed each year by bank erosion (net erosion after accounting for minor floodplain deposition). This is equivalent to ~358 tons per mile of channel length. Extrapolated to the entire length of the Conestoga River drainage network (638 miles), the resultant load would be ~227,800 tons of sediment. This is equivalent to about 480 tons per square mile of watershed area (watershed area is 474 square miles). This value is the same as that obtained from our model results for the time period of >100 years after dam breaching began (see Figure 63).

Finally, we compare these estimates of bank erosion to reservoir sedimentation studies in the region. Bathymetric surveys of reservoirs indicate that yields for the Gunpowder Falls for the period of 1913 to 1997 range from 253 to 1,367 tons per square mile (Dendy and Champion, 1978; Ortt et al., 2000). The estimate of 480 tons per square mile for the Conestoga based on our modeling of bank erosion from milldam breaching is within this range of values.

Bank erosion is only one of several potential sources of sediment to streams. Other important sources include upland soil erosion from construction sites and agricultural lands. The key difference between these sources and that of bank erosion of historic sediment from a breached milldam is location and potential for sediment transport. Freeze-thaw, for example, produces disaggregated fine sediment that is dropped from the near-vertical stream bank to the toe of the bank, adjacent to the stream channel. Bank collapse and other types of failure drop masses of sediment of various sizes into the stream channel and along its margins. Fine sediment from these direct channel margin sources is more likely than any other sediment in a watershed to be transported downstream.

The results presented here indicate that total N and sorbed P concentrations in stream bank sediments are relatively high and, given the measured bank erosion rates, could represent a significant proportion of nutrients entering streams in the Chesapeake Bay watershed of Pennsylvania. Our computer simulation of stream corridor erosion based on the power function for sediment production (see Figures 60-63) yields an estimate of ~ 4 million cubic-ft/yr, or ~162,500 tons of sediment production per year for a watershed similar to the Conestoga, with ~151 breached milldams (see Figure 63). For the mean values of N and P determined here, the predicted loads associated with eroded stream corridor sediment are ~200 and 100 tons of N and P, respectively.

6.4 Estimates of original and remaining volumes of sediment in millpond reservoirs

Each millpond contains a volume and mass of historic sediment that is a function of dam height, valley gradient, and valley bottom topography underlying the millpond. Long narrow valleys, for example, will trap less sediment than wide valleys. Valley-margin colluvium that has accumulated at the base of hillslopes over long periods of geologic time reduces the storage volume of valleys. A simple means of getting a rough estimate of reservoir sediment in a millpond is to estimate volume from the product of pond length, width, and depth (see Table below). The total volume of a “slab” of sediment in the reservoir can be reduced by some amount to account for the variable topography underlying the millpond sediment. Here, we assume that at least 30% of the valley bottom is not available for storage of millpond sediment. For the ten millpond sites investigated in this report, the amount of sediment predicted to be stored in the millponds varies from ~25,000 to 368,000 tons (assuming a bulk density of 1.04 g/cm^3).

	Pond (reservoir sedimentation)				
Stream Site	**Area Covered (sq-ft)**	**Max Depth (ft)**	**Slab Volume (cu-ft)**	**70% Slab Volume (cu-ft)**	**70% Slab Tonnage (tons)**
Big Beaver Creek	250,000	5	1,250,000	875,000	28,400
Big Spring Run	250,000	4.5	1,125,000	787,500	25.560
Conoy Creek	250,000	5.9	1,475,000	1,032,500	33,520
Gunpowder Falls	550,000	9	4,950,000	3,465,000	112,480
Hammer Creek	250,000	4.5	1,125,000	787,500	25,560
Little Conestoga Creek West Branch	800,000	12.8	10,240,000	7,168,000	232,690
Mountain Creek	1,400,000	9	12,600,000	8,820,000	286,320
Penns Creek	1,800,000	9	16,200,000	11,340,000	368,120
Valley Creek	500,000	13.1	6,550,000	4,585,000	148,840
White Clay Creek	850,000	3	2,550,000	1,785,000	57,950

It also is possible to estimate the total volume and mass of sediment eroded from the millpond along the incised stream corridor (see table below). As in the estimate of total reservoir sediment, we use the product of channel length, average width, and depth to get volume, and then convert to tons using an estimate of bulk density (1.04 g/cm^3). For the ten sites studied here, the estimate of volume of sediment (total) eroded from the stream corridor varies from ~5000 to 103,000 tons. Those sites where the dam breach occurred many decades ago generally have greater amounts of sediment eroded from the reservoir.

	Incised Stream Corridor (eroded volume)			
Stream Site	**Avg Width (ft)**	**Length (ft)**	**Volume (cu-ft)**	**Channel Tonnage (tons)**
Big Beaver Creek	55	890	244,750	7,950
Big Spring Run	12	3,200	172,800	5,610
Conoy Creek	35	1,788	369,200	11,990
Gunpowder Falls		3,977	3,182,700	103,320
Hammer Creek	30	1,500	202,500	6,570
Little Conestoga Creek West Branch		8,098	3,310,400	97,490
Mountain Creek		3,880	1,349,900	43,820
Penns Creek		7,956	2,246,400	72,920
Valley Creek	55	3,800	2,737,900	88,880
White Clay Creek	15	3,500	157,500	5,110

From the difference between these two estimates, it is possible to calculate the percent of reservoir sediment that remains. These values are shown in the table below, and indicate that more than half of the reservoir sediment remains in all but two of the sites investigated here. For these two sites, Gunpowder Falls at the Hoffman milldam and Valley Creek at a dam near its mouth, only 8 and 40%, respectively, of the original reservoir sediment remains. Both dams breached in the early 20th c., and both have relatively narrow valleys, so these two factors appear to have resulted in relatively high proportions of sediment removal since breaching. These estimates are approximate, and can only be verified with a substantial amount of field work and geophysical work in order to determine the geometry of the substrate beneath the millpond sediment.

	Sediment Remaining from 70% Slab			
Stream Site	**Volume (cu-ft)**	**Volume (cu-yd)**	**Remaining Tonnage (tons)**	**Percent of initial (%)**
Big Beaver Creek	630,250	23,300	20,460	72
Big Spring Run	614,700	22,800	19,960	78
Conoy Creek	663,278	24,600	21,530	64
Gunpowder Falls	282,259	10,500	9,160	8
Hammer Creek	585,000	21,700	18,990	74
Little Conestoga Creek West Branch	3,857,585	142,900	125,230	54
Mountain Creek	7,470,120	276,700	242,500	85
Penns Creek	9,093,589	336,800	295,200	80
Valley Creek	1,847,100	68,400	59,960	40
White Clay Creek	1,627,500	60,300	52,830	91

7 Conclusions

This report provides evidence that a previously little recognized process—stream corridor erosion from breached millpond reservoirs—is a substantial source of suspended (i.e., fine grained) sediments and nutrients within the Chesapeake Bay watershed. Furthermore, the processes and rates of stream bank erosion documented here are not directly related to modern land use activity (e.g., storm water runoff from urban development), but rather to a series of land use activities that began as much as several centuries ago. These prior activities transformed valley bottom landscapes, first through reservoir sediment accumulation following milldam construction, then by stream bed incision and bank erosion following milldam breaching. Assumptions and models regarding Chesapeake Bay water quality focus largely on modern land use—particularly agriculture and construction—as the dominant sources of high suspended sediment and nutrient loads in the majority of the region's waterways. This work documents, however, that historic sediment and associated nutrients eroded from the stream corridor upstream of breached millponds are also an important component of the total load of each in modern streams.

Erosion data collected for ten breached millpond reservoirs reveals that stream bank sediment production rates are highest shortly after dam breaching and diminish with time, asymptotically approaching zero for at least a century. A best-fit power function for sediment production rate versus time since dam breach is as follows:

$$P_a = 14.82 \times a^{-0.698}$$

with $R^2 = 0.70$, where:

$$P_a = sediment\ production\ rate\ in\ SPU\ at\ age, a$$

$$a = age, or\ time\ elapsed\ post\ dam\ breach\ in\ years$$

and SPU represents a normalized sediment production rate in cubic feet of sediment per linear foot of channel length per foot of bank height.

This power function can be used to predict sediment production by stream corridor erosion in an incised millpond for a given length of stream channel at a given time period after dam breaching. For example, sediment production ten years after dam breaching is 2.97 SPU. For a bank height of 10 ft, the annual volume of sediment produced along one foot of channel length would be 10 ft × 1 ft × 2.97 ft^3/ft/ft/yr, or 29.7 ft^3/yr. This is equivalent to 0.97 tons per ft of channel length per year. For 100 ft of channel length, the annual amount of sediment predicted to be eroded from the stream corridor is 100 ft × 0.97 tons/ft = 97 tons. If the bank height were only half this amount, for example, then the estimates of sediment production would be halved. Clearly, bank height is an important parameter. This investigation shows that bank height is a function of milldam height and distance upstream of the dam, with highest banks nearest to the dam.

From 40 to 100 years after dam breaching, the background rate of sediment production determined in this report is about 0.6 to 1 SPU. Two possible causes of continued bank erosion long after dam breaching are bank collapse from wetting and drying after high-flow events and freeze-thaw during winter cold periods. Freeze-thaw is documented here as a very important process in bank erosion of fine-grained millpond sediment. All banks examined here are near vertical, a function of deep channel incision into easily eroded, fine-grained, cohesive sediment. Low stream flow relative to high banks results in constant undercutting, which leads to collapse during wetting-drying events. Near-vertical banks also are prone to freeze-thaw because they are exposed to lower air temperatures during the winter and night time. In addition, channel flow at the base of near vertical banks can sweep away material shed by collapse or freeze-thaw processes, resetting the bank for future erosion. Given the suite of interacting bank erosion processes described here, it is possible that bank erosion will continue at a slowly diminishing rate long after dam breaching.

The range of estimates of sediment production presented here is similar to that obtained by Schenk and Hupp (2009) from their analysis of bank pins at five sites along the Little Conestoga Creek, a tributary to the Conestoga River, over a three-year period from July 2004 to June 2007. The Schenk and Hupp (2009) estimates of bank erosion are for a single bank, not the entire channel width, and are not normalized with respect to bank height, so they cannot be compared directly to our sediment production rate estimates. Furthermore, our estimates are based on examination of millpond reaches rather than spot locations. For the five sites monitored, Schenk and Hupp (2009) obtained estimates of bank erosion that range from ~0.1 to 0.5 ft/yr. Multiplying a mean bank height of 5.2 ft for the Little Conestoga Creek (determined with lidar) by bank erosion rates of 0.1 to 0.5 ft/yr results in estimated SPU values of 0.5 to 2.7 ft^3/ft/ft/yr. These estimates overlap the range of 0.6 to 1 ft^3/ft/ft/yr (SPU, or essentially ft/yr) reported here.

We simulate the breaching of 151 of 160 dams over a 300-year period, similar to the number of milldams in the Conestoga watershed of Lancaster County. From 110 to 150 years after the start of the simulation, for model years 2010-2050, sediment production is about 4 million cubic-ft/yr, or ~162,500 tons per year. These model results are comparable to the annual average suspended sediment load measured at the USGS gage station at the mouth of the Conestoga River.

Total N and sorbed P concentrations in stream bank sediments are relatively high and, given the measured bank erosion rates, could represent a significant proportion of nutrients entering streams in the Chesapeake Bay watershed of Pennsylvania. Our computer simulation of stream corridor erosion based on the power function for sediment production (see Figures 60-63) yields an estimate of ~ 4 million cubic-ft/yr, or ~162,500 tons of sediment production per year for a watershed similar to the Conestoga, with ~151 breached milldams (see Figure 63). For the mean values of N and P determined here, the predicted loads associated with eroded stream corridor sediment are ~200 and 100 tons of N and P, respectively. Thus, the P load from bank erosion in the Conestoga watershed alone accounts for ~3 % of the 6.5 million lb reduction needed by the 2010 target date for the Chesapeake Bay Agreement, despite the fact that the Conestoga watershed comprises just 0.76% of the area of the Chesapeake Bay watershed.

For the ten millpond sites investigated in this report, the amount of sediment predicted to be stored in the millponds varies from ~25,000 to 368,000 tons. The estimate of volume of sediment (total) eroded from the stream corridor varies from ~5000 to 103,000 tons. Those sites where the dam breach occurred many decades ago generally have greater amounts of sediment eroded from the reservoir. More than half of the reservoir sediment remains in all but two of the sites investigated here. For the two exceptions, the dams breached in the early 20th c. and valley shape is long and narrow. These two factors appear to have resulted in relatively high proportions of sediment removal since breaching.

Clearly the amounts of sediment produced by stream channel erosion are large in absolute terms and, in relative terms, are likely to be similar to or greater than amounts from other major sources such as agriculture. Channel erosion is likely to continue to contribute significantly to sediment and nutrient loads over a centuries-long timeframe for four reasons:

5. dams were once regionally pervasive, and many have breached, but not all, leading to regional base-level fall;
6. dam breaching and incision have led to the formation of an entirely new regional eroding channel network;
7. production from breached reservoirs does not decline to zero over a century-long period of study; and
8. the sediment produced from the network consists largely of soil that was mobilized from the uplands and stored in the valley bottoms.

This report provides an assessment of the current trajectory, and likely future trajectory, of these incised channel networks. It is, however, important to recognize that, prior to disturbance, valley bottoms were not characterized by regionally pervasive eroding channel networks. Valley bottoms, rather, were characterized by regionally pervasive seeps, springs, and wetlands. Those features that were characterized by long-term stability, up until burial, are now being eroded. Strategies for reducing nutrient and sediment loads to the Chesapeake Bay must acknowledge this change in trajectory in order to have an impact.

8 Works Cited

Arulanandan, K., Gillogley, E. & Tully, R., 1980. *Development of a Quantitative Method to Predict Critical Shear Stress and Rate of Erosion of Natural Undisturbed Cohesive Soils*, Vicksburg, MS: U.S. Army Engineers, Waterways Experiment Station.

Bridgens, H., 1858. Atlas of Cumberland County, Pennsylvania.

Bridgens, H., 1864. Bridgen's Atlas of Lancaster County, Pennsylvania, from actual surveys by H.F. Bridgens and assistant.

Brune, G., 1953. Trapping efficiency of reservoirs. *Transactions American Geophysical Union*, 34(3), 407-418.

Buffington, J.M. & Montgomery, D.R., 1997. A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers. *Water Resources Research*, 33(8), 1993–2030.

Cantelli, A. et al., 2007. Numerical model linking bed and bank evolution of incisional channel created by dam removal. *Water Resources Research*, 43(W07436). Available at: http://www.agu.org/pubs/crossref/2007/2006WR005621.shtml [Accessed September 21, 2009].

Cantelli, A., Paola, C. & Parker, G., 2004. Experiments on upstream-migrating erosional narrowing and widening of an incisional channel caused by dam removal. *Water Resources Research*, 40, W03304.

Chow, V.T., 1959. *Open Channel Hydraulics*, New York: McGraw-Hill.

Couper, P.R. & Maddock, I.P., 2001. Subaerial river bank erosion processes and their interaction with other bank erosion mechanisms on the River Arrow, Warwickshire, UK. *Earth Surface Processes and Landforms*, 26(6), 631-646.

Darby, S.E. & Thorne, C.R., 1996. Development and Testing of Riverbank-Stability Analysis. *Journal of Hydraulic Engineering*, 122(8), 443-454.

Dendy, F. & Champion, W., 1978. *Sediment deposition in U.S. reservoirs : summary of data reported through 1975*, Washington: Agricultural Research Service, U.S. Dept. of Agriculture.

Downs, A.E., 1890. *Valley Forge, Pa. 1890*, Available at: http://hdl.loc.gov/loc.gmd/g3824v.pm008670 [Accessed December 23, 2009].

Downs, J.B., 2004. *Mills of Augusta County*, Staunton, VA: Lot's Wife Publishing.

Doyle, M.W., Stanley, E.H. & Harbor, J.M., 2003. Channel adjustments following two dam removals in Wisconsin. *Water Resources Research*, 39(1), 1011.

Evans, J. et al., 2000. Sediment yields controlled by intrabasinal storage and sediment conveyance over the interval 1842-1994: Chagrin river, northeast Ohio, U.S.A. *Journal of Soil and Water Conservation*, 55(3), 264-270.

Evans, J.E. et al., 2000. Lessons from a Dam Failure. *The Ohio Journal of Science*, 100(5), 121-131.

Fraley, L.M., 2006. *Interaction Between Channel Morphology and Spatial Patterns of Sediment Storage and Remobilization in Valley Creek, Valley Forge National Historical Park, Pennsylvania*. M.S. Thesis. University of Maryland Baltimore County.

Fraley, L.M., Miller, A.J. & Welty, C., 2007. *Characterization of Sediment Storage and Remobilization in Valley Forge National Historical Park*, Philadelphia, PA: U.S. Department of the Interior, National Parks Service, Northeast Region. Available at: http://www.nps.gov/nero/science/FINAL/Vafo_sediment/VAFO_sediment.htm [Accessed December 22, 2009].

Fraley, L.M., Miller, A.J. & Welty, C., 2009. Contribution of In-Channel Processes to Sediment Yield of an Urbanizing Watershed. *JAWRA Journal of the American Water Resources Association*, 45(3), 748-766.

Gellis, Allen C., William S. L. Banks, Michael J. Langland, and Sarah K. Martucci. 2004. *Summary of suspended-sediment data for streams draining the Chesapeake Bay Watershed, water years 1952-2002*. Scientific Investigations Report. Washington D.C.: U.S. Department of the Interior, U.S. Geological Survey. http://pubs.er.usgs.gov/usgspubs/sir/sir20045056.

Gellis, Allen C., Cliff R. Hupp, Milan J. Pavich, Jurate M. Landwehr, Willam S. L. Banks, Bernard E. Hubbard, Michael J. Langland, Jerry C. Ritchie, and Joanna M. Reuter. 2009. *Sources, Transport, and Storage of Sediment at Selected Sites in the Chesapeake Bay Watershed*. Scientific Investigations Report. Reston, VA: U.S. Department of the Interior, U.S. Geological Survey. http://pubs.er.usgs.gov/usgspubs/sir/sir20085186.

Gilbert, G.K., 1917. *Hydraulic-mining debris in the Sierra Nevada*, Washington D.C.: U.S. Department of the Interior, U.S. Geological Survey. Available at: http://pubs.er.usgs.gov/usgspubs/pp/pp105.

Gottschalk, L.C., 1964. Reservoir Sedimentation. In V. T. Chow, ed. *Handbook of Applied Hydrology*. New York: McGraw Hill, pp. 1-33.

Hanson, G. & Cook, K., 2004. Determination of Material Rate Parameters for Headcut Migration of Compacted Earthen Materials. In *Dam safety 2004 : the annual conference of the Association of State Dam Safety Officials : proceedings, September 26-30, 2004, Pointe South Mountain Resort, Phoenix, Arizona.* Lexington, KY: Association State Dam Safety Officials. Available at: http://seprl.ars.usda.gov/research/publications/publications.htm?seq_no_115=168159.

Hooke, J., 1979. An analysis of the processes of river bank erosion. *Journal of Hydrology*, 42(1-2), 39-62.

Howard, A.D., 1982. Equilibrium and time scales in geomorphology: Application to sand-bed alluvial streams. *Earth Surface Processes and Landforms*, 7(4), 303-325.

Julian, J.P. & Torres, R., 2006. Hydraulic erosion of cohesive riverbanks. *Geomorphology*, 76(1-2), 193-206.

Keefer, H.A., 1934. Recollections, Historical and Otherwise, Relating to Old Pine Grove Furnace. *Potomac Appalachian Trail Club Bulletin*. Available at: http://www.patc.us/history/archive/pine_grv.html [Accessed November 5, 2009].

Kirk, W., 1883. Breou's Official Series of Farm Maps, Chester County. Available at: http://ancestortracks.com/Chester_resources.html [Accessed December 23, 2009].

Langendoen, E.J. & Simon, A., 2000. *Stream channel evolution of Little Salt Creek and North Branch West Papillion Creek, eastern Nebraska*, Oxford, MS: National Sedimentation Laboratory. Available at: http://www.ars.usda.gov/SP2UserFiles/Place/64080510/AGNPS/Concepts/Doc/Nebraska.pdf [Accessed November 5, 2009].

Lawler, D.M., 1992. Process dominance in bank erosion systems. In P. Carling & G. E. Petts, eds. *Lowland Floodplain Rivers: Geomorphical Perspectives*. British Geomorphological Research Group Sysmposia Series. Chichester: Wiley, pp. 117-159.

Lawler, D.M., 1986. River Bank Erosion and the Influence of Frost: A Statistical Examination. *Transactions of the Institute of British Geographers*, 11(2), 227-242.

Lawler, D.M., 1995. The impact of scale on the processes of channel-side sediment supply: a conceptual model. In W. R. Osterkamp, ed. *Effects of Scale on Interpretation and Management of Sediment and Water Quality*. Boulder CO: International Association of Hydrological Sciences, pp. 175-184. Available at: http://iahs.info/redbooks/a226/iahs_226_0175.pdf [Accessed November 17, 2009].

Lawler, D.M., 1993. The measurement of river bank erosion and lateral channel change: A review. *Earth Surface Processes and Landforms*, 18(9), 777-821.

Lawler, D.M., Thorne, C.R. & Hooke, J.M., 1997. Bank erosion and instability. In C. R. Thorne, R. D. Hey, & M. D. Newson, eds. *Applied Fluvial Geomorphology for River Engineering and Management*. Chichester: Wiley, pp. 137-172.

Major, J.J. et al., 2008. Initial Fluvial Response to the Removal of Oregon's Marmot Dam. *Eos, Transactions American Geophysical Union*, 89(27), 241-252.

Martenet, S.J., 1865. Martenet and Bond's map of Montgomery County, Maryland. Available at: http://hdl.loc.gov/loc.gmd/g3843m.la000299.

Nichols, B., 1873. Atlas Blair and Huntingdon Counties, Pennsylvania.

Nichols, B., 1874. Atlas of Centre County, Pennsylvania.

Nichols, B., 1876. Atlas of York County, Pennsylvania.

O'Connor, J., Major, J. & Grant, G., 2008. The Dams Come Down: Unchaining U.S. Rivers. *Geotimes*, 53(3), 22-28.

Ortt, R.A.J. et al., 2000. *Bathymetric Survey and Sedimentation Analysis of Loch Raven and Prettyboy Reservoirs*, Baltimore, MD: Maryland Geological Survey. Available at: http://www.mgs.md.gov/coastal/pub/FR99-4.pdf [Accessed August 26, 2008].

Osman, A.M. & Thorne, C.R., 1988. Riverbank Stability Analysis. I: Theory. *Journal of Hydraulic Engineering*, 114(2), 134-150.

Painter, S.M. & Bowen, J.S., 1847. Map of Chester County, Pennsylvania.

Petts, G.E., 1984. *Impounded rivers: perspectives for ecological management*, New York: Wiley.

Pizzuto, J. & O'Neal, M., 2009. Increased mid-twentieth century riverbank erosion rates related to the demise of mill dams, South River, Virginia. *Geology*, 37(1), 19-22.

Schenk, E.R. & Hupp, C.R., 2009. Legacy Effects of Colonial Millponds on Floodplain Sedimentation, Bank Erosion, and Channel Morphology, Mid-Atlantic, USA. *Journal of the American Water Resources Association*, 1-10.

Schumm, S.A., Harvey, M.D. & Watson, C.C., 1984. *Incised Channels: Morphology, Dynamics, and Control*, Highlands Ranch, CO: Water Resources Publications.

Sidney, J., 1857. Map of the city and county of Baltimore, Maryland. Available at: http://hdl.loc.gov/loc.gmd/g3843b.la000283.

Simon, A. & Darby, S., 1997. Disturbance, Channel Evolution and Erosion Rates: Hotophia Creek, Mississippi. In *Management of Landscapes Disturbed by Channel Incision*. Oxford, MS: University of Mississippi, pp. 476-481.

Simon, A. et al., 2000. Bank and near-bank processes in an incised channel. *Geomorphology*, 35(3-4), 193-217.

Slawson, D., 2004. *Physical Habitat Recovery in a Former Dam Impoundment*. Ph. D. Pennsylvania State University. Available at: http://etda.libraries.psu.edu/theses/approved/WorldWideIndex/ETD-503/index.html.

United States, 1840. *Sixth Census, or, Enumeration of the Inhabitants of the United States: As Corrected at the Department of State in 1840*, United States, Bureau of the Census. Available at: http://www.census.gov/prod/www/abs/decennial/1840.htm.

United States, 1880. *Tenth Census of the United States, 1880*, Washington, DC: United States, Census Office. Available at: http://www.census.gov/prod/www/abs/decennial/1880.htm.

United States, 1870. *The Statistics of the Wealth and Industry of the United States: Embracing the Tables of Wealth, Taxation, and Public Indebtedness, of Agriculture, Manufactures, Mining, and the Fisheries, with Which Are Reproduced, from the Volume on Population, the Major Tables of Occupations*, Washington, DC: United States, Bureau of the Census. Available at: http://www.census.gov/prod/www/abs/decennial/1870.htm.

Verstraeten, G. & Poesen, J., 2000. Estimating trap efficiency of small reservoirs and ponds: methods and implications for the assessment of sediment yield. *Progress in Physical Geography*, 24(2), 219-251.

Voli, M. et al., 2009. Preliminary Reconstruction of a Pre-European Settlement Valley Bottom Wetland, Southeastern Pennsylvania. *Water Resources Impact*, 11(5), 11-12.

Walter, R.C. & Merritts, D.J., 2008. Natural Streams and the Legacy of Water-Powered Mills. *Science*, 319(5861), 299-304.

Wolman, M.G., 1959. Factors influencing erosion of a cohesive river bank. *American Journal of Science*, 257(3), 204-216.

Wynn, T.M. & Mostaghimi, S., 2006. Effects of riparian vegetation on stream bank subaerial processes in southwestern Virginia, USA. *Earth Surface Processes and Landforms*, 31(4), 399-413.

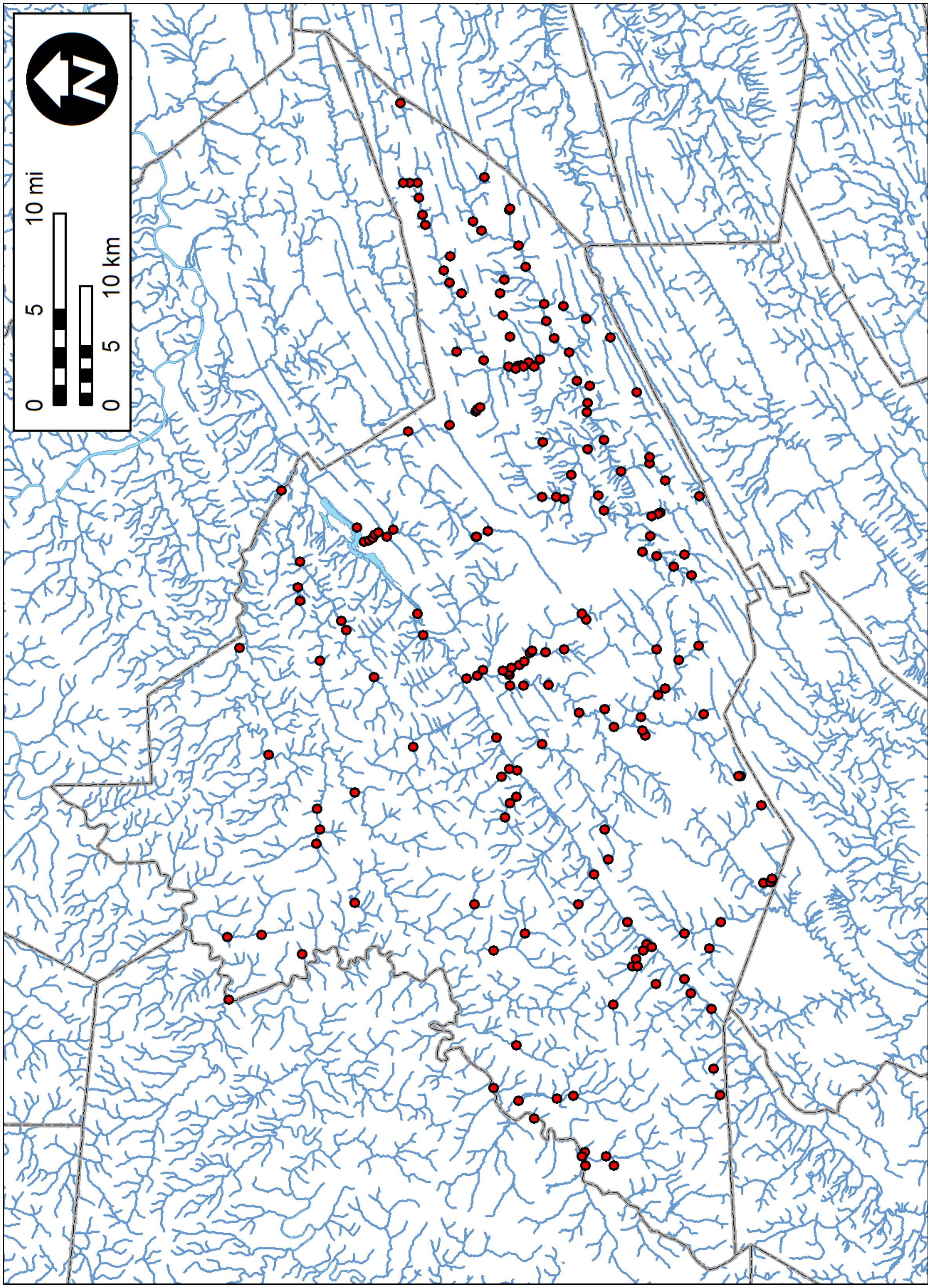
Wynn, T., Henderson, M. & Vaughan, D., 2008. Changes in streambank erodibility and critical shear stress due to subaerial processes along a headwater stream, southwestern Virginia, USA. *Geomorphology*, 97(3-4), 260-273.

Appendices

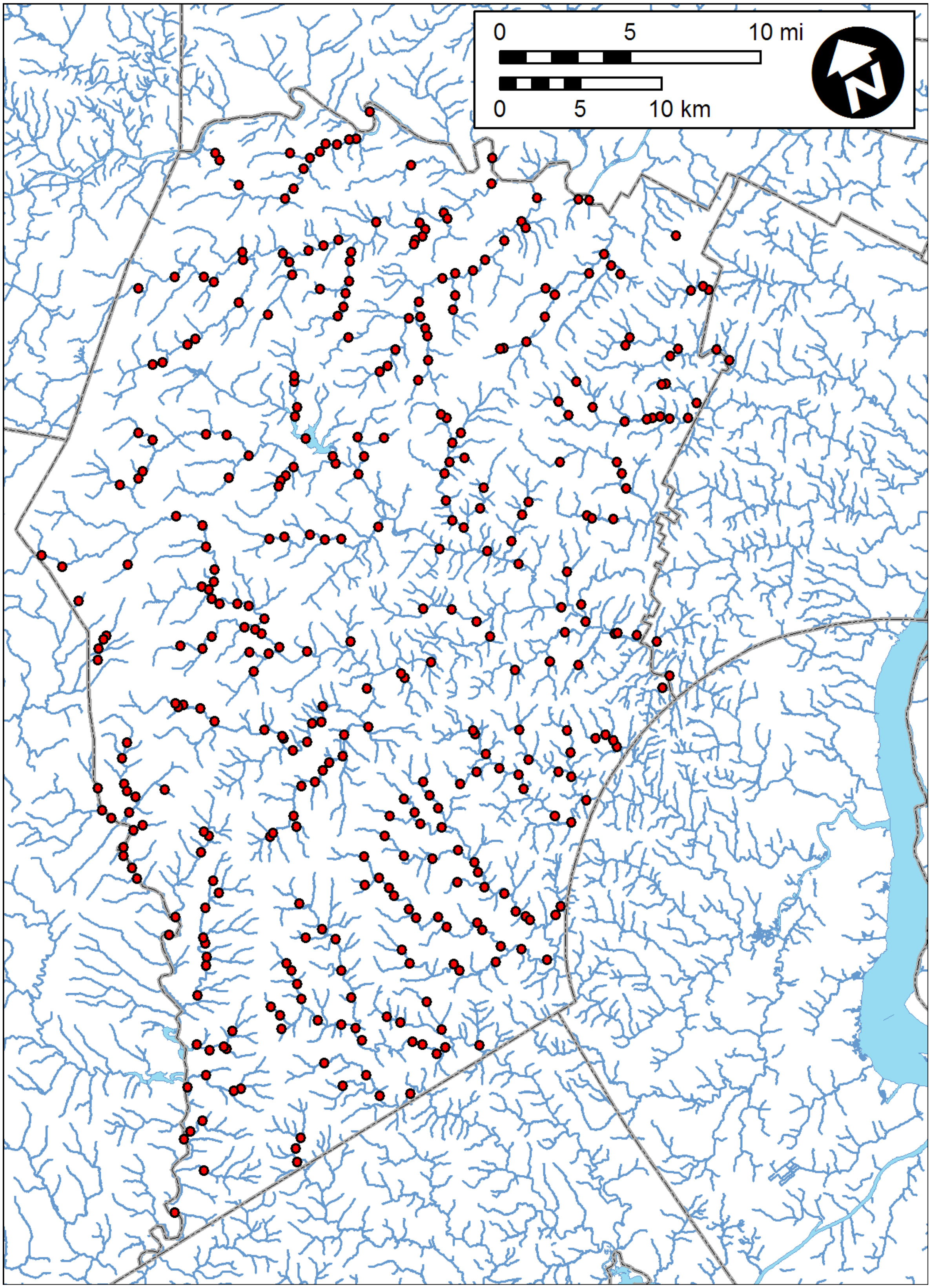
A. County Maps of Historical Dams

We digitized mill dam locations from historic atlases and maps for several counties as listed in the following table.

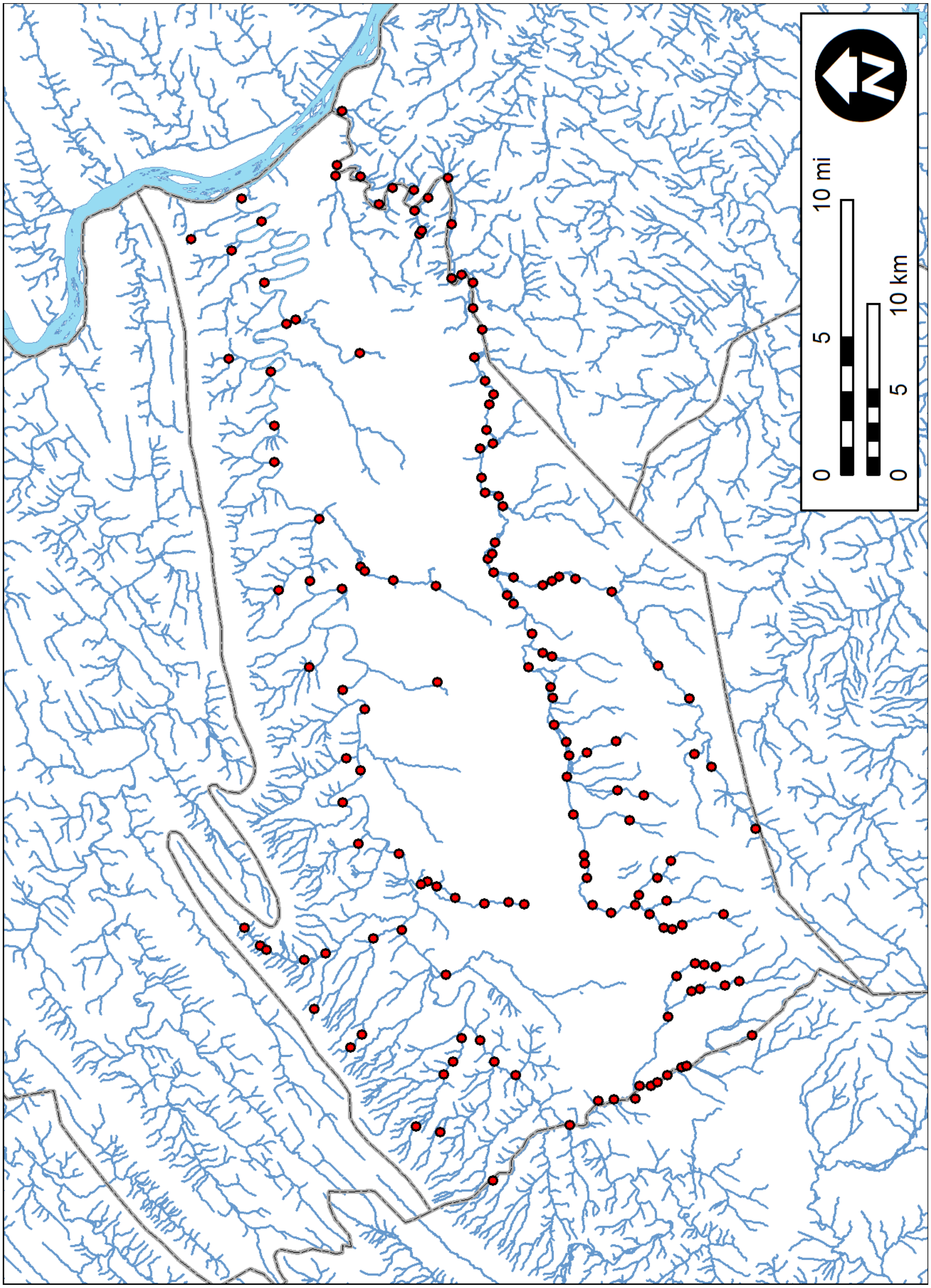
County	Cartographer	Year	Title
Centre Co., PA	Nichols	1874	Atlas of Centre County, Pennsylvania
Chester Co., PA	Painter and Bowen	1847	Map of Chester County, Pennsylvania
Cumberland Co., PA	Bridgens	1858	Atlas of Cumberland County, Pennsylvania
Huntingdon Co., PA	Nichols	1873	Atlas Blair and Huntingdon Counties, Pennsylvania
Lancaster Co., PA	Bridgens	1864	Bridgen's Atlas of Lancaster County, Pennsylvania
York Co., PA	Nichols	1876	Atlas of York County, Pennsylvania



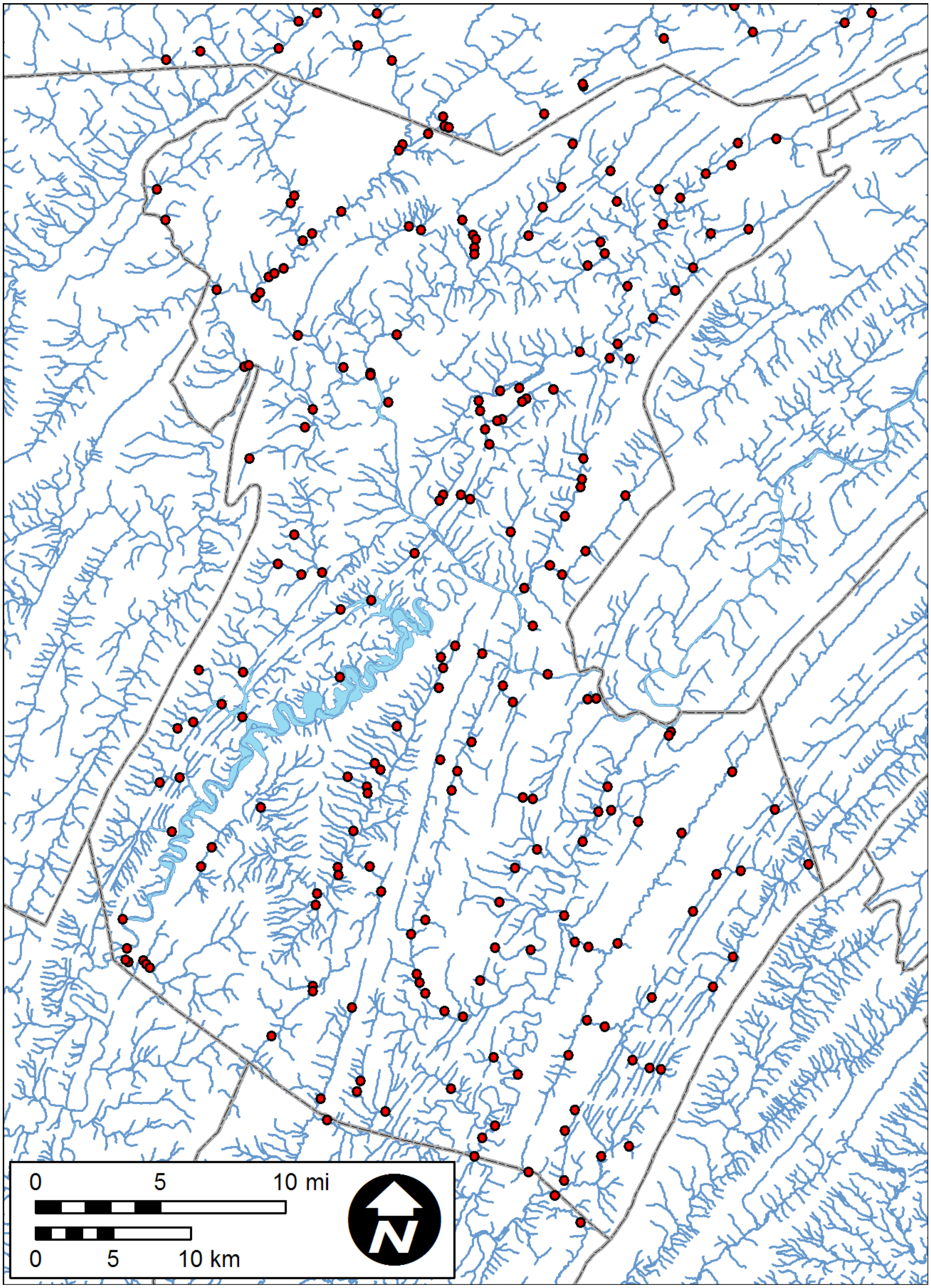
Dams located from *Atlas of Centre County, Pennsylvania* (Nichols, 1874).



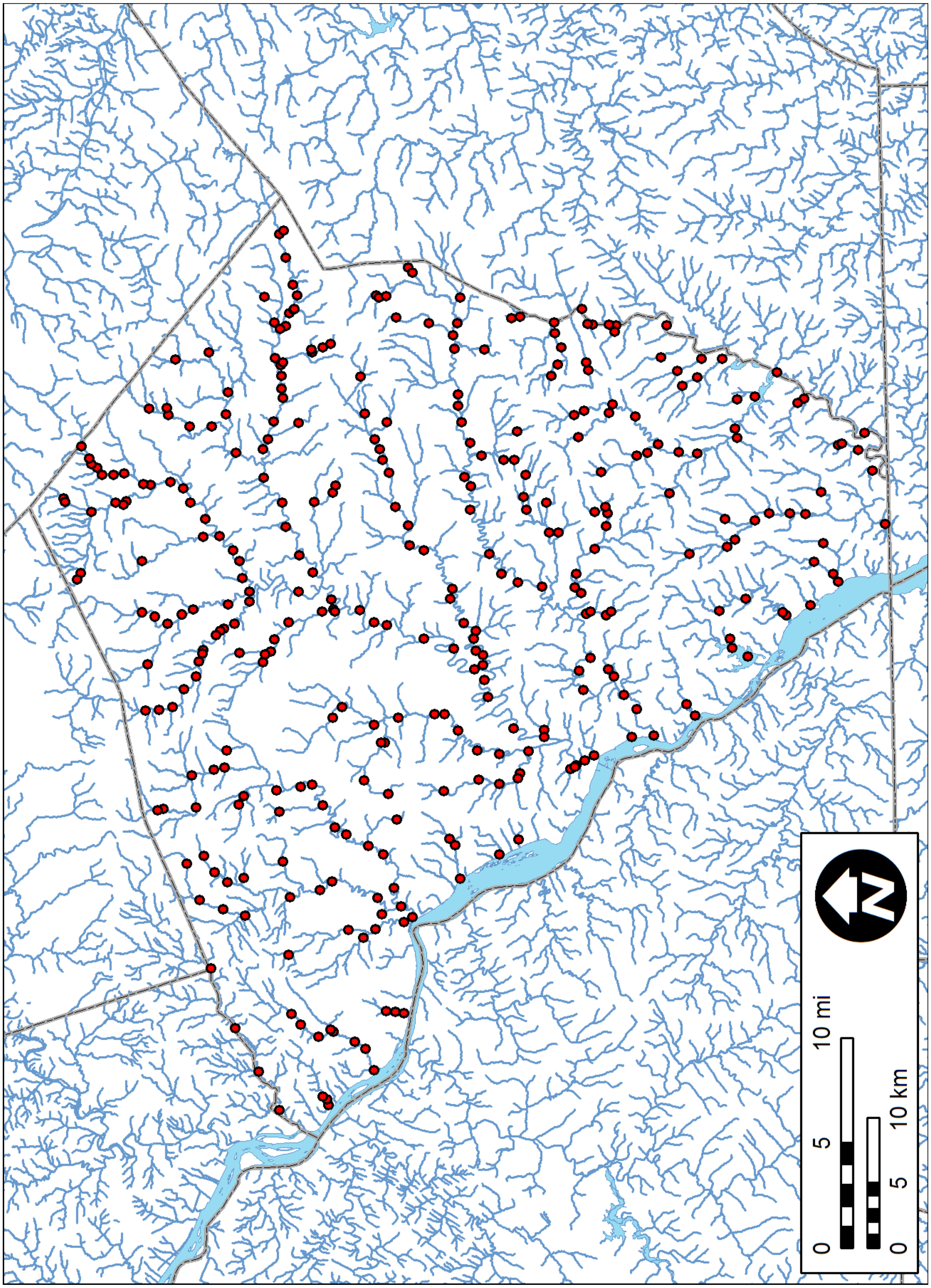
Dams located from *Map of Chester County, Pennsylvania* (Painter and Bowen, 1847).



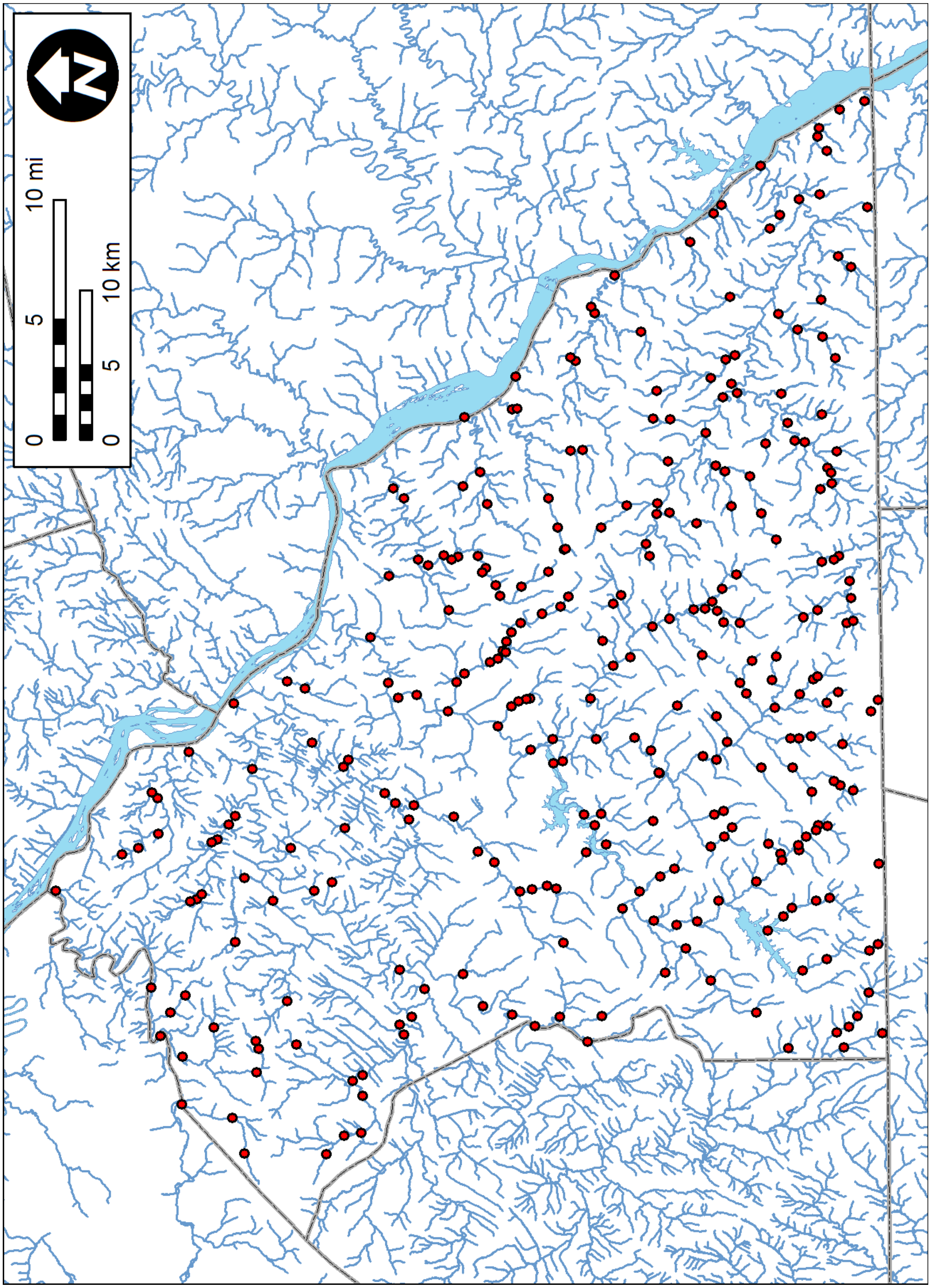
Dams located from *Atlas of Cumberland County, Pennsylvania* (Bridgens, 1858).



Dams located for Huntingdon County from *Atlas of Blair and Huntingdon Counties* (Nichols, 1873).



Dams located from *Bridgen's Atlas of Lancaster County, Pennsylvania* (Bridgens, 1864).



Dams located from *Atlas of York County, Pennsylvania* (Nichols, 1876).

B. Methodologies

Estimating Change from Digital Orthophotos

Overview

Imagery provides a tremendous amount of information about landcover and objects on the ground. It provides rather less information about topography, unless it is viewable in stereo or is distributed with a DTM. Analyzing change of relatively small and low-relief features such as streams presents particular challenges.

Orthoimagery

Our goal was to estimate erosion rates on stream channels that generally are less than 50 feet in width. For our analysis we used imagery with the following characteristics:

- orthorectified
- leaf-off conditions
- resolution 1 to 2 foot
- images acquired less than 5 years apart

Several field sites had imagery that was suitable for comparison; these data sources are listed in the table below.

Location	**Year**	**Ground resolution, color**	**Source**	**Horizontal Accuracy Assessment Report (PDF file)**
Big Beaver Creek	2001	2 ft, b/w	Lancaster County	
Big Beaver Creek	2005	1 ft, color	PAMAP	Horizontal Accuracy Assessment Report ATBlock 2005 I.pdf
Conoy Creek	2001	2 ft, b/w	Lancaster County	
Conoy Creek	2005	1 ft, color	PAMAP	Horizontal Accuracy Assessment Report ATBlock 2005 I.pdf
Mountain Creek	2003	2 ft, color	PAMAP	
Mountain Creek	2007	1 ft, color	PAMAP	Horizontal Accuracy Assessment Report ATBlock 2007 3.pdf

Aerial Photography

Georeferenced aerial photography was not used in this analysis because the potential horizontal accuracy from that method is poor. Hughes, et al., 2006 show that horizontal accuracy of ±5 m, with 10% chance of greater error, is achievable based on their georectification of 1:20,000-scale, historic aerial photography. The aerial photos used in that study are favorable to their analysis in a number of ways:

- the town of Pendleton provides many well-defined ground control points that are roughly co-planar and close in elevation to the object of interest

- the Umatilla River ranges from about 50 feet to 250 feet in width, with a valley flat hundreds to thousands of feet in width
- the channel centerline migrated significantly in places during the period of measurement (1964, 1971)
- the focus of their change analysis was channel migration, rather than erosion or deposition

That methodology might not be appropriate for change analysis of smaller streams in the mid-Atlantic Piedmont and Ridge and Valley provinces. The channels that we characterize in this report, at 5 feet to 50 feet in width, are smaller than the Umatilla River studied by Hughes et al (2006). Most identifiable ground features are >20 feet above the streams and terraces; if used as ground control points, these features would introduce additional distortion on top of camera error and topographic displacement.

For the purposes of this study, scanned aerial photos were georeferenced using as control points features that were close in elevation to the stream reach of interest. Control points included bridges, dams, structures on terrace surfaces and boulders in the stream itself. Most frames contained fewer than five control points. The resulting image is useful for determining whether particular features were present or absent, identification of regions of significant change, and the nature of that change. We chose not to measure change using georeferenced aerial photos because, in the context of this study, horizontal error of ±5 m would be quite significant.

Feature Digitization

Water edges were digitized for each set of images. Water edges were digitized as opposed to bank edge because the water has high contrast with the sedimentary deposits. Changed areas were then digitized by evaluating changes over time in the location of the digitized water edges with respect to other features such as visible bars and terrace deposits.

Feature Attribution

The resulting change polygons were attributed with the following fields:

- FeatureType (where the value is one of: terrace, bar, or slope)
- ChangeType (where the value is one of: erosion, deposition, or translation)
- ElevationChange

ElevationChange represents the change in elevation of that area over the period of measurement. Elevation change values were assigned based upon a variety of data, including stadia-rod measurements, cross-section surveys, and lidar. Image interpretations were confirmed by comparison with recent field surveys of terrace edges, bank edges, water edges and other topographic breaklines.

Estimating Volume Change

Volume change for each polygon was obtained by multiplying polygon area by the elevation change between the two time periods. These values were then summarized for each study area.

Stratigraphic Horizons and Local Datum Surfaces

Overview

Most GIS users are familiar with the concept of horizontal and vertical geographic datums that are used to define a coordinate system. There are, however, other types of datums that relate to stratigraphic, geomorphic and hydrographic features that are of use when interpreting and measuring Earth features. In the case of streams in general, and legacy sediment in particular, there are at least two readily observable local datums: water surface elevation and bank elevation. These datums are visible in the field and in high-resolution topographic data such as lidar or aerial photogrammetric surveys.

The bank elevation is often coincident with a terrace elevation. Terraces are readily identifiable as near-planar surfaces that extend between valley walls, and slope gently down-valley. Where valleys are relatively narrow the terraces will not be as broad and may appear as benches on either side of the stream. Where valleys are broad the terraces will appear as distinct valley-bottom flats with a channel through them. Terraces are often paired, that is left-bank and right-bank terrace elevations are the same.

Terraces have frequently been mistaken for flood plains formed by overbank deposition. Terrace surfaces were, in fact, formed under ponded or slackwater conditions and represent a distinct stratigraphic horizon that has been subaerially exposed through processes of base-level fall and channel incision.

Interpreting Legacy Sediment Features on Bare Earth Lidar

When interpreting Lidar for historic reservoir sediment (i.e., legacy sediment) surfaces, one should look for:

- planar surfaces with sharp breaks in slope at what is usually called the bank edge
- bank collapse features that have modified terrace edges
- scour on otherwise planar terrace surfaces
- incipient channel formation on terrace surfaces
- tributaries that cross a terrace and drop sharply into the receiving stream
- side valleys that lack drainage outlets / terraces that fill side valleys
- tributaries that curve upstream at the outlet

Delineation of Terrace Surfaces with Lidar in ArcGIS

In general, the delineation of terrace surfaces with lidar for a stream reach is accomplished with the following steps:

1) Obtain a lidar-derived bare earth DTM
2) Calculate a slope raster from the bare earth DTM
3) Calculate a hillshade to aid in lidar interpretation
4) Create a PointZ feature dataset
5) Create points on the terrace surface (interpreting the lidar as described above) and bank tops (where no terrace is not apparent) using the bare earth DTM as the elevation source

6) Use inverse distance weighted (IDW) interpolation to create, from the spot elevations, a new height-field raster that approximates a terrace horizon surface
7) Select the raster cells in the bare earth DTM that are less than the terrace horizon surface plus some factor and sloping less than some threshold
8) Convert the resulting terrace extent raster to polygon features for display
9) Manually edit the polygon features to remove upland areas and dissolve remaining polygons

Important products of this exercise are the terrace horizon surface raster and the terrace extent polygon features.

Delineation of Water Surfaces in ArcGIS

1) Obtain a lidar-derived bare earth DTM
2) Calculate flowlines (see Hydrology Tools) or manually digitize flowlines
3) Edit flowlines to remove obvious errors
4) Convert flowlines from Polyline features to PolylineZ features using the bare earth DTM as the elevation source
5) Assign HydroID values to the streamlines (see ArcHydro documentation)
6) Use ArcHydro to 'Smooth' the flowlines which will remove spikes in the data and barriers such as bridges
7) Use IDW interpolation of the smoothed flowline vertices to create a water horizon surface

Important products of this exercise are the water horizon surface raster and the stream flowlines.

Calculation of Channel Volume

It is possible to estimate channel volume using a terrace horizon surface and bare earth DTM.

1) Obtain a lidar-derived bare earth DTM
2) Obtain or create a terrace horizon surface raster (see steps 1-6 of 'Delineation of Terrace Surfaces in ArcGIS')
3) Create a bounding polygon around the region of interest.
4) Calculate the difference between the terrace horizon surface raster and the bare earth using the region of interest polygon to constrain the analysis extent. This step produces a raster dataset that represents depth below the terrace horizon
5) Calculate the channel volume from the map of depth below terrace horizon

Important products of this analysis are the depth below terrace horizon raster, and output of the surface volume calculation.

Determining Bank Height Distribution

Create terrace surface raster, and manually digitize and smooth stream lines. The terrace surface raster is interpolated from the Z values of manually selected points on terrace surfaces. In ArcInfo, the remaining steps are as follows:

1) Create an empty PointZM feature dataset;

2) Use the ArcInfo Divide tool to create points along each streamline at a 20m interval (these contain the values for distance M along the line, and the elevation Z at that point);
3) Use 3D Analyst to create a new PointZ layer, obtaining Z values from the terrace surface raster;
4) To the dataset created in 1, add fields "water", "distance", "terrace", and "height" to the attribute table;
5) Update the fields "water" and "distance" using scripts executed from raster calculator;
6) Join the dataset created in 3 to the dataset created in 1 on the ObjectID field;
7) Update the field "terrace" with the Z value from the joined data using a script executed from raster calculator;
8) Update the field "height" by subtracting "water" from "terrace";
9) Export the tabular data to a comma separated value text file;
10) Create a histogram from the CSV file.

C. Production by Station

Site	Station	Method	Start Date	End Date	Period, days	Period, years	Change value	Change unit	Length, ft	Bank Height, ft	Production, ft^3/ft/ft/yr (SPU)	Breach Date	Breach Age at End Date, yr
Big Beaver Creek	Reach	Bank Edge Digitization	4-Apr-2005	2-Apr-2009	1,459	4.00	27,379	cubic foot	890	5.0	1.54	1-Jan-1972	37.28
Big Beaver Creek	Reach	Bank Edge Digitization	1-Apr-2001	4-Apr-2005	1,464	4.01	66,193	cubic foot	890	5.0	2.39	1-Jan-1972	33.28
Big Spring Run	T6LB (S)	Bank Pin	11-Sep-2008	9-Jul-2009	301	0.82	-0.41	linear foot	1	4.5	-0.49	1-Jan-1916	93.58
Big Spring Run	T5LB (K)	Bank Pin	11-Sep-2008	9-Jul-2009	301	0.82	-0.19	linear foot	1	4.5	-0.23	1-Jan-1916	93.58
Big Spring Run	T6RB (T)	Bank Pin	11-Sep-2008	2-Oct-2008	21	0.06	-0.01	linear foot	1	4.5	-0.19	1-Jan-1916	92.82
Big Spring Run	USGS RB (M)	Bank Pin	22-May-2008	5-Sep-2009	471	1.29	-0.18	linear foot	1	4.5	-0.14	1-Jan-1916	93.74
Big Spring Run	USGS RB (L)	Bank Pin	22-May-2008	5-Sep-2009	471	1.29	0.16	linear foot	1	4.5	0.13	1-Jan-1916	93.74
Big Spring Run	T1RB (A)	Bank Pin	11-Sep-2008	5-Sep-2009	359	0.98	0.24	linear foot	1	4.5	0.24	1-Jan-1916	93.74
Big Spring Run	USGS RB X-Section (N)	Bank Pin	22-May-2008	5-Sep-2009	471	1.29	0.52	linear foot	1	4.5	0.40	1-Jan-1916	93.74
Big Spring Run	USGS RB X-Section (O)	Bank Pin	22-May-2008	5-Sep-2009	471	1.29	0.60	linear foot	1	4.5	0.46	1-Jan-1916	93.74
Big Spring Run	T3RB (G)	Bank Pin	11-Sep-2008	5-Sep-2009	359	0.98	0.47	linear foot	1	4.5	0.48	1-Jan-1916	93.74
Big Spring Run	T2LB (E)	Bank Pin	11-Sep-2008	5-Sep-2009	359	0.98	0.55	linear foot	1	4.5	0.56	1-Jan-1916	93.74
Big Spring Run	T5LB (J)	Bank Pin	11-Sep-2008	5-Sep-2009	359	0.98	0.59	linear foot	1	4.5	0.60	1-Jan-1916	93.74
Big Spring Run	T1RB (B)	Bank Pin	11-Sep-2008	5-Sep-2009	359	0.98	1.17	linear foot	1	4.5	1.19	1-Jan-1916	93.74
Big Spring Run	T2LB (D)	Bank Pin	11-Sep-2008	5-Sep-2009	359	0.98	1.25	linear foot	1	4.5	1.27	1-Jan-1916	93.74
Big Spring Run	T4LB (I)	Bank Pin	11-Sep-2008	5-Sep-2009	359	0.98	1.29	linear foot	1	4.5	1.31	1-Jan-1916	93.74
Big Spring Run	T3RB (F)	Bank Pin	11-Sep-2008	5-Sep-2009	359	0.98	1.39	linear foot	1	4.5	1.41	1-Jan-1916	93.74
Big Spring Run	T4LB (H)	Bank Pin	11-Sep-2008	5-Sep-2009	359	0.98	2.10	linear foot	1	4.5	2.13	1-Jan-1916	93.74
Big Spring Run	XS-3	Cross Section	1-Jul-2004	1-Jul-2009	1,826	5.00	2.60	square foot	1	4.1	0.13	1-Jan-1916	93.56
Big Spring Run	XS-4	Cross Section	1-Jul-2004	1-Jul-2009	1,826	5.00	5.42	square foot	1	5.3	0.20	1-Jan-1916	93.56
Big Spring Run	XS-5	Cross Section	1-Jul-2004	1-Jul-2009	1,826	5.00	10.30	square foot	1	4.2	0.49	1-Jan-1916	93.56
Big Spring Run	XS-11	Cross Section	1-Jul-2004	1-Jul-2009	1,826	5.00	19.36	square foot	1	4.4	0.88	1-Jan-1916	93.56
Conoy Creek	Reach	Bank Edge Digitization	1-Apr-2001	4-Apr-2005	1,464	4.01	60,259	cubic foot	1788	5.5	1.53	1-Jan-1972	33.28
Conoy Creek	XS-4	Bank Pin	15-Feb-2006	25-Jul-2008	691	1.89	0.68	linear foot	1	5.4	0.36	1-Jan-1972	36.59
Conoy Creek	XS-1	Bank Pin	15-Feb-2006	25-Jul-2008	891	2.44	1.30	linear foot	1	7.4	0.53	1-Jan-1972	36.59
Conoy Creek	XS-5	Bank Pin	15-Feb-2006	25-Jul-2008	891	2.44	4.16	linear foot	1	4.5	1.70	1-Jan-1972	36.59
Conoy Creek	XS-2	Bank Pin	15-Feb-2006	25-Jul-2008	891	2.44	4.84	linear foot	1	8.0	1.98	1-Jan-1972	36.59

Site	Station	Method	Start Date	End Date	Period, days	Period, years	Change value	Change unit	Length, ft	Bank Height, ft	Production, ft^3/ft/ft/yr (SPU)	Breach Date	Breach Age at End Date, yr
Conoy Creek	XS-3	Bank Pin	15-Feb-2006	25-Jul-2008	891	2.44	4.85	linear foot	1	7.3	1.99	1-Jan-1972	36.59
Conoy Creek	XS-1	Cross Section	15-Feb-2006	18-Jul-2008	884	2.42	2.40	square foot	1	5.9	0.17	1-Jan-1972	36.57
Conoy Creek	XS-4	Cross Section	15-Feb-2006	25-Jul-2008	891	2.44	6.15	square foot	1	5.4	0.47	1-Jan-1972	36.59
Conoy Creek	XS-2	Cross Section	15-Feb-2006	25-Jul-2008	891	2.44	10.01	square foot	1	5.5	0.74	1-Jan-1972	36.59
Conoy Creek	XS-3	Cross Section	15-Feb-2006	18-Jul-2008	884	2.42	15.33	square foot	1	5.2	1.21	1-Jan-1972	36.57
Gunpowder Falls	Reach	Lidar Volume	1-May-1932	1-Apr-2005	26,633	72.97	3,182,741	cubic foot	3977	11.3	0.97	1-May-1932	72.97
Hammer Creek	XS-4	Cross Section	25-May-2004	11-Apr-2006	686	1.88	-9.40	square foot	1	3.5	-1.44	5-Sep-2001	4.60
Hammer Creek	XS-4	Cross Section	14-Aug-2007	23-Oct-2008	436	1.19	1.95	square foot	1	2.6	0.64	5-Sep-2001	7.14
Hammer Creek	XS-5	Cross Section	25-May-2004	26-Dec-2006	945	2.59	10.08	square foot	1	3.0	1.32	5-Sep-2001	5.31
Hammer Creek	XS-5	Cross Section	14-Aug-2007	23-Oct-2008	436	1.19	5.35	square foot	1	3.0	1.48	5-Sep-2001	7.14
Hammer Creek	XS-5	Cross Section	2-Aug-2002	6-Aug-2003	369	1.01	18.38	square foot	1	3.6	5.08	5-Sep-2001	1.92
Hammer Creek	XS-5	Cross Section	26-Jun-2001	23-Oct-2008	2,676	7.33	131.43	square foot	1	3.0	5.94	5-Sep-2001	7.14
Hammer Creek	XS-4	Cross Section	2-Aug-2002	8-Aug-2003	371	1.02	25.41	square foot	1	3.4	7.38	5-Sep-2001	1.92
Hammer Creek	XS-5	Cross Section	26-Dec-2006	14-Aug-2007	231	0.63	15.63	square foot	1	3.0	8.16	5-Sep-2001	5.94
Hammer Creek	XS-5	Cross Section	6-Aug-2003	25-May-2004	293	0.80	26.47	square foot	1	3.5	9.45	5-Sep-2001	2.72
Hammer Creek	XS-4	Cross Section	26-Jun-2001	23-Oct-2008	2,676	7.33	180.71	square foot	1	2.6	9.66	5-Sep-2001	7.14
Hammer Creek	XS-4	Cross Section	8-Aug-2003	25-May-2004	291	0.80	36.98	square foot	1	4.7	9.93	5-Sep-2001	2.72
Hammer Creek	XS-4	Cross Section	11-Apr-2006	14-Aug-2007	490	1.34	54.49	square foot	1	3.4	11.99	5-Sep-2001	5.94
Hammer Creek	XS-5	Cross Section	26-Jun-2001	2-Aug-2002	402	1.10	55.52	square foot	1	3.4	14.65	5-Sep-2001	0.91
Hammer Creek	XS-4	Cross Section	26-Jun-2001	2-Aug-2002	402	1.10	71.28	square foot	1	2.6	24.80	5-Sep-2001	0.91
Little Conestoga Creek West Branch	Reach	Lidar Volume	1-Jan-1930	1-Apr-2004	27,119	74.30	3,310,415	cubic foot	8098	7.6	0.72	1-Jan-1930	74.30
Little Conestoga Creek West Branch	Denlingers Mill	Point of Reference	2-Nov-2006	15-Aug-2009	1,017	2.79	1.94	linear foot	1	13.8	0.70	1-Jan-1930	79.7
Mountain Creek	Reach	Bank Edge Digitization	1-Apr-2003	23-Apr-2007	1,483	4.06	54,342	cubic foot	2005	6.5	1.03	1-Dec-1985	21.41
Mountain Creek	XS-1	Bank Pin	18-Dec-2007	7-Aug-2009	598	1.64	0.96	linear foot	1	8.9	0.58	1-Dec-1985	23.70
Mountain Creek	XS-2	Bank Pin	18-Dec-2007	7-Aug-2009	598	1.64	1.42	linear foot	1	8.4	0.87	1-Dec-1985	23.70
Mountain Creek	XS-3	Bank Pin	13-Aug-2008	7-Aug-2009	359	0.98	1.09	linear foot	1	6.3	1.11	1-Dec-1985	23.70
Mountain Creek	XS-4	Bank Pin	13-Aug-2008	7-Aug-2009	359	0.98	1.35	linear foot	1	6.8	1.37	1-Dec-1985	23.70
Mountain Creek	XS-2	Bank Pin	18-Dec-2007	22-May-2008	156	0.43	1.73	linear foot	1	8.4	4.04	1-Dec-1985	22.49
Mountain Creek	XS-1	Cross Section	15-Jan-2008	23-Jun-2009	525	1.44	21.33	square foot	1	7.4	2.01	1-Dec-1985	23.58

Site	Station	Method	Start Date	End Date	Period, days	Period, years	Change value	Change unit	Length, ft	Bank Height, ft	Production, ft^3/ft/ft/yr (SPU)	Breach Date	Breach Age at End Date, yr
Mountain Creek	XS-3	Cross Section	13-Aug-2008	7-Aug-2009	359	0.98	19.80	square foot	1	6.6	3.04	1-Dec-1985	23.70
Mountain Creek	XS-4	Cross Section	13-Aug-2008	7-Aug-2009	359	0.98	21.52	square foot	1	6.9	3.15	1-Dec-1985	23.70
Mountain Creek	XS-2	Cross Section	15-Jan-2008	23-Jun-2009	525	1.44	33.38	square foot	1	6.1	3.78	1-Dec-1985	23.58
Mountain Creek	Reach	Lidar Volume	1-Dec-1985	23-Apr-2007	7,813	21.41	1,349,880	cubic foot	3880	6.0	2.71	1-Dec-1985	21.41
Penns Creek	Reach	Lidar Volume	1-Jun-1968	28-Apr-2006	13,845	37.93	2,246,411	cubic foot	7956	6.3	1.19	1-Jun-1968	37.93
Valley Creek	Reach 12	Cross Section and Bank Edge	1-Jun-2004	1-Jul-2005	395	1.08	1,342	cubic foot	1673	6.29	0.13	1-Jan-1920	85.56
Valley Creek	Reach 4	Cross Section and Bank Edge	1-Jun-2004	1-Jul-2005	395	1.08	2,472	cubic foot	445	11.48	0.48	1-Jan-1920	85.56
Valley Creek	Reach 11	Cross Section and Bank Edge	1-Jun-2004	1-Jul-2005	395	1.08	6,569	cubic foot	2059	6.01	0.53	1-Jan-1920	85.56
Valley Creek	Reach 10	Cross Section and Bank Edge	1-Jun-2004	1-Jul-2005	395	1.08	4,803	cubic foot	1509	5.47	0.58	1-Jan-1920	85.56
Valley Creek	Reach 8	Cross Section and Bank Edge	1-Jun-2004	1-Jul-2005	395	1.08	4,344	cubic foot	605	10.25	0.70	1-Jan-1920	85.56
Valley Creek	Reach 9	Cross Section and Bank Edge	1-Jun-2004	1-Jul-2005	395	1.08	17,481	cubic foot	2739	8.75	0.73	1-Jan-1920	85.56
Valley Creek	Reach 7	Cross Section and Bank Edge	1-Jun-2004	1-Jul-2005	395	1.08	9,394	cubic foot	693	13.12	1.03	1-Jan-1920	85.56
Valley Creek	Reach 6	Cross Section and Bank Edge	1-Jun-2004	1-Jul-2005	395	1.08	6,109	cubic foot	640	6.84	1.40	1-Jan-1920	85.56
Valley Creek	Reach 3	Cross Section and Bank Edge	1-Jun-2004	1-Jul-2005	395	1.08	2,578	cubic foot	230	7.66	1.47	1-Jan-1920	85.56
Valley Creek	Reach 2	Cross Section and Bank Edge	1-Jun-2004	1-Jul-2005	395	1.08	6,463	cubic foot	405	10.12	1.58	1-Jan-1920	85.56
Valley Creek	Reach 5	Cross Section and Bank Edge	1-Jun-2004	1-Jul-2005	395	1.08	12,890	cubic foot	647	11.21	1.78	1-Jan-1920	85.56
Valley Creek	Reach 1	Cross Section and Bank Edge	1-Jun-2004	1-Jul-2005	395	1.08	15,009	cubic foot	538	8.20	3.40	1-Jan-1920	85.56
White Clay Creek	Site 6	Bank Pin	25-Aug-2008	4-Sep-2009	375	1.03	0.08	linear foot	1	3.0	0.08	2-Jan-1900	109.75
White Clay Creek	Site 7	Bank Pin	25-Aug-2008	4-Sep-2009	375	1.03	0.37	linear foot	1	3.0	0.36	2-Jan-1900	109.75
White Clay Creek	Site 1	Bank Pin	25-Aug-2008	4-Sep-2009	375	1.03	0.39	linear foot	1	3.0	0.38	2-Jan-1900	109.75
White Clay Creek	Site 4	Bank Pin	25-Aug-2008	4-Sep-2009	375	1.03	0.49	linear foot	1	3.0	0.48	2-Jan-1900	109.75
White Clay Creek	Site 5	Bank Pin	25-Aug-2008	4-Sep-2009	375	1.03	0.67	linear foot	1	3.0	0.65	2-Jan-1900	109.75
White Clay Creek	Site 2	Bank Pin	25-Aug-2008	4-Sep-2009	375	1.03	0.74	linear foot	1	3.0	0.72	2-Jan-1900	109.75

D. Production by Field Area

Site	Method	Start Date	End Date	Period, days	Period, years	Change Value	Change Unit	Length, ft	Bank Height, ft	Production, ft^3/ft/ft/yr (SPU)	Breach Date	Breach Age at End Date, yr
Big Beaver Creek	Bank Edge Digitization	1-Apr-2001	4-Apr-2005	1464	4.01	66193	cubic foot	890	5.00	2.39	1-Jan-1972	33.28
Big Beaver Creek	Bank Edge Digitization	4-Apr-2005	2-Apr-2009	1459	4.00	27379	cubic foot	890	5.00	1.54	1-Jan-1972	37.28
Big Spring Run	Bank Pin	22-May-2008	5-Sep-2009	471	1.29	0.43	linear foot	1	4.50	0.33	1-Jan-1916	93.74
Big Spring Run	Bank Pin	11-Sep-2008	5-Sep-2009	359	0.98	1.00	linear foot	1	4.50	1.02	1-Jan-1916	93.74
Big Spring Run	Cross Section	1-Jul-2004	1-Jul-2009	1826	5.00	9.42	square foot	1	4.51	0.43	1-Jan-1916	93.56
Conoy Creek	Bank Edge Digitization	1-Apr-2001	4-Apr-2005	1464	4.01	60259	cubic foot	1788	5.50	1.53	1-Jan-1972	33.28
Conoy Creek	Bank Pin	15-Feb-2006	25-Jul-2008	851	2.33	3.17	linear foot	1	6.52	1.31	1-Jan-1972	36.59
Conoy Creek	Cross Section	15-Feb-2006	18-Jul-2008	884	2.42	8.86	square foot	1	5.56	0.69	1-Jan-1972	36.57
Conoy Creek	Cross Section	15-Feb-2006	25-Jul-2008	891	2.44	8.08	square foot	1	5.46	0.61	1-Jan-1972	36.59
Gunpowder Falls	Lidar Volume	1-May-1932	1-Apr-2005	26633	72.97	3182741	cubic foot	3977	11.32	0.97	1-May-1932	72.97
Hammer Creek	Cross Section	26-Jun-2001	2-Aug-2002	402	1.10	63.40	square foot	1	3.03	19.73	5-Sep-2001	0.91
Hammer Creek	Cross Section	26-Jun-2001	23-Oct-2008	2676	7.33	156.07	square foot	1	2.79	7.80	5-Sep-2001	7.14
Hammer Creek	Cross Section	2-Aug-2002	6-Aug-2003	369	1.01	18.38	square foot	1	3.58	5.08	5-Sep-2001	1.92
Hammer Creek	Cross Section	2-Aug-2002	8-Aug-2003	371	1.02	25.41	square foot	1	3.39	7.38	5-Sep-2001	1.92
Hammer Creek	Cross Section	6-Aug-2003	25-May-2004	293	0.80	26.47	square foot	1	3.49	9.45	5-Sep-2001	2.72
Hammer Creek	Cross Section	8-Aug-2003	25-May-2004	291	0.80	36.98	square foot	1	4.67	9.93	5-Sep-2001	2.72
Hammer Creek	Cross Section	25-May-2004	26-Dec-2006	945	2.59	10.08	square foot	1	2.96	1.32	5-Sep-2001	5.31
Hammer Creek	Cross Section	11-Apr-2006	14-Aug-2007	490	1.34	54.49	square foot	1	3.39	11.99	5-Sep-2001	5.94
Hammer Creek	Cross Section	26-Dec-2006	14-Aug-2007	231	0.63	15.63	square foot	1	3.03	8.16	5-Sep-2001	5.94
Hammer Creek	Cross Section	14-Aug-2007	23-Oct-2008	436	1.19	3.65	square foot	1	2.79	1.06	5-Sep-2001	7.14
Little Conestoga Creek West Branch	Point of Reference	2-Nov-2006	15-Aug-2009	1017	2.79	1.94	linear foot	1	13.78	0.70	1-Jan-1930	79.67
Little Conestoga Creek West Branch	Lidar Volume	1-Jan-1930	1-Apr-2004	27119	74.30	3310415	cubic foot	8098	7.63	0.72	1-Jan-1930	74.30
Mountain Creek	Bank Edge Digitization	1-Apr-2003	23-Apr-2007	1483	4.06	54342	cubic foot	2005	6.50	1.03	1-Dec-1985	21.41
Mountain Creek	Bank Pin	18-Dec-2007	22-May-2008	156	0.43	1.73	linear foot	1	8.40	4.04	1-Dec-1985	22.49
Mountain Creek	Bank Pin	18-Dec-2007	7-Aug-2009	598	1.64	1.19	linear foot	1	8.65	0.72	1-Dec-1985	23.70
Mountain Creek	Bank Pin	13-Aug-2008	7-Aug-2009	359	0.98	1.22	linear foot	1	6.55	1.24	1-Dec-1985	23.70
Mountain Creek	Cross Section	15-Jan-2008	23-Jun-2009	525	1.44	27.35	square foot	1	6.76	2.89	1-Dec-1985	23.58
Mountain Creek	Cross Section	13-Aug-2008	7-Aug-2009	359	0.98	20.66	square foot	1	6.78	3.10	1-Dec-1985	23.70
Mountain Creek	Lidar Volume	1-Dec-1985	23-Apr-2007	7813	21.41	1349880	cubic foot	3880	6.00	2.71	1-Dec-1985	21.41
Penns Creek	Lidar Volume	1-Jun-1968	28-Apr-2006	13845	37.93	2246411	cubic foot	7956	6.28	1.19	1-Jun-1968	37.93
Valley Creek	Cross Section and Bank Edge	1-Jun-2004	1-Jul-2005	395	1.08	7454	cubic foot	1015	8.78	1.15	1-Jan-1920	85.56
White Clay Creek	Bank Pin	25-Aug-2008	4-Sep-2009	375	1.03	0.46	linear foot	1	3.00	0.45	3-Jan-1900	109.75