ESTIMATING VOLUME, NUTRIENT CONTENT, AND RATES OF STREAM BANK EROSION OF LEGACY SEDIMENT IN THE PIEDMONT AND VALLEY AND RIDGE PHYSIOGRAPHIC PROVINCES, SOUTHEASTERN AND CENTRAL PA

A Report to the Pennsylvania Department of Environmental Protection

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EXECUTIVE SUMMARY

In this report, we provide data on the approximate distribution of legacy sediments in four Pennsylvania Counties (Lancaster, York, Centre, and Huntingdon), rates of bank erosion of legacy sediment along stream corridors in three of the four counties, concentrations of nutrients (total sorbed phosphorous and total nitrogen) in stream bank sediments in all four counties, and estimated quantities of legacy sediment stored within the 419 square mile Conestoga River Watershed that drains much of Lancaster County. We selected these four counties in order to provide representative examples of the two main physiographic provinces (Piedmont, and Ridge and Valley) that constitute most of the land area within Pennsylvania's Chesapeake Bay watershed.

The Legacy Sediment Workgroup, established by the Pennsylvania Department of Environmental Protection (PADEP), defined legacy sediment as follows:

> Sediment that was eroded from upland hill slopes after the arrival of early Colonial American settlers and during centuries of intensive land uses; that was deposited in valley bottoms along stream corridors, burying pre-settlement streams, floodplains, wetlands, and valleys; and that altered and continues to impair the hydrologic, biologic, aquatic, riparian, and chemical functions of pre-settlement and modern environments. Legacy sediment often accumulated behind ubiquitous low-head mill dams and in their slackwater environments, resulting in thick accumulations of fine-grained sediment.

Bank erosion is the main process by which sediment is mobilized from stream corridors. Within these corridors, floodplains, alluvial fans, and river terraces can become sources rather than a sinks for suspended sediments in many streams. Significantly, the more sediment stored in the stream corridor, the greater the potential and probability for sediment to be mobilized.

Reservoirs behind low-head dams on small to moderate-sized streams, with moderate to low gradients, readily fill with sediment when streams carry high, suspended sediment loads. Centuries-old human activities, particularly the damming of streams for water power at a time when streams carried unusually high loads of sediment from excessive upland soil erosion (via deforestation and intensive farming during the 18th to 19th centuries) led to the storage of large volumes of sediment in stream corridors throughout the mid-Atlantic region.

We document here a direct correlation between mill dam density and post-settlement "legacy" sediment storage in the four counties studied. The first step in documenting the impact of legacy sediment within the Chesapeake Bay Watershed is to locate Early American mill dams using historical maps and records, combined with the field and remote sensing methods outlined here. Today, most mill dams are defunct, ill-repaired, breached or altered from their original state, and many mill dams remnants blend into the landscape and appear, now, to be part of the natural riparian system. This obscurity, and modern society's loss of knowledge of the ubiquity of Early American mill dams, is why the significance of legacy sediments has been overlooked until now.

We hypothesize that the remarkable abundance of water-powered mills in the eastern US, >65,000 by the year 1840 (as deduced from our analysis of the 1840 US Census of industrial activity), and the close spacing of mills dams along streams, led to widespread accumulation of legacy sediment in many stream corridors. Our research shows that mill dams and legacy sediment occur in watersheds throughout the Piedmont and the Valley and Ridge provinces of Pennsylvania and Maryland. For example, Lancaster, York, Huntingdon, and Centre Counties had 334, 244, 206 and 186 mill dams, respectively, as enumerated by our analysis of 19th Century county and township atlases.

Based on the 1840 US Census, the average mill density for Pennsylvania per county is 0.24 (mills per square mile), or one mill every four square miles statewide. Thirty-four Pennsylvania counties had mill densities greater than or equal to the statewide average, including sixteen counties within the Chesapeake Bay watershed. Of the counties we investigated for this study, Lancaster (0.40) and Huntingdon (0.29) have the highest densities of mills as of 1840, followed by York (0.28) and Centre (0.09) Counties. Mills and mill dams continued to be constructed into the early 20th Century, so the 1840 census represents minimum numbers of mills. In addition, we note that although the mill density for Centre County (Ridge and Valley) is low (0.09), we observe that the mill and mill dam density is concentrated in the broad, limestone and shale valleys, where legacy sediment accumulation is widespread. Furthermore, we observe that the densities of mills in many counties within the Chesapeake Bay watershed, including in Maryland, Virginia, and West Virginia, are high, from which we infer that legacy sediment accumulation is not limited to the counties investigated here.

When dams breach, streams incise into the sediment trapped in the reservoirs upstream of the dam, producing terraces which appear as large valley flats that commonly are mistaken for modern floodplains. They differ from floodplains in that they no longer are actively storing sediment from the stream channel, and they become net sources rather than sinks of sediment.

Examination of continuous U. S. Geological Survey (USGS) gage station data collected since 1985 reveals that 10 of the 11 stream stations with the highest sediment yields (load per unit area) in the Chesapeake Bay Watershed are located in the Piedmont physiographic province. We propose that the spatial variability and anomalies in the USGS sediment yield data are associated with the amount and nature of legacy sediment stored in the stream corridor, and the timing of its remobilization. Whereas construction of > ten thousand mill dams in Pennsylvania and Maryland streams trapped large amounts of sediment for centuries, widespread stream incision and remobilization of that sediment today is the result of dam breaching and removal that have occurred during the past ~100 to 150 years.

Bank erosion is prevalent when thick sections of fine-grained, cohesive material overlie a thin basal layer of coarser-grained non-cohesive material, such as unconsolidated gravel and sand. This is a common condition in both the Piedmont and the Valley and Ridge physiographic provinces. As the fine-grained legacy sediment is removed, the bed of the channel widens and becomes mantled with patches of gravel. As bars develop and enlarge, channels erode the opposing banks and branch around the bars, forming braided streams.

Our examination of the pre-settlement landscape in dozens of trenches and stream bank exposures, combined with geochemical and palynological analysis of the pre-settlement

material, indicates that valley bottoms were broad riparian wetlands, with small (possibly anabranching and chain-of-pool) streams and low vegetated islands within the flood zone, possibly impacted by beaver ponds. Pre-settlement channel forms are small and rarely observed, despite excellent exposure of pre-settlement floodplains. Channel depths of 0.25-0.5 m are constrained by the distance between planar bedrock valley floors and pre-settlement floodplain surfaces. These characteristics could be of importance to stream restoration efforts based upon analog methods.

In essence, what once were wetlands and marshes, with small, shallow anabranching channels that frequently flowed overbank, are becoming braided gravel-bed streams. In the process, fine-grained sediment stored for more than a century is being transported downstream toward the Chesapeake Bay.

The valley fill surfaces produced by legacy sediment are readily observed from air photos and digital elevation data. Lidar (light detection and ranging) is especially useful because it has sufficient resolution (2-m grid cell size) to resolve legacy sediment fill terraces and incised channels. It is not possible to distinguish these two from one another with databases of lower resolution, such as the 1/3 arc-second USGS National Elevation Data. By mapping the legacy sediment surfaces along stream corridors, we estimate how much legacy sediment has been removed by channel erosion. On the W. Br. Little Conestoga, for example, 46% of the ~320,000 tons of sediment stored behind one dam (Denlingers Mill, 20 ft high) has been eroded since the dam breached in 1901. The long-term average rate of erosion is 0.17 tons/ft/yr (tons per linear foot of stream length per year). This corresponds to an average bank erosion rate of 1.1 ft/yr, using an average bank height of 8 ft. This number is very similar to that we have calculated by repeat measurements of the distance between the bank edge and a line of fence posts along a corral.

Using a range of calculations of legacy sediment volumes for the Conestoga watershed, we estimate that from 45% to 122% of the suspended sediment measured at the Conestoga River mouth USGS/SRBC gage station could be from bank erosion of legacy sediment. If all suspended sediment measured at the mouth of the Conestoga River came from the stream corridor, bank erosion rates for the entire watershed (644 miles of stream length, average bank height ~4-5 ft) would be ~0.3 ft/yr.

In contrast, our measurements of bank erosion rates are greater than 0.3 ft/yr. For the six study sites, bank erosion rates range from 0.7 to 3.3 ft/yr. The corresponding sediment production rates range from 0.2 to 0.9 tons/ft/yr, with a mean of 0.39 ± 0.24 and a median of 0.34. Hammer Creek at the Pumping Station site, where a dam was removed in 2001, is higher than all others (average bank erosion rate = 3.3 ft/yr for the past 5 yrs). Removing this value from the six data points yields a mean value of 0.31 ±0.09 tons/ft/yr (note the lower standard of deviation). We selected sites to monitor because bank erosion is occurring and measurable, so these values represent the high end of bank erosion rates in the region. There are some sites with little or no bank erosion (e.g., unbreached dam site, or site with bank stabilization), but there are also many sites with incised streams and eroding banks. A regional average is likely to be slightly less than the numbers presented here, but locally as high or higher.

Our estimates also are consistent with measured rates of bank erosion from 15 Growing Greener project reports that were compiled by Kreider (2006). These reports, based on

channel cross section and bank pin erosion measurements, indicate similar bank erosion and sediment production rates.

For those streams for which lidar is not yet available, we combine known dam locations with 1/3 arc-second USGS National Elevation Data to generate longitudinal elevation profiles that extend from the head of a stream to its mouth (typically its confluence with a larger stream). This approach illustrates where sediment was trapped in reservoirs behind the dams, but we are not able to use these longitudinal profiles to estimate volume of legacy sediment. LiDAR will be available for all of Pennsylvania within 2-3 years, however, and at that time the algorithms and procedures that we are developing can be used to do the same types of legacy sediment analyses anywhere with LiDAR coverage.

Our analyses of legacy sediments from stream banks in five watersheds in four counties show average N concentrations ranging from 400-2100 ppm (overall mean = 1160 ppm), and average P concentrations ranging from 340-958 ppm. Total P and N concentrations in legacy sediments are high, and, given our measured bank erosion rates, represent a significant proportion of nutrients entering streams in the Chesapeake Bay watershed of Pennsylvania. Combining the bank erosion rates and nutrient concentrations yields nutrient loads to streams from bank erosion that range from 0.3 to 4.1 lbs/ft/yr for nitrogen and from 0.2 to 1.8 lbs/ton/yr for phosphorus. These concentrations are based on dry mass calculations, which permit direct correlation to dry mass sediment loads from streams. For example, field moist bulk densities of typical legacy sediment in Lancaster County ranges from 1.3 to 1.4 g/cm^3, whereas the dry bulk density ranges from 1.27 to 1.30 g/cm^3. Therefore, a small (<8%) reduction in nutrient load concentrations might be necessary to correct for a slightly greater density of eroded field moist legacy sediment.

The erosion rates and nutrient loads we measured in this study for Pennsylvania's Chesapeake Bay watershed are consistent with bank erosion rates, sediment loads and nutrient loads measured in other watersheds in the U.S. and around the world.

The annual P load from bank erosion in the Conestoga watershed alone accounts for ~2.1% of the 6.5 million lb reduction needed by the 2010 target date for the Chesapeake Bay Agreement, despite the Conestoga watershed being just 0.76% of the area of Chesapeake Bay watershed.

We conclude that stream bank erosion of legacy sediment is an important source of sediment and nutrients to tributaries of the Chesapeake Bay, and is at least as significant as runoff from upland sources in some watersheds. The results we present here regarding the stream corridor as a significant source of sediment and nutrients could lead to an essential new addition to the Chesapeake Bay Watershed Model.

I. Introduction: Sediment and Nutrient Loads to the Chesapeake Bay

The 64,000 square mile Chesapeake Bay watershed drains parts of six states (New York, Pennsylvania, Delaware, Maryland, Virginia and West Virginia) and the District of Columbia, and is vital to the economy and quality of life in the eastern U.S. (Figure 1). In 2000, due to degraded water quality and habitat, the Chesapeake Bay was listed as an impaired water body under the Federal Clean Water Act. That same year, the Chesapeake Bay Commission, its member states, the District of Columbia, and EPA signed an agreement known as "Chesapeake 2000: A Watershed Partnership", to commit to reducing nutrient and sediment loads sufficiently by 2010 to remove the Bay from the Federal 303d list of impaired waterways.

A. Sediment and Nutrient Load Reduction Goals for the Chesapeake Bay

In 1992, before the Environmental Protection Agency (EPA) listed the Chesapeake Bay as an impaired water body, Bay partners had agreed to reduce controllable nitrogen and phosphorous loads to the Bay by 40% below 1985 levels before the year 2000. Using this desired reduction as a goal, the Chesapeake Bay Program (CBP) developed watershed-scale computer models to assign nutrient allocations for each of the nine major tributaries to the Bay, including the Susquehanna River in Pennsylvania.

As of 2000, with continued environmental degradation in the Bay and its listing as an impaired water body, these tributary allocations were designated as caps, not to be exceeded regardless of increased population and/or economic growth. Specified target reductions were distributed among Bay tributaries in order to reduce sediment and nutrients loads to meet 2010 statewide cap allocations. As a result of these commitments, Pennsylvania is required to reduce sediment discharges to the Chesapeake Bay to ≤0.995 million tons, nitrogen discharges to ≤71.9 million pounds, and phosphorus discharges to ≤1.1 million pounds by the year 2010.

Between 1985 and 2002 Pennsylvania has reduced nitrogen loads within the Chesapeake Bay watershed by 12 million pounds (PA DEP Tributary Strategy Fact Sheet). To meet the Strategy goals, Pennsylvania must reduce nitrogen loads an additional 31 million by 2010. This represents a significant challenge for the Commonwealth. Recently implemented BMPs have helped increase the Commonwealth's ability to meet the TS reduction goals, and the development of a new Legacy Sediment/Stream Restoration BMP would further enhance these reduction rates.

B. The Chesapeake Bay Watershed Model

The current version of the Chesapeake Bay watershed model (hereafter referred to as the Watershed Model) estimates nutrient and sediment loads coming from each of the tributaries to the Bay in order to ensure that cap loads are not exceeded. Best management practices (BMPs) are changes in land use, land cover, or technology that can

reduce the load of sediment or nutrients to a stream, and the Watershed Model calculates the reduction attained for a given area using an accounting of BMPs and BMP efficiencies.

There are three basic parts, or sub-models, in the Watershed Model:

1) a hydrologic sub-model, which calculates surface water runoff and subsurface (groundwater) flow;
2) a non-point source sub-model, which simulates soil erosion and pollutant loads from land to rivers via the flow of water in the hydrologic sub-model and the different types of land use on each part of the landscape; and
3) a river sub-model in which water and associated loads of sediment and nutrients are carried down-current in streams and rivers to lakes, reservoirs, and ultimately the Bay.

With regards to the second sub-model, nearly all of the sediment and nutrient loads are derived from upland slopes, and primarily as runoff from upland farm slopes. Modern land use is considered to be the most important factor in calculating nutrient and sediment loads. Agricultural lands, in fact, are assumed to be the *major* source of sediment and nutrient loads to streams. Because sediment loads are not generated by known point sources, all sediment allocations are applied to non-point source loads (PA Tributary Strategy Fact Sheet, 2003). Some nutrient loads, on the other hand, can come from point sources, as in the case of outflow from a wastewater treatment plant. With regards to the third sub-model, stream corridors are treated primarily as conduits that carry water, sediment, and nutrients, not as a source of sediment and nutrients.

C. Legacy Sediment: A Newly Recognized Source of Sediment and Nutrients to the Chesapeake Bay

Whereas the Watershed Model focuses primarily on upland, non-point sources of sediment and nutrients, our research during the past four years shows that bank erosion of historic ("legacy") sediment stored in the stream corridor could account for 50 to 80% of the suspended sediment load in some, and perhaps even many, watersheds throughout the Piedmont and the Valley and Ridge physiographic provinces[1] of Pennsylvania and Maryland. Furthermore, our detailed laboratory analyses indicate that these sediments contain high concentrations of nitrogen (up to 4.3 lbs/ton) and phosphorus (up to 1.9 lbs/ton) that likewise are not included in Watershed Model calculations.

[1] The Piedmont physiographic province is characterized by gently rolling hills, broad sub-planar uplands, and low hillslope gradients, typically less than 4-8 degrees, developed on limestone and schist, whereas the Valley and Ridge province has much steeper slopes in general, and a much larger area with steeper slopes developed on ridges of quartzite and hills of shale. Valley bottoms in the Valley and Ridge commonly are underlain by limestone, and are very similar to valleys in the Piedmont. The key difference is that Piedmont streams don't have the adjacent high ridges of resistant rocks or the large supplies of sediment derived from them (see Figure 4).

II. Scope and Objectives of this Report

As a result of our early reports of these findings, we received funding from the PA DEP, through the Environmental Stewardship Program, and the PA Chesapeake Bay Commission in May, 2006, for the purpose of broadening the scope of this work, increasing the number of study sites, and accelerating the rate of data collection and analysis. The funding was used to purchase equipment needed for nutrient analyses, and to hire a GIS research specialist (Michael Rahnis) and part-time laboratory geochemist (Karen Mertzman). This document is a report of these new data, and our assessment of the role of legacy sediment in providing sediment and nutrient loads to PA tributaries to the Chesapeake Bay. This report is intended to be used as a guide for PA DEP in its policy decisions regarding nutrient and sediment load reduction through stream restoration and related practices.

A. Scope of this Report

In this report, we provide data on mill dam locations in four Pennsylvania Counties, rates of bank erosion of legacy sediment along stream corridors in three of the four counties, and the concentrations of nutrients (phosphorous and nitrogen) in stream bank sediments in all four counties. The product of the erosion rates and nutrient concentrations yields the associated nutrient loading to streams from the stream corridor.

The report begins with a summary of fundamental concepts related to the storage and transport of sediment on the landscape and in waterways. A discussion of legacy sediment and its storage and erosion in the stream corridor is provided as a background to subsequent sections in which we document bank erosion rates at different sites in Lancaster, York, and Centre Counties (Table 1). For each of these counties, as well as for Huntingdon County, we present maps from historic documents to assess the number and locations of 19th c. mill dams that might have trapped sediment in the stream corridor. Lancaster and York Counties are in the Piedmont physiographic province, whereas Centre and Huntingdon Counties are in the Valley and Ridge physiographic province. We selected these counties in order to provide representative examples of the two provinces, which constitute most of the land area within Pennsylvania's Chesapeake Bay watershed.

Stream	**Watershed**	**County**	**Physiographic Province**	**Bank Erosion Data**	**Nutrient Data**
Little Conestoga	Conestoga	Lancaster	Piedmont	Yes-multiple sites and stream reaches	Yes-2 sites
Hammer Creek	Conestoga	Lancaster	Piedmont	Yes-1 reach, multiple cross sections	Yes-1 site
Big Spring Run	Conestoga	Lancaster	Piedmont	Yes—1 reach, multiple cross sections	Yes-1 site
Big Beaver Run	Pequea	Lancaster	Piedmont	Yes-1 stream reach (~3000 ft)	In progress
Conoy Creek	Conoy	Lancaster	Piedmont	Yes—multiple sites	Yes-2

				along 2 stream reaches	sites
E. Br. Codorus Cr.	Codorus	York	Piedmont	Yes-1 stream reach	Yes-1 site
Penns Creek	Juniata	Centre	Valley & Ridge	Yes-1 stream reach	Yes-1 site
Emmas Creek	Little Juniata	Huntingdon	Valley & Ridge	No	Yes-1 site

Table 1. Streams, watersheds, counties, and physiographic provinces in this study.

B. Objectives of this Report

We have four goals in assessing legacy sediment for this report, and these goals shaped the data collection and results that are presented in the central part of the report. **The first goal is to identify the approximate distribution and quantity of legacy sediment in storage**. We do this partly through the compilation of historic data on number and locations of mill dams. In addition, we combine known dam locations with 10-m digital elevation data (2-m grid cell size LiDAR in the case of the Little Conestoga watershed in Lancaster County) to generate longitudinal elevation profiles that extend from the head of a stream to its mouth (typically its confluence with a larger stream) and include the location of each mill dam. This approach illustrates where sediment was trapped in reservoirs behind the dams.

The second goal in assessing legacy sediment is to demonstrate how much incision has occurred since dam breaching at particular sites. For the Little Conestoga, its West Branch, and the Indian Run tributary, for example, we use LiDAR (very high resolution topographic data) to show the profile of the top of the legacy sediment surface for comparison with the modern stream channel (water surface). In places where a mill dam is breached and the channel incised, the present water surface is deep within the legacy sediment, and we use LiDAR to measure this amount. In one case, the Hammer Creek site, we present data collected by DEP scientists for the measured amount of sediment eroded since a dam was removed in 2001. Typically, after dam breaching a stream incises back to the level of the pre-European settlement floodplain, or sometimes deeper to the level of bedrock at the valley floor. In these cases of incision into thick reservoir fill deposits, stream banks are high. Given the well-known link between bank height and rate of bank erosion, deeply incised streams at locations of past mill dam reservoirs clearly are potential sources of sediment. Where dams are not breached, the fill surface merges with the present stream channel and banks are generally low.

The third goal is to estimate rates of erosion and volume of legacy sediment removed via bank erosion at sites where dam breaching and incision have occurred. Bank erosion rates are highly variable in space and time, with more bank erosion likely to occur during years of greater annual stream flow and higher velocity flows associated with storms. Bank erosion rates based on several years or decades of data better reflect long-term average values than data collected over a period of months to a year. Funding for this project began in May, 2006, and only one significant storm occurred since that time, in July. It was not possible for us to implement enough monitoring sites (e.g.,

monumented channel cross sections), or to collect data from monitored sites over a sufficiently long time span for the purpose of this report. Instead, we attempted to do something that we consider to be even more accurate and valuable. Where possible, we used high-resolution digital imagery in conjunction with recent high-precision GPS (global positioning system) surveys to assess rates of bank erosion over a period of several to 13 years.

With each storm, this stream corridor erosion database grows and becomes more accurately representative of annual mean values and the spatial and temporal variability in those values. Nevertheless, the data that we collected to date, in combination with some that we compiled from additional sources, provides a reasonable estimate of the approximate range of stream bank erosion rates, and is the best available data for bank erosion in Pennsylvania.

For the Little Conestoga Creek watershed, for which we have LiDAR, we use this data in conjunction with field work, trenching, and hydraulic coring to estimate the volume of legacy sediment along entire lengths of streams. Furthermore, we use the geometry of incised channels to estimate the volume of sediment removed from breached mill ponds. In cases where we know the timing of dam breaching, we are able to calculate long-term rates of stream corridor erosion. In one case, the Denlingers mill site at the mouth of the West Branch of the Little Conestoga Creek, the dam breached in 1901, so we are able to estimate a centennial-scale rate of removal of mill pond sediment.

The fourth goal is to determine the concentration of two nutrients, nitrogen and phosphorous, in the stream bank sediments stored along stream corridors. This was done for all sites listed above, with exception of Big Beaver Run, which is the newest of our study sites. These concentrations are combined with bank erosion rates to estimate nutrient loading to streams from erosion of legacy sediment stored in the steam corridor.

From the data presented here, we conclude in the final section of this report that stream bank erosion is an important source of sediment and nutrients to tributaries of the Chesapeake Bay, and is at least as significant as runoff from upland sources in some watersheds. Importantly, remobilization of historic sediment that has been stored in the stream corridors of the Piedmont and Valley and Ridge provinces for centuries is not fully recognized in the present version of the Watershed Model, which focuses instead on modern land use patterns and their impacts on sediment transport. For these reasons, the results we present here regarding the stream corridor as a significant source of sediment and nutrients could lead to an essential new addition to the Watershed Model.

III. Background: Sources and Yields of Sediment to the Chesapeake Bay and the Significance of Legacy Sediment

A schematic diagram of possible sources of sediment to a stream illustrates that all sediment ultimately comes from one of two sources: the uplands (hillslopes) or the stream corridor (Figure 2a). Both serve as sources or sinks of sediment, and their role

varies with space and time. Fluxes carry sediment from uplands to the stream corridor, but the fluxes are one way, in that sediment is not carried back to the uplands once eroded.

A. Sediment from Upland Sources

Sediment is transported to streams from upland sources by mass movement (including creep and landslides), rilling and gullying, and slope wash. During its transit, some sediment might be stored temporarily on hillslopes. Under the modern climatic regime, landslides are very rare in the Piedmont physiographic province, and not very common in the Valley and Ridge physiographic province. Rilling and gullying were widespread in both physiographic provinces throughout the mid-Atlantic region in the 19th and early 20th centuries, but our analysis of historic air photos indicates that these processes are increasingly rare since implementation of post-1940s soil erosion control practices. Slope wash and localized rilling and gullying are likely to be the most common mechanisms for transporting sediment to streams from upland sources in the mid-Atlantic region at present. The rates at which these processes move sediment to the stream corridor depend largely upon land cover, land use activities, hill slope steepness, and rainfall/runoff conditions.

B. Sediment Sinks and Sources in the Stream Corridor, and Processes of Bank Erosion

Sediment in the stream corridor can be stored in floodplains, alluvial terraces, and alluvial fans. In the mid-Atlantic region, these landforms act as temporary sinks that can hold sediment for time periods that vary from days to tens of thousands--and perhaps even hundreds of thousands--of years. Any one of these landforms can become a sediment source to the stream via channel migration and bank erosion, or even by surface scour during high flood events and channel avulsions. The stream channel itself stores sediment in the form of point bars and medial bars, but these features are part of the active channel bed during high flow and are frequently in transit unless a stream is aggrading (e.g., if a dam is built on the stream). Here, we are more concerned with the much larger volumes of sediment that are becoming remobilized after being in storage for decades to centuries.

> *Significantly, the more sediment stored in the stream corridor, the greater the potential for sediment to come from the stream corridor.*

Bank erosion of floodplains, alluvial fans, and terraces is typically the primary process to mobilize sediment from the stream corridor, making the landforms a source rather than a sink. Bank erosion proceeds laterally and usually occurs through multiple processes (Ritter et al, 2004; Thorne, 1982). The three major processes are weakening of the bank material, mass wasting of the weakened material, and fluvial entrainment of the loosened sediment. Feedbacks occur among these processes. For example, fluvial entrainment of the least resistant (most non-cohesive) bank material occurs during higher velocity flows, leading to undercutting and formation of overhanging ledges in the more cohesive

material (Figure 2b). These ledges are more prone to collapse (mass wasting). Large slabs of cohesive sediment can fall into streams after storms that cause widespread undercutting. Banks become weakened when saturated, a condition that occurs frequently after rain storms in high, steep banks consisting of fine-grained material (e.g., silt and clay) with poor drainage.

Bank erosion is prevalent when thick sections of fine-grained, cohesive material overlie a thin basal layer of coarser-grained non-cohesive material, such as unconsolidated gravel and sand. As discussed next, this is a common condition in both the Piedmont and the Valley and Ridge physiographic provinces because of the relatively recent full-glacial period. Underground water moves readily through the non-cohesive gravel and sand, promoting its erosion and leading to pronounced undercutting at the base of the channel bank.

Fluvial entrainment removes material that accumulates at the base of a bank as it collapses into the stream channel. This removal promotes further bank retreat, as it reduces lateral support for the uneroded bank. This feedback results in sustained bank erosion, and high, steep banks.

C. Geomorphology and Temporal Variability of Sediment Sources to Streams

Sediment sources and transport processes were quite different prior to the modern warm, interglacial period of the past ~12,000 years. Under climatic conditions associated with the full-glacial period that persisted from ~50 to 12 thousand years ago, the Piedmont physiographic province was dominated by periglacial processes, particularly rapid creep processes known as gelifluction (associated with frozen ground and freeze-thaw) and solifluction (associated with saturated soil). At that time, gravel in residual soils was brought to the soil surface by freeze-thaw activity and transported down sideslopes along valleys by rapid creep and shallow sliding. Some tributaries draining sandstone and conglomerate ridges (e.g., the Cocalico Hills in northern Lancaster County) transported gravel downstream to confluences with larger streams and built gravel bars and small alluvial fans.

In the Valley and Ridge, both periglacial and glacial environments existed, as the margin of the North American ice sheet was just north of present-day State College. Substantial amounts of coarse, bouldery gravel were generated by freeze-thaw processes and moved downslope by rock slides, gelifluction, and solifluction. Tributary streams transported substantial loads of coarse sediment from quartzite ridges and deposited it in extensive alluvial fans at confluences with larger streams in lower-gradient shale and limestone valleys.

In both the Piedmont and the Valley and Ridge, gravel supplies to streams were much greater during the 40 thousand years prior to the modern warm interglacial period. This observation is important, because some of the gravel remains stored on hillslopes (particularly the toes of slopes) and valley bottoms (particularly alluvial fans at tributary

confluences). If re-mobilized, gravel in streams can accelerate bank erosion, as discussed above.

D. Physiography and Spatial Variability of Sediment Loads to the Bay

Examination of continuous U. S. Geological Survey (USGS) gage station data collected since 1985 reveals that 10 of the 11 stream stations with the highest sediment yields (load per unit area) are located in the Piedmont physiographic province, and only one of the seven stations (14%) in the Valley and Ridge province has a high yield (Figure 3). Of the 18 stations in the Piedmont, 11 (61%) have high sediment yields.

This finding is unexpected, in that geomorphic data from around the world show that sediment yields are strongly correlated with hillslope gradient, because soil erosion occurs at much greater rates on steeper slopes. Comparison of hillslope gradients in the Piedmont and Valley and Ridge provinces shows that the Piedmont has low hillslope gradients (64% of the area of Lancaster and 47% of York County have slopes <8%), whereas the Valley and Ridge province has much steeper slopes in general, and a much larger area with steeper slopes (37% of Centre County has slopes <8%; Figure 4). What makes this finding even more striking is that the Piedmont has broad, low-gradient uplands bounded by short, relatively steeper slopes along streams that dissect the uplands. This attribute is important, because few geomorphic processes can move sediment across long, low-gradient slopes. Mass wasting along low-gradient slopes is dominated by creep, which is the slowest of the sediment transport processes on hillslopes.

It could be argued that the cause of the anomalously high sediment yields from Piedmont watersheds is modern land use. Perhaps agriculture, or construction activities, is more common in Piedmont watersheds than in the Valley and Ridge? This hypothesis is unlikely to explain the discrepancy, however, because many of the gage stations with low yields are also from watersheds with modern agricultural activity. Another possibility is that more gage stations are needed in order to more accurately assess spatial variations in the data. The Valley and Ridge province has only seven stations and the Allegheny Plateau two, whereas the Piedmont has 18.

E. Legacy Sediment as an Explanation for Anomalously High Sediment Loads from the Piedmont

We propose that the spatial variability and anomalies in the USGS sediment yield data are associated with the amount and nature of historic sediment stored in the stream corridor, and the timing of its remobilization. The process of remobilization is enhanced by widespread stream incision that leads to bank erosion. We observe that incision is the result of dam breaching and removal. Dams typically breach naturally during storms, particularly when obsolete and no longer maintained. More recently, many historic dams are being removed deliberately, because of the safety hazards they pose and the desire to improve fish habitat and passage.

Mill dams and legacy sediment occur in watersheds throughout the Piedmont and the Valley and Ridge provinces of Pennsylvania and Maryland, but several aspects of stream corridor sediment in the Piedmont might lead to its greater likelihood of yielding higher modern rates of sediment loading to streams. The first of these is the greater proportion of fine-grained, cohesive material in the banks, which results from the different bedrock types and stream gradients (coarser-grained bedrock and steeper gradients in the Valley and Ridge) in the two provinces. The second is the amount of incision and heights of banks in the Piedmont, which are quite deep and high, respectively, in many places.

Another possibility is that many Piedmont dams only recently began to breach, whereas those on the steeper Valley and Ridge streams breached longer ago. The reasoning in this case is that a gage station established near a recently breached dam would record a higher load than if it were installed many decades after the dam had breached. Two of the gage stations with exceedingly high loads in the headwaters of the Conestoga watershed, for example, are near the town of Churchtown, where multiple historic dams for mills and forges existed until the 1970s. The gage stations at these locales might have captured relatively transient pulses of sediment associated with recent dam breaching. Historic low-head dams in the Piedmont might be less prone to destruction than those in the Valley and Ridge during storms because they are on lower gradient streams with finer sediment loads. It also is possible that Piedmont mills and associated dams and races were abandoned later than those of the Valley and Ridge due to economic or social differences. In Lancaster and York Counties, for example, some traditional water-powered mills still operate.

IV. Legacy Sediment: Definition, Origin, and Historic Accumulation

A. Definition and Origin of Legacy Sediment

The Legacy Sediment Workgroup, established by the Pennsylvania Department of Environmental Protection (PADEP), defined legacy sediment as follows:

> Sediment that was eroded from upland hill slopes after the arrival of early Colonial American settlers and during centuries of intensive land uses; that was deposited in valley bottoms along stream corridors, burying pre-settlement streams, floodplains, wetlands, and valleys; and that altered and continues to impair the hydrologic, biologic, aquatic, riparian, and chemical functions of pre-settlement and modern environments. Legacy sediment often accumulated behind ubiquitous low-head mill dams and in their slackwater environments, resulting in thick accumulations of fine-grained sediment.

Large amounts of legacy sediment accumulated and were stored in stream corridors in the mid-Atlantic region for several reasons. First, modern analogs throughout the world indicate that early American erosion rates probably were very high during the first wave of land-clearing and deforestation for farming. Pre-European settlement soils were much

thicker than today, and most of the mid-Atlantic region was covered with an extensive, old-growth forest of mixed deciduous and conifer trees with an extensive root structure that protected this soil from erosion. Our own estimates of soil erosion for the first 150 years of settlement in Lancaster County are as high as 4 to 9 inches of topsoil. Over a large area, this is a substantial amount of sediment.

Second, our research reveals that many of the streams in the mid-Atlantic Piedmont region were wetlands prior to the arrival of European settlers, and would have been unable to transport the large amounts of sediment supplied from upland hill slopes.

> *The most important cause of the widespread, prolonged, and thick accumulation of sediment in stream corridors, however, was the widespread, prolonged alteration of streams for the purpose of water-powered milling (see Figure 6).*

Dam building for water-powered mills began in the eastern US in the late 1600s and persisted until the early 20th century. European settlers began building dams that spanned valley bottoms as soon as they arrived in order to harness water power to run saw mills, grist mills, cooper shops, machine shops, forges, foundries, and many other mechanical operations that required energy. Dams also were built to store water in reservoirs for other activities, such as at mine sites where water was needed for many aspects of mineral processing.

Legacy sediment grades to the level of dams, and it thickens downstream to the locations of dams, which indicates that damming was of prime importance to the trapping of sediment in streams that were sediment-laden during 18th-early 20th century American history. We have found dams submerged by sediment, but only in the case where backwater effects from a downstream dam caused the sedimentation, not as a result of an overwhelming supply of sediment to an un-dammed stream segment.

B. Dams, Races, Mills, and Reservoir Sedimentation

Mill sites were especially abundant in the mid-Atlantic region during the 18th to early 20th centuries because of intensive agricultural activity (i.e., the need for mills to process local goods), the concurrent rise of industrialism, the ideal physiographic setting for mill dams and races, and the proximal locations of major urban areas and ports (Baltimore, Philadelphia, Washington, DC, and New York City). Southeastern Pennsylvania and Maryland were the wheat basket of early America, and central Pennsylvania and northern Maryland were the center of the mining industry, particularly for iron.

> *The remarkably large number of water-powered mills in the eastern US, which was >65,000 by 1840 AD (see Figure 6), and the close spacing of mills and dams along streams, led to widespread accumulation of sediment in stream corridors.*

The typical mill dam spacing is 3 km along low-gradient streams (0.001-0.002) in the Piedmont region and limestone and shale valleys of the Valley and Ridge. As discussed in subsequent sections for specific study sites, our field mapping and LiDAR imagery analysis (n>90 millponds) demonstrate pervasive backwater effects along streams in the form of aggradational wedges of fine-grained legacy sediment that thin and extend upstream of known locations of mill dams for several km, even into un-dammed tributaries.

Historic data on hundreds of these dams in southeastern PA indicates that the great majority of them were between 6 and 13 ft in height, with an average height of 8 ft in Lancaster County and 10 ft in York County. Stream gradients are slightly steeper in York County, which probably accounts for the need for slightly higher dams to impound sufficient water in reservoirs upstream of mills. [Our compilation of detailed records for dams and mills in York and Lancaster County is available on request.]

Reservoirs behind low-head dams on small to moderate-sized streams fill readily with sediment when streams carry large amounts of sediment and stream gradients are low. Modern reservoirs provide an analog for this filling, as in the example of a USDA pond built in the early 20th century, which filled completely with sediment in less than 30 years (Figure 5a and b). Sediment wedges behind dams generally have gradients ~30-60% lower than those of valley floors, a phenomenon also noted in studies of aggradation upstream of Byzantine era dams in Israel and of early 20th century check dams in the American Southwest.(Leopold and Bull 1979; Leopold 1992).

Sedimentation occurred in all mill dam reservoirs that we examined along the streams listed in Table 1, as well as on other streams not presented here. Historic documents and maps in Pennsylvania and Maryland reveal that mill dams were rebuilt after floods, and were shifted up or downstream and raised as ponds filled with sediment. Races and ponds were partly dredged or flushed out in an effort to extend their usable lifetimes. Races also were relocated and extended, sometimes reaching a mile in length. With time, newer races were dug in the legacy sediment behind older mill dams. Sequences of historic maps show that ponds gradually became smaller, and eventually disappeared on late-19th c. maps. In some cases, only races are present on early 20th c. maps, and many of these are gone by the late 20th c.

A typical example of the impact of milling on streams is given by Hammer Creek in northern Lancaster County (Figure 5). The 1864 map of Elizabeth township shows multiple mill dams and races along Hammer Creek (Figure 5d). One of these dams, shown in ~1910 in Figure 5c, is breached today, and the stream channel is deeply incised into the reservoir sediment. At the remnants of the dam, the stream flows along the base of the wall of the dam on its upstream side, then crosses over rubble from the dam base near right bank. A 25-ft dam was built at Speedwell Forge just upstream in the 1960s, submerging the dams and ponds of the two upstream mill sites shown in the 1865 map. Further upstream, at the Pump Station site just north of Rte 322, a dam was rebuilt at least once within an older stack of legacy sediment, and the reservoir for this newer dam submerged an older dam and small sediment-filled reservoir on a minor tributary (Walnut

Run) to Hammer Creek. In 2001, this newer dam—inset within the older reservoir fill--was removed. The stream has been monitored by PA DEP scientists to document the removal of sediment from the upstream reservoir (discussed in Section V-D). The reservoir actually consists of at least two sets of sediment fill, the younger of which is inset within the older and higher stack of legacy sediment. Both sedimentary deposits are being eroded since incision that occurred after dam removal.

C. Characteristics of Streams with Legacy Sediment

Stacks of fine-grained, horizontally bedded, often laminated sediments are ubiquitous along streams of the Piedmont and those in the in the Valley and Ridge with limestone and shale bedrock. The finely laminated nature of one to several meters of sediment is more characteristic of lacustrine (lake) than fluvial deposition, and indicates quiet, slackwater or backwater deposition rather than deposition along point bars of streams or on floodplain surfaces by overbank flow during flooding. Furthermore, at hundreds of sites, we observe that the top surface of the fill—often incorrectly assumed to be a stream's modern floodplain—grades downstream to the crest of an historic dam.

> *From these characteristics, we conclude that much of the sediment stored in steam corridors in Pennsylvania and Maryland is associated with 18th-early 20th c. mill damming. This fact matters greatly, because it links both historic sedimentation along streams and the more recent incision and bank erosion -to the processes of dam building and breaching, respectively.*

Along a given stream, both incised and un-incised sections often are found adjacent to one another, because some dams are still in place whereas others breached long ago, perhaps during hurricanes and storms of the 1970s or 1990s. Still others were removed recently for safety and fish passage reasons. When a dam is unbreached, a shallow channel flows across the sediment fill and spills over the dam (Figure 7a). At locations where a mill dam is breached, the channel has incised into the fill (Figure 7b). The depth of incision is roughly proportional to the time since dam breaching, but from the limited data we have, incision can occur within weeks to months of breaching unless other grade control structures (e.g., bridges, sewer lines, or culverts) impede incision.

Once incision has propagated upstream through the entire mill pond reservoir—which includes the stream reach impacted by backwater effects above the flat water of the original mill pond--the stream begins to erode its banks by the processes of undercutting, collapse, and entrainment described above. Simultaneously, adjacent tributaries begin to incise once the wave of incision passes their mouths.

Deep stream channel incision through the historic sediment that filled tens of thousands of mill pond reservoirs is revealing early American valley bottoms as they existed at the time of European settlement. As banks erode, we are presented with an ever-changing lateral view of pre-settlement valley bottoms (Figure 8). The pre-settlement horizon generally appears as a thin (<0.5 m), dark greyish brown to black, organic-rich (roughly

20-25 weight %C) silty clay above a basal gravel and forms a resistant horizon. The large amount of disseminated organic matter, combined with the abundance of fresh wood, leaves, seeds, and other organic detritus, gives the pre-settlement material a dark gray to black color. Forty-nine radiocarbon ages from the dark organic-rich sediment sampled from the base of stream bank exposures and trenches throughout Pennsylvania and Maryland range from 11,500 to 300 yr BP (Figure 9).

The age range spanned by these deposits indicates that pre-settlement floodplains and/or marshes were stable throughout the warm interglacial Holocene Epoch. Over a period of ~10,000 years, sedimentation rates were <0.03 cm/yr. From our stratigraphic investigation, including the use of trenches and coring, we observe that pre-settlement stream channels were small and shallow, carried little sediment, and frequently flowed overbank onto a broad mosaic of wetland types.

Based on isotope geochronology (Appendix 1), about 97% of the 5-m-thick post-settlement alluvium in the mill pond reservoir at Denlinger's Mill on the W. Br. Little Conestoga was deposited between 1730 and 1850 (Figure 10). At Big Spring Run, a tributary to Mill Creek south of Lancaster City, roughly 80% of the 0.9-m-thick alluvium overlying the organic stratum was deposited between 1730 and 1850 (Figure 11). Our analysis of the sediments at both sites indicates that they were deposited by the year 1850 or earlier (as some of the upper surface might have been eroded), and indicates that these reservoirs reached their sediment storage capacity by at least 1850.

Although we don't have the same level of analytical detail for other sites, we conclude from historic documents and maps that many mill ponds had reached capacity by the late 1900s. This conclusion was noted earlier when we described historic maps which illustrate ponds that are smaller and, eventually, gone on later versions of maps.

D. Causes of Remobilization of Legacy Sediment and Processes of Erosion

The preceding sections demonstrate that aggradation—the widespread filling of valley bottoms with sediment—began immediately after dam building and persisted for as long as 150 years throughout whole regions. Many historic mill dams still remain intact, and at these sites shallow water with a nearly flat surface spills over the dam (c.f. Figure 7a, and Little Conestoga at mile mark 14 on Figure 22, and W. Br. Little Conestoga at mile mark 3.4 on Figure 23).

At sites where dams are breached, however, channels are incised into the fill (c.f., Little Conestoga from mile marks 3 to 11, Figure 22, or W. Br. Little Conestoga from mile marks 4 to 8). We have found streams with both types of reaches adjacent to one another, downstream of large areas with impervious surfaces (e.g., the Little Conestoga Creek downstream of Park City mall, which has no stormwater detention; see Figure 22).

> *We conclude that stream channel incision, which leads in turn to bank erosion, occurs not after a pond fills to its capacity with sediment, but after its dam is breached.*

Removal of the dam produces an instantaneous drop in base level, providing an increase in potential energy equivalent to the height of dam removed. For example, consider the sediment-filled reservoir shown in Figure 5b. Dam breaching at that site led to a channel incised into the fill (on right bank below power line on photo). The difference between the historic mill dam reservoirs in the mid-Atlantic region and the reservoir shown in Figure 5b is that the mill dam reservoirs filled long ago, and their wide, stable surfaces adjacent to the modern stream channel became vegetated. In Pennsylvania and Maryland, many of these fill surfaces became pastures. It is probable that many farmers, acting over several generations, aided in the process of conversion of filled mill ponds to pasture land, referred to by farmers as "bottom land".

E. Conceptual Models of Streams formed in Sediment-Filled Reservoirs

Doyle et al (2000) have described a conceptual model for the evolution of a channel after dam breaching, and base their model on surveys of two sediment-filled reservoirs and the channels that cut into them after dam removals in Wisconsin. In their model, the channel first incises to the new base level at the dam site, and a knickpoint then propagates upstream through the reservoir fill. With time, the deepened channel undercuts the base of the banks along the channel, especially at meander bends. Gradually, banks retreat by undercutting and collapse, as explained in Section IIIB.

This basic model is appropriate for Piedmont and Valley and Ridge streams in the Cheasapeake Bay watershed, but the particular stratigraphy of pre-settlement and historic sediments stored in the steam corridors of the mid-Atlantic region affect the evolution of channels after dam breaching. In the Pennsylvania and Maryland streams that we have studied, bank erosion is accelerated in many places by the presence of a basal gravel layer between the bedrock valley floor and the organic-rich pre-settlement horizon (discussed in Section IIIC and Appendix 1; see also Figure 12). This basal gravel, a long-term lag of resistant minerals formed by weathering and erosion, consists largely of iron-stained, angular to sub-rounded quartz pebbles and cobbles derived from quartz veins that riddle Paleozoic rocks in the Appalachian region. Toward valley side slopes, the gravel coarsens, thickens and merges with Pleistocene (ice age) periglacial solifluction lobes and colluvium. Many streams in the mid-Atlantic region were forced to one side of the valley bottom or the other after mill ponds filled with sediment, probably to provide more land for pasture or for purposes of establishing property boundaries and reducing flooding. Unfortunately, once streams along valley margins incise through the legacy sediment, they have ready access to the coarse gravels stored along the toes of slopes.

Gravel accelerates bank erosion in at least three ways. First, it promotes undercutting beneath more cohesive, fine-grained sediments. Second, the gravel itself impacts banks downstream once it is eroded and in transport, and contributes to bank erosion. Third, gravel—which travels as bed load--has a longer travel-time in the channel than sand, silt,and clay, which travel mostly as suspended load. As a result, gravel occurs as relatively slow-moving bars in the channel, and these bars deflect stream flow into the stream banks (Figures 12 and 13).

The processes outlined here document the transformation of sediment-filled reservoirs to incised channels with bedrock floors and high banks that slowly transport gravel along the bed and rapidly carry silt and clay downstream (Figure 13). As the fine-grained legacy sediment is removed, the bed of the channel widens and becomes mantled with patches of gravel. As bars develop and enlarge, channels erode the opposing banks and branch around the bars, forming braided streams.

> *In essence, what once were wetlands and marshes, with small, shallow anabranching channels that frequently flowed overbank, are becoming braided gravel-bed streams. In the process, fine-grained sediment stored for more than one hundred years is washing downstream toward the Chesapeake Bay.*

Stream reaches can be identified based on their location with respect to prior mill ponds, with a reach beginning at a dam and extending upstream to the next dam. These reaches are significantly affected by the locations of dams not only because of the base level control after dam breaching, but also because of the relation of bank height and sediment thickness (also volume) to the locations of dam.

In Figure 13, for example, we see two "pond" reaches. The dam in the lower reach is breached, and the channel upstream is incised, exposing legacy sediment, the pre-settlement floodplain/wetland mosaic, colluvium, and bedrock. As gravel is eroded from the older deposits, it is transported along the incised channel, forming bars like that shown on right bank at a meander bend. The pre-settlement organic-rich horizon forms a prominent ledge on left bank that protrudes into the channel as the bank retreats on the outside of the meander bend. The dam at the upper reach of the stream is still in place, and the stream above it is not incised. The valley is likely to be filled with sediment, as in the case of the reservoir in Figure 5b, or Lake Mill located at mile mark 14, Figure 22.

In Figure 14, a LiDAR-derived digital terrain model (DTM) of a portion of Little Conestoga Creek in the vicinity of the Conestoga Country Club (see mile marks 8 to 11 on Figure 22), one complete mill pond reach is shown in plan view. This reach is very similar to that shown as the lower reach in Figure 13. During the 18th and 19th centuries, a 10-ft dam at the Levans Mill site (and possibly an older one just downstream) that ponded water along two large meander bends resulted in sedimentation that produced wide valley flats. The sediment wedge in this "pond" reach thins upstream. The dam breached in ~1930, and the Conestoga Country Club golf course was built shortly thereafter. We cored the flat on left bank upstream of the mill dam, and mapped and surveyed the entire reach of stream upstream to the mill dam at J. Stoneroads (also breached). Coring and bank exposures indicate that the channel is not yet fully incised to bedrock at many locations. The bank heights are greatest near the dam, although remnants of the dam are still in place and the channel is not yet fully incised. On right bank on the outside of the meander bend just upstream of Levans Mill dam, the channel has eroded deeply into coarse colluvial gravel and exposed substantial areas of bedrock. On left bank ~400 yards upstream of the dam is exposed a corduroy road at the base of the legacy sediment. At this same location, the channel is eroding along the left valley

margin, again exposing bedrock and colluvium, and causing the incision of legacy sediment at the mouth of a small tributary, which appears on Figure 14 as a gully flowing from south to north. Part of this reach received Growing Greener funding for restoration in 2007.

V. Results of this Work: Quantifying Legacy Sediment Storage, Erosion, and Nutrient Concentrations

During the past six months, since receiving funding from PA DEP and the PA Chesapeake Bay Commission, we have added numerous sites to our research effort in order to assess the distribution of legacy sediment throughout Pennsylvania, to quantify bank erosion rates at multiple locales, and to quantify nutrient loading from bank erosion. At present, we have studied 44 sites in Pennsylvania and 20 sites in Maryland (Figure 15a). Our Pennsylvania Piedmont study sites are in Lancaster and York Counties, whereas Centre and Huntingdon Counties are in the Valley and Ridge physiographic province. We selected these counties in order to provide representative examples of the two provinces, which constitute most of the land area within Pennsylvania's Chesapeake Bay watershed.

For some of the study sites, we have much more data than others, for one of two reasons. First, we began working at some sites as early as 2003-2005, prior to the recent initiative to assess legacy sediment in terms of its contribution to sediment and nutrient loading to the Bay. Until 2006, we focused on Piedmont sites because of their proximity to our research base at Franklin and Marshall College. Second, Lancaster County GIS Office has substantial holdings of high-resolution digital topographic databases dating back to 1993, including 2005 LiDAR for much of the stream corridor in the Conestoga watershed. We are able to assess bank erosion rates much more easily and accurately with the high-resolution data available for Lancaster County, and are limited in our ability to do so in other counties. For counties without such databases, we must rely upon repeat surveying and bank erosion pins to quantify bank erosion.

For the above reasons, five sites in particular provide significant information regarding legacy sediment volumes and erosion rates (Figure 15a and b). These sites are the Hammer Creek pumping station (site 54), Big Spring Run (site 53), the W. Br. of the Little Conestoga at Denlingers Mill (site 51), Conoy Creek at the Masonic Homes (site 26), and Big Beaver Run (site 17). In addition, for a sixth site, the East Branch Codorus Creek in York County (site 34), we use data provided by Aquatic Resource Restoration Company (ARRC) for erosion rates (sites 33-36 on Figure 15a).

In the case of nutrient analysis, we are able to sample sites anywhere and to measure the concentrations of nutrients in our lab at Franklin and Marshall College. As a result, we have nutrient data for three sites for which we do not yet have erosion data. These sites are Levans Mill on the Little Conestoga (Lancaster County), Penns Creek (Centre County), and Emmas Creek (Huntingdon County). Conversely, for our newest study site

at Big Beaver Run, we only have erosion rate data, as we have not yet completed the nutrient analysis (work in progress).

These nine sites are discussed in the following section, and are followed by a concluding section that summarizes our estimates of bank erosion rates, nutrient concentrations, and nutrient loading from legacy sediment for the seven sites for which we have both bank erosion and nutrient concentration. Over the next few months, this database will include even more sites for which we have both types of information.

A. Quantifying Legacy Sediment Storage: Locating Historic Dams

Identifying the locations of historic mill dams is the first step in determining where legacy sediment is likely to be stored, and where it is most likely to be thickest. Based on this type of data alone, it is possible to infer which areas and streams are likely to have more legacy sediment in storage.

We use historic 19th c. maps and documents to locate dams and, in some cases, to infer dam locations from races and mills (Figure 16). Although some older maps have been valuable to find dams at specific locations, only 19th c. township maps have provided enough aerial coverage to enable us to locate dams across entire counties. We have found historic low-head dams in the field that are not on any maps that we have examined; these might have been built much earlier than the maps we use and perhaps the associated mill was gone, so the structure was not included during 19th century map-making. Another possibility is that the dam was built after the maps that we use, although we have examined maps in series to account for this possibility. Finally, it is possible that some small dams simply were not included in 19th c. maps.

As we locate historic dams, we add them to a growing GIS database. For Lancaster and York Counties, we have substantial information on dam heights, mill production, timing of dam building, etc. These databases are available upon request, as are the GIS shapefiles for the dam locations.

Here, we present the locations of mill dams for York and Lancaster Counties (Figure 17), Centre County (Figure 18), and Huntingdon County (Figure 19). The corresponding numbers of historic mill dams are as follows: York: 244; Lancaster: 334; Centre: 186; and Huntingdon: 206. Lancaster and York Counties have the highest densities of mill dams, followed by Huntingdon and then Centre Counties (see Figure 6).

B. Quantifying Legacy Sediment Storage: Estimates of Reservoir Fill Volumes

We use the Conestoga watershed, for which we have the highest resolution topographic data (2-m grid cell size LiDAR DEM), to estimate volume of sediment stored in its stream corridors. For reference, the boundaries of the Conestoga watershed are shown highlighted in gray in Figure 1, the watershed map of the Chesapeake Bay. The Conestga watershed is 0.7% of the area of the Chesapeake Bay watershed.

We used three different approaches to compute volume of legacy sediment stored in the Conestoga, which provide a range of reasonable estimates. First, using a mean dam height of 8 ft, average valley width (328 ft) measured from air photos and lidar data at ~40 sites, and pond extent (~7900 ft) based on average stream gradient (0.001) and mean dam height, we calculate reservoir volume from the number of recorded dams in the watershed (n = 163) to obtain a minimum estimate of 61 x 10^6 $yards^3$ of stored sediment. Second, to account for dam-induced backwater effects, base-level rise, and tributary aggradation, we assume that 4 ft (half the mean dam height) of sedimentation occurred along all streams in the Conestoga watershed (in aggregate 644 miles long), yielding a maximum estimate of 162 x 10^6 $yards^3$ of sediment. Finally, using high-resolution LiDAR imagery to measure aggradational surface area, half the mean dam height for sediment depth for the Little Conestoga tributary, and a proportionally factor to extrapolate throughout the entire Conestoga watershed, we calculate 84 x 10^6 $yards^3$ of stream corridor sediment storage. These estimates correspond with a loss of ~2.8-7.4 inches of soil from the hillslopes during early American land clearing and farming.

These estimates provide a range of plausible volumes of legacy sediment initially stored in the Conestoga watershed, from 61 x 10^6 to 162 x 10^6 $yards^3$ of sediment. Using a bulk density of 1.22 $tons/yd^3$, this range corresponds with an estimate of 74 to 198 x 10^6 tons of legacy sediment. We consider the value of 84 x 10^6 $yards^3$ (102 x 10^6 tons) to be a plausible estimate.

Our work in progress includes doing similar computations for other tributaries, including Codorus Creek in York County, Penns Creek in Centre County, and Emmas Creek in Huntingdon County.

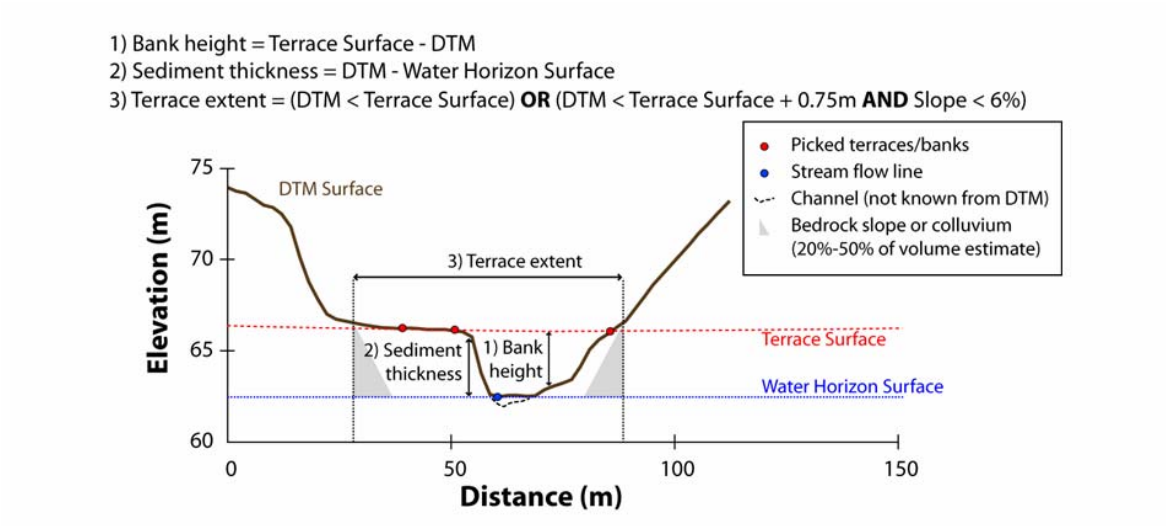
C. Quantifying Legacy Sediment Storage and Erosion: Longitudinal Profiles of Streams and Valley Fill (Legacy Sediment) Surfaces

The valley fill surfaces produced by legacy sediment are readily observed from air photos and digital elevation data (c.f., Figure 14). LiDAR is especially useful because it has sufficient resolution (2-m grid cell size) to resolve legacy sediment fill terraces and incised channels. It is not possible to distinguish these two from one another with databases of lower resolution, such as the 1/3 arc-second USGS National Elevation Data.

Figure 20 illustrates how we use LiDar to map bank heights and the depth of incision into those banks (to the stream water surface). In this case, the mouth of the West Branch of the Little Conestoga Creek, the terrace height (~bank height) varies from 4 to >19 ft and corresponds with the dam height of 20 ft at Denlingers Mill (Figure 24). Note that the terrace/bank height is greatest with increasing proximity to the dam in the downstream direction, and that the fill surface is graded to the crest of the dam. From this data, we are able to estimate that this single 2.3-mile long mill pond reservoir, including its backwater area, still contains about 171,659 tons of legacy sediment.

Using the approach illustrated schematically in the diagram below, we estimate that 147,686 tons of sediment has been removed by channel incision and erosion since the dam breached in 1901. About half (46%) of the sediment originally stored in this

reservoir has been eroded since 1901. Using the measured bank heights along this reach of the W. Br. Little Conestoga, we calculate that the average rate of sediment produced by bank erosion since 1901 (~105 years) was 0.17 tons/ft/yr (tons per linear foot of stream length per year). This corresponds to an average bank erosion rate of 1.1 ft/yr, using an average bank height of 8 ft. This number is very similar to that we have calculated by repeat measurements of the distance between the bank edge and a line of fence posts along a corral on left bank ~100 ft to 300 ft upstream of the breached dam.



Two-dimensional representation of method of assessing volume of legacy sediment in storage (remaining) and removed by channel erosion, using a digital terrain model (DTM).

A similar analysis could be done for the entire length of the W. Br. Little Conestoga, or any stream where we have LiDAR data coverage. Figure 21 shows the area of coverage for the Little Conestoga (are 64 mi^2), of which the W. Br. is one of the largest tributaries. In Figure 21 we show the area of the legacy sediment valley fill surface (referred to as the terrace extent) throughout the watershed, and the locations of known mill dams. Longitudinal profiles of the stream flow line (channel water surface) and legacy sediment surfaces are shown for the entire W. Br. Little Conestoga, Indian Run, and the Little Conestoga, in Figures 22, 23, and 26. From this information, it is possible to estimate the entire volume of sediment stored along the Little Conestoga, and the amount removed by incision and bank erosion, as was done for the Denlingers Mill site. The procedure used for this type of analysis is outlined in Figures 25 and 26, and the GIS computations are listed in Appendix 12.

For those streams for which LiDAR is not yet available, we combine known dam locations with 1/3 arc-second USGS National Elevation Data to generate longitudinal elevation profiles that extend from the head of a stream to its mouth (typically its confluence with a larger stream). This approach illustrates where sediment was trapped in reservoirs behind the dams, but we are not able to use these longitudinal profiles to

estimate volume of legacy sediment. LiDAR will be available for all of Pennsylvania within 2-3 years, however, and at that time the algorithms and procedures that we are developing can be used to do the same types of legacy sediment analyses anywhere with LiDAR coverage.

D. Quantifying Rates of Bank Erosion and Legacy Sediment Removal

In this section, we first present results of a first-order approach at estimating the contribution of bank erosion to the suspended load in the Conestoga watershed. From this analysis, we infer what rates of bank erosion would be necessary to generate this amount of sediment. Following this analysis, we provide data on bank erosion rates at six sites, and a compilation of data from 15 other sites.

a. Sediment Budget Analysis for the Conestoga Watershed Using a reservoir fill volume of 84 x 10^6 $yards^3$ for the Conestoga watershed (see Section V-B), we develop a post-dam breach, centennial-scale, watershed-wide sediment budget for the Conestoga basin. From air photos, lidar topographic profiles, and channel cross section surveys, we calculate that, on average, channel cross-sectional area is 10% of the valley-fill cross sectional area. Making the assumption that this percentage was removed by channel incision and lateral bank erosion since dam breaching, and noting that historic records indicate many dams breached since the early 20th c, we calculate an average annual stream sediment load for the past 100 years of ~102,000 ton/year. This is 63% of the average annual suspended sediment load, 162,131 tons/yr, measured at a gage station near the mouth of the Conestoga since 1985[20].

> *If we use the full range of estimates of legacy sediment volumes, then 45% to 122% of the suspended sediment measured at the Conestoga River mouth gage station could be from bank erosion of legacy sediment.*
>
> *If all suspended sediment measured at the mouth of the Conestoga River came from the stream corridor, bank erosion rates for the entire watershed (644 miles of stream length, average bank height ~4-5 ft) would be ~0.3 ft/yr.*

b. Rates of Bank Erosion Measured at Six Sites Our measurements of bank erosion rates (6 sites for periods of 1.5 to 105 yrs) yield averages that vary from 0.7 to 3.3 ft/yr. These values are much greater than the 0.3 ft/yr estimated above as the average rate of bank erosion necessary to produce all suspended sediment passing by the Conestoga River mouth each year.

(Note: There are sites where little or no erosion is occurring, as in cases where dams are not breached, or channel stabilization controls are in place. We focused on sites with measurable rates of bank erosion for this report, but are monitoring several sites where little erosion is occurring. As a consequence, the values presented here probably are higher than actual regional averages. We view them as a good estimate of the high end of the range of erosion rates.)

We also present our data in terms of sediment production rates (volume = bank height * lateral bank erosion rate * length of stream eroded, which is converted to tons with a 1.22 tons/cubic yard conversion factor). For the six study sites, sediment production rates range from 0.2 to 0.9 tons/ft/yr, with a mean of 0.39 ± 0.24 and a median of 0.34. Hammer Creek at the Pumping Station site is higher than all others; this is the site where a dam was removed in 2001. Removing this value from the six data points yields a mean value of 0.31 ±0.09 tons/ft/yr (note the lower standard of deviation).

A compilation of our bank erosion measurements, including the data collection procedure and time period of estimation, is presented in Table 2 and illustrated in Figure 43. Figures that illustrate each of the sites and the data collection procedures are presented in Figures 28-42, along with longitudinal profiles and photographs of most of the sites.

c. Compilation of Growing Greener Project Report Data on Bank Erosion Rates
These estimates also are consistent with measured rates of bank erosion from 15 Growing Greener project reports that were compiled by Kreider (2006). These reports, based on channel cross section and bank pin erosion measurements, indicate similar bank erosion and sediment production rates (Table 3). The compilation converts bank erosion rates to sediment production rates, based on stream channel length and bank height for the area studied. The compiled data vary from 0.2 to 4 ton/ft/yr (tons per linear ft of stream channel per year) in all but 2 cases, which are much higher (6 and 10 ton/ft/yr). The average value for the lower 13 rates is 1.1 ton/ft/yr, just slightly higher than the average for our data.

d. Potential for Bank Erosion of Legacy Sediment Based on this work, we developed a matrix that illustrates a way to assess the potential of a stream corridor to provide sediment via bank erosion. Where legacy sediment is thickest and channel incision deepest, the amount of bank erosion generally is greatest. However, some sites have significant thicknesses of legacy sediment but are not yet incised (e.g., dam unbreached, or other grade control structure in place). These sites also have a great potential for bank erosion in the future, if conditions change.

Locality [Site #]	Bank Erosion Method	Erosion Time Period, yrs	Average Bank Erosion Rate, ft/yr	Bank Erosion tons/ft/yr	Source of Bank Erosion Data
Big Spring Run [53] Lancaster County	TGS, 12 Xsections	1.5	1.1	0.2	LandStudies Inc. and F&M
Denlinger's Mill [51] Lancaster County	LiDAR;Monum	105;2	0.7-1.1	0.17	F&M
Levan's Mill 52] Lancaster County	TGS; IP	NA	NA	IP	
Hammer Creek [54] Lancaster County	TGS; LL; 6 Xsections	5	3.3 upstream of dam breach	0.94	DEP
Conoy Cr. (T1) [26] Lancaster County	TGS; LL; BP DOQ; GPS	1 to 5 yrs	1.3 (locally much higher)	0.34	F&M and LandStudies, Inc.
EB Codorus Cr. [34] York County	DOQ; TGS; BP; GPS	1-3 yrs	1 to 2	0.4	ARRC and F&M
Big Beaver Run [17] Lancaster County	DOQ; GPS	12	0.9 (locally much higher)	0.3	F&M
Penns Creek [57] Centre County	GPS	NA	NA	IP	F&M
Emmas Creek [23] Huntingdon County	GPS	NA	NA	IP	F&M

TGS = Total Geodetic Station surveying
LL = laser level surveying
DOQ = digital orthophoto quad repeat analysis
LiDAR = LiDAR analysis
BP = Bank pin measurements
GPS = GPS surveying of bank edge
Xsection= monumented cross sections
R&V = Ridge and Valley
Monum=survey of fixed object with reference to bank over time
IP = data collection in progress
NA = not applicable

Table 2. Compilation of bank erosion rates, and associated sediment production rates from bank erosion, for 6 sites investigated in detail for this study.

Creek (County or State)	Length of Stream (ft)	Measured Erosion Rates (tons per year)	Sediment Production Rate (tons/ft/year)
Choconut (Susquehanna)[1]	7,920	50,000	6.3
Codorus - East Branch (York)[2]	5,410	2,070	0.4
Codorus Creek-South Branch Granary Rd. (York)[3]	2,200	2,900	1.3
Codorus Creek-South Branch SBCC 026 (York)[4]	400	450	1.1
Codorus Creek-South Branch SBCC 015 (York)[5]	550	578	1.1
Codorus Creek-South Branch SBCC 025 (York)[6]	300	1200	4.0
Codorus Creek-South Branch Phase I (York)[7]	1,770	1,083	0.6
Codorus Creek-South Branch Phase II (York)[8]	2,050	500	0.2
Codorus Creek-South Branch Phase III (York)[9]	4,170	2,180	0.5
Conewago (Adams)[10]	800	8,000	10.0
Cowanshannock (Armstrong)[11]	80	31	0.4
Cowanshannock (Armstrong)[12]	50	52	1.0
Crabby (Chester)[13]	400	1,444	3.6
Long Draught Branch (MD)[14]	1,607	57	0.0
Octoraro -West Branch (Lancaster)[15]	1,650	1,200	0.7

Table 3. Compilation of bank erosion data from Growing Greener project reports, compiled by J. Kreider for LandStudies, Inc (2006). Footnotes in column 1 are cited in Kreider, which providse references for the data collectors, including ARRC, Skelley and Loy, and LandStudies, Inc.

E. Quantifying Nutrients Stored in Stream Bank Sediment

a. Analytical Methods Nutrient contents of stream bank sediments were measured using three analytical instruments: (1) Inductively Coupled Plasma (ICP) Optical Emission Spectrometry for trace metals and phosphorus; (2) Flow Injection Analysis (FIA) for 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 trace elements that are sorbed onto clay and Fe-Al oxide surfaces, which can be become available for plant uptake under optimum E_h/pH conditions.

Field and laboratory procedures are presented in Appendix 2. Appendix 3 lists the results of analyses of certified reference standards that were analyzed as unknowns and subsequently used to assess quality assurance and quality control parameters related to our analytical procedures. In general, 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.

b. Nutrient Contents of Stream Banks Our analyses of stream bank sediments from five watersheds in four counties and two physiographic provinces are summarized in Table 4 and Figure 44. These data show average N concentrations ranging from 400-2100 ppm (overall mean = 1160 ppm), which equates to a loading of 0.8 to 4.3 lbs N/ton of eroded sediment. The concentrations of P in stream banks range from 340-958 ppm (overall mean = 556 ppm), which equates to 0.7 to 1.9 lbs P/ton of eroded sediment. The concentration of stream bank P is generally 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. Compilations of detailed analytical results for each site are listed in Appendices 4-11, with examples illustrated in Figures 45-50.

Excess concentrations of sediment- and soil-derived nutrients degrade water quality and negatively impact aquatic ecosystems. Under the Chesapeake Bay Agreement, in 2003 the Chesapeake Bay Program agreed to reduce annual nutrient and sediment loads by 100 million pounds of nitrogen, 6.5 million pounds of phosphorus and 0.9 million tons of sediment by the year 2010. These reductions are expected to substantially improve water quality in the Chesapeake Bay. Before these reductions can become a reality, however, it is imperative that the all processes that control nutrient and sediment loads in streams are clearly delineated.

Locality [Site #]	N (ppm)	N Load (lbs/ton)	C (ppm)	C Load (lbs/ton)	P (ppm)	P Load (lbs/ton)	Type
Big Spring Run [53] Lancaster County	1658	3.32	15869	31.74	539	1.08	Average
Denlinger's Mill [51] Lancaster County	1089	2.18	10865	21.73	727	1.45	Average
Levan's Mill 52] Lancaster County	1368	2.74	27844	55.69	568	1.14	Average
Hammer Creek [54] Lancaster County	2162	4.32	30857	61.71	958	1.92	Aggregate
Conoy Cr. (T1) [26] Lancaster County	415	0.83	5640	11.28	532	1.06	Aggregate
Conoy Cr. (T2) [26] Lancaster County	533	1.07	6813	13.63	493	0.99	Aggregate
EB Codorus Cr. [34] York County	790	1.58	10540	21.08	527	1.05	Average
EP Codorus Cr. [34] York County	554	1.11	8691	17.38	527	1.05	Aggregate
Penns Creek [57] Centre County	1256	2.51	13398	26.80	480	0.96	Average
Penns Creek [57] Centre County	1142	2.28	12952	25.90	429	0.86	Aggregate
Emmas Creek [23] Hungtingdon County	1758	3.52	23582	47.16	339	0.68	Aggregate

Table 4. Summary of measured total nitrogen (N), carbon (C), and phosphorus (P) concentrations in stream bank deposits in the Piedmont and Ridge and Valley Physiographic Provinces of Pensylvania. Nitrogen and carbon were measured by elemental combustion analysis and gas chromatography. Phosphorus concentrations were measured using the U.S. EPA 3051 microwave digestion method, combined with and inductively coupled plasma spectrometer and a flow injection spectrophotometer. Average values represent the average of individual analyses in 10 cm increments throughout the entire stream bank vertical profile. Aggregate values reflect single measurements of pooled (aggregate) samples from throughout the vertical stream bank sediment profile. See Appendices 4-11 for full analytical results for these sample sites.

VI. Discussion of Results

Our data show that total P and N concentrations in stream bank sediments are high, and, given our measured bank erosion rates, represent a significant proportion of nutrients entering streams in the Chesapeake Bay watershed of Pennsylvania (Table 4). The Conestoga, for which we have 20 years of sediment and nutrient data from a USGS/SRBC gage station, provides an illustrative example. Gage station data show that the annual suspended sediment loads from the Conestoga watershed are approximately 180,000 tons (Gellis et al., 2005). If 50% of this sediment load stems from stream bank erosion (a minimum value ranging to as high as 80%), and if the average yield of P from stream bank sediments is 1.5 lb/ton, then the annual load of P from bank erosion from the Conestoga watershed is 135,000 lb. Thus, the P load from bank erosion in the Conestoga watershed alone accounts for ~2.1% of the 6.5 million lb reduction needed by the 2010 target date for the Chesapeake Bay Agreement, despite the Conestoga watershed being just 0.76% of the area of Chesapeake Bay watershed. Eliminating bank erosion from the Conestoga watershed of Lancaster County (114 stream miles) would have the same, or greater, effect as eliminating soil erosion from 1,350 mi^2 of the Chesapeake Bay watershed.

A. Implications of Nutrients from Eroded Stream Banks

Phosphorus and nitrogen are essential nutrients for plant growth in agriculturally productive regions. Nitrogen becomes available to plants when microbes mineralize organic N into inorganic ammonium and nitrate. Nitrates are soluble in water and readily move in aqueous soil solutions. Phosphorus is relatively insoluble in water (< 0.01mg L^{-1}), and is available to plants by sorption, desorption and precipitation after P is released during physical and chemical weathering of rocks and minerals of low solubility (Sharpley, 2000).

Increased concentrations of total P can cause increased concentrations of soluble and sediment-associated P in surface runoff (Romkens and Nelson, 1974, Galeone, 2003). The transfer of phosphorus from soils to watersheds is a function of three geodynamic processes: (1) chemical processes, such as soil mineralogy, concentrations of ions in solution and the quantities of ions adsorbed to soil particles (Holford and Mattingly, 1976); (2) physical processes, such as grain size, bulk density and landscape morphology (Sharpley, 1985); and (3) hydrologic processes, such as rainfall intensity and duration, soil moisture, infiltration rates and residence time of water in the soil matrices (Nagpal, 1986).

From an ecological perspective, high nutrient contents in surface waters lead to eutrophication, the enhancement of phytoplankton productivity due to nutrient enrichments. In general, phytoplankton growth is limited by the availability of P in freshwater systems, and is N limited in marine systems. The Pennsylvania Chesapeake Bay Tributary Strategy recognizes P as the limiting nutrient in the State's surface waters, and that efforts to reduce P loads are tangibly linked to reducing sediment loads (PA Tributary Strategy Fact Sheet, 2005).

It has been assumed that most P is lost from soils by erosion and overland flow. Water flowing over a soil surface can dissolve and transport soluble and easily desorbable P, or detach and transport particulate P (Nash et al., 2002). In most soils, the concentration of soluble or readily desorbable P is small, due to the low solubility of P and the high sorption capacities of P by clays and metal oxides. As a result, most P is transported by sorption onto particulates. Sorbed P can be loosely bound by electrostatic forces onto particulate surfaces (adsorbtion), or occluded by stronger chemical bonds (absorption) (Sharply, 2000).

Virtually all dissolved P transported by overland and stream flow is biologically available, but particulate P entering streams must undergo solubilization reactions before becoming available to aquatic organisms. The long-term fate of P transport via streams is desorption or dissolution of P from sediments that settle to the bottom of lakes or estuaries. In such benthic sediments, P sorbed onto clays and Fe-Al oxides are the main sources of desorbable and bioavailable P, while the physical and chemical attributes of the overlying water column greatly influences the rates of desorption and dissolution of P from the underlying sediments. Turbidity from storms, temperature changes, and oxidation states strongly affect desorption and dissolution of P. For example, reducing conditions strongly enhance the dissolution of sorbed P, particularly from Fe-P oxides (c.f., Sallade and Sims, 1997).

The transport and subsequent reactions of particulate P originate not only from upland soil erosion, but also from the beds and banks of streams. As shown here, most stream banks in Pennsylvania are composed of clays, silts, and fine sands, which are enriched in P due to their high sorption capacity for P. In natural ecosystems and areas where soil conservation practices have minimized upland soil erosion, the relative contribution of stream bank erosion in the transport of particulate P is a greater proportion than from upland sources (c.f., Pierzynski et al., 2005).

The contribution of suspended sediment and P loads in streams from bank erosion is well documented in the U.S. and Europe. Stream bank erosion contributes 45-50% of the suspended sediment load to streams in Iowa (Odgaard, 1984; Schilling and Wolter, 2000), and up to 80-90% in some streams in other Midwestern states (Simon et al., 1996) and in Europe (Krovang et al., 1997). In Minnesota, stream bank erosion contributes 30-45% of the suspended sediment load and 7-10% of the total P load in the Blue Earth River (Sekely et al., 2002), whereas in Illinois and Denmark, the P loads from bank erosion are 60% and 90%, respectively. In a two year study of fifteen small, lowland, rural streams in Denmark, Laubel et al. (2003) document that bank erosion contributes 40-70% of the suspended sediment load and 15-40% of the total P load. The Danish streams are deeply incised, with steep banks that contain an average P concentration of roughly 600 ppm.

In a related study, Mayer et al. (1998) observed strong correlations between suspended sediment surface area and total nitrogen loads in streams, and emphasized the potential impact of fine particulates from streams for nitrogen loading and coastal nitrogen

budgets. They conclude that suspended sediments must be considered an essential factor in the delivery of watershed nutrients to coastal ecosystems, including the transport and delivery of nitrogen. The concentrations of total N observed in suspended sediments from turbid rivers in the US, Brazil, and China (Mayer et al., 1998) match the concentrations of total N we measure in stream bank sediments in the Chesapeake Bay watershed.

The erosion rates and nutrient loads we measured in this study for Pennsylvania's Chesapeake Bay watershed (Tables 2, 3, and 4) are consistent with bank erosion rates, sediment loads and nutrient loads measured in other watersheds in the U.S. and around the world.

B. Recommendations for Stream Bank Sampling for Nutrients

We provide the following recommendations for stream bank sampling to facilitate other workers in the collection of representative geochemical data for stream banks: (1) Nutrient contents within a single stream bank profile can vary widely; (2) Collection of samples from stream banks to estimate nutrient loads from bank erosion, therefore, should not rely on one sample from a narrow stratigraphic range, as an analysis of this single sample could yield concentrations that do not represent the average concentration for the stream bank. For example, a sample from the upper 20 cm of stream bank sediments at Penns Creek (Centre County) yields a N content of ca. 3,000 ppm (6 lbs/ton), but a sediment sample collected from a depth of 170-190 cm below the surface yields a N value of 800 ppm (1.6 lbs/ton); (3) To achieve nutrient concentrations that represent the average nutrient loads within the bank, we recommend using one of two sampling strategies, both of which include sampling the entire sediment profile capable of eroding and/or collapsing into the stream: Method A – sampling in discrete 10 cm increments and either (i) analyzing each sample individually and calculating an average concentration, or (ii) splitting each sample into representative subsamples (e.g, by means of a geochemical splitter) and aggregating all individual samples into a single, homogeneous aggregate sample; Method B – sampling the entire profile by collecting a continuous scraping of the section from top to bottom, and analyzing the single homogenized sample for bulk nutrient content.

VII. Conclusions

From the data presented here, we conclude that stream bank erosion is an important source of sediment and nutrients to tributaries of the Chesapeake Bay, and is at least as significant as runoff from upland sources in some watersheds. Bank erosion rates measured at six sites in Lancaster and York Counties typically are in the range of 0.2 to 0.9 tons/ft/yr, and average 0.3 tons/ft/yr (see Table 4 and Figure 44). In addition, data compiled from 15 Growing Greener project reports indicate similar sediment production rates from bank storage that vary from 0.2 to 4 tons/ft/yr in all but 2 cases, which are much higher (6 and 10 tons/ft/yr; Kreider, unpub. document, 2006). The average value for the lower 13 rates is 1.1 tons/ft/yr, just slightly higher than the average for our data.

Our analyses of stream bank sediments from five watersheds in four counties and two physiographic provinces show average N concentrations ranging from 400-2100 ppm (overall mean = 1160 ppm), which equates to a loading of 0.8 to 4.3 lbs N/ton of eroded sediment. The concentrations of P in stream banks range from 340-958 ppm (overall mean = 556 ppm), which equates to 0.7 to 1.9 lbs P/ton of eroded sediment. Combining the bank erosion rates and nutrient concentrations yields nutrient loads to streams from bank erosion that range from 0.3 to 4.1 lbs/ft/yr for nitrogen and from 0.2 to 1.8 lbs/ft/yr for phosphorus (Table 5).

Locality [Site #]	**County**	**Province**	**Bank Erosion (tons/ft/yr)**	**N Load (lbs/ft/yr)**	**P Load (lbs/ft/yr)**	**Source of Bank Erosion Data**
Big Spring Run [53]	LNC	Piedmont	0.2	0.7	0.2	LandStudies Inc. and F&M
Denlinger's Mill [51]	LNC	Piedmont	0.17	0.4	0.2	F&M
Levan's Mill 52]	LNC	Piedmont	Data collection in progress	--	--	F&M
Hammer Creek [54]	LNC	Piedmont	0.94	4.1	1.8	DEP and F&M
Conoy Cr. (T1) [26]	LNC	Piedmont	0.34	0.3	0.4	F&M and LandStudies, Inc.
Conoy Cr. (T2) [26]	LNC	Piedmont	0.34	0.4	0.3	F&M and LandStudies, Inc.
EB Codorus Cr. [34]	York	Piedmont	0.4	0.6	0.4	ARRC and F&M
EP Codorus Cr. [34]	York	Piedmont	0.4	0.4	0.4	ARRC and F&M
Big Beaver Run [17]	LNC	Piedmont	0.3	Data collection in progress	Data collection in progress	F&M
Penns Creek [57]	Centre	R&V	Data collection in progress	--	--	F&M
Penns Creek [57]	Centre	R&V	Data collection in progress	--	--	F&M
Emmas Creek [23]	HUNTDN	R&V	Data collection in progress	--	--	F&M
Growing Greener Data (average of 7 sites)	York	Piedmont	0.74	Compilation by LandStudies (J. Kreider) Data from ARRC, Skelly and Loy, and Izaak Walton League		
Growing Greener Data (W. Br. Octoraro Cr.)	LNC	Piedmont	0.7	LandStudies Inc.		

Table 5. Summary of bank erosion and nutrient load data for nine sites. All nutrient concentration data are from Walter, completed in our laboratory at Franklin and Marshall College.

The P load from bank erosion in the Conestoga watershed alone accounts for ~2.1% of the 6.5 million lb reduction needed by the 2010 target date for the Chesapeake Bay Agreement, despite the Conestoga watershed being just 0.76% of the area of Chesapeake Bay watershed. Eliminating bank erosion from the Conestoga watershed of Lancaster County would have the same, or greater, effect as eliminating soil erosion from 1,350 mi^2 of the Chesapeake Bay watershed. This example illustrates the potential effectiveness of legacy sediment removal as a viable and effective means to reduce sediment and nutrient loads to the Chesapeake Bay.

Remobilization of historic sediment that has been stored in the stream corridors of the Piedmont and Valley and Ridge provinces for centuries is not fully recognized in the present version of the Watershed Model, which focuses instead on modern land use patterns and their impacts on sediment transport. For these reasons, the results we present here regarding the stream corridor as a significant source of sediment and nutrients could lead to an essential new addition to the Watershed Model.

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ACRONYMS

DEM	digital elevation model
DOQ	digital orthophoto quadrangle
DOQQ	digital orthophoto quarter quadrangle
DTM	digital terrain model
LiDAR	light detection and ranging