Reviews in Engineering Geology

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Reviews in Engineering Geology 2013;21;183-203
doi: 10.1130/2013.4121(14)

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The Geological Society of America
Reviews in Engineering Geology XXI
2013

The rise and fall of Mid-Atlantic streams: Millpond sedimentation, milldam breaching, channel incision, and stream bank erosion

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ABSTRACT

For safety and environmental reasons, removal of aging dams is an increasingly common practice, but it also can lead to channel incision, bank erosion, and increased sediment loads downstream. The morphological and sedimentological effects of dam removal are not well understood, and few studies have tracked a reservoir for more than a year or two after dam breaching. Breaching and removal of obsolete milldams over the last century have caused widespread channel entrenchment and stream bank erosion in the Mid-Atlantic region, even along un-urbanized, forested stream reaches. We document here that rates of stream bank erosion in breached millponds

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Merritts, D., Walter, R., Rahnis, M., Cox, S., Hartranft, J., Scheid, C., Potter, N., Jenschke, M., Reed, A., Matuszewski, D., Kratz, L., Manion, L., Shilling, A., and Datin, K., 2013, The rise and fall of Mid-Atlantic streams: Millpond sedimentation, milldam breaching, channel incision, and stream bank erosion, *in* De Graff, J.V., and Evans, J.E., eds., The Challenges of Dam Removal and River Restoration: Geological Society of America Reviews in Engineering Geology, v. XXI, p. 183–203, doi:10.1130/2013.4121(14).

remain relatively high for at least several decades after dam breaching. Cohesive, fine-grained banks remain near vertical and retreat laterally across the coarse-grained pre-reservoir substrate, leading to an increased channel width-to-depth ratio for high-stage flow in the stream corridor with time. Bank erosion rates in breached reservoirs decelerate with time, similar to recent observations of sediment flushing after the Marmot Dam removal in Oregon. Whereas mass movement plays an important role in bank failure, particularly immediately after dam breaching, we find that freeze-thaw processes play a major role in bank retreat during winter months for decades after dam removal. The implication of these findings is that this newly recognized source of sediment stored behind breached historic dams is sufficient to account for much of the high loads of fine-grained sediment carried in suspension in Mid-Atlantic Piedmont streams and contributed to the Chesapeake Bay.

INTRODUCTION

Dam removal, particularly of small dams, has become increasingly common since the 1980s (cf. Heinz Center, 2002). The reasons commonly cited for dam removal include safety, aquatic and riparian habitat improvement, and economics. Low-head dams (<7 m in hydraulic height) have been dubbed "drowning machines" because submerged hydraulic jumps downstream of the dams can trap and drown victims (Tschantz and Wright, 2011). Dams fragment fluvial systems and associated aquatic and riparian ecosystems (Graf, 1999). Removing dams eliminates safety hazards, restores variable hydrologic flows, and allows for unimpeded passage of fish and other aquatic organisms. For tens of thousands of obsolete low-head dams built to power mills, forges, and other industries in the eighteenth to early twentieth centuries, removal can be more cost effective than continued maintenance.

Despite safety, ecologic, and economic advantages, however, dam removal also can lead to channel incision, bank erosion, and increased sediment loads downstream. The morphological and sedimentological effects of dam removal are not well understood, and few studies have tracked a reservoir for more than a year or two after dam breaching (Csiki and Rhoads, 2010). As a result, considerable uncertainty exists regarding channel evolution trajectories and rates of stream bank erosion over a period of decades following dam breaching.

In this paper, we examine rates of erosion of fine-grained sediment upstream of three breached low-head dams in Pennsylvania for which prebreach conditions and time of breach are known (two cases) or are constrained to within several years (one case) (Fig. 1). These dams, which were breached 10, 26, and ~39 yr ago, are used to quantify rates of sediment production from breached reservoirs over decadal time scales. The three dams are ≤4 m in height and extended across the entire valley width. Because water flowed freely over their crests before removal, they are referred to as run-of-river dams.

In addition to rates of erosion, we examine the processes by which incised stream banks retreat laterally across the coarse-grained floors of the breached reservoirs. Our primary concern is to determine rates of erosion of sediment from banks of incised streams that are in different stages of post-dam-breach condition, and to assess how these rates change with time. Fine-grained sediment and nutrients are the leading pollutants in the Chesapeake Bay, the largest estuary in the United States and an

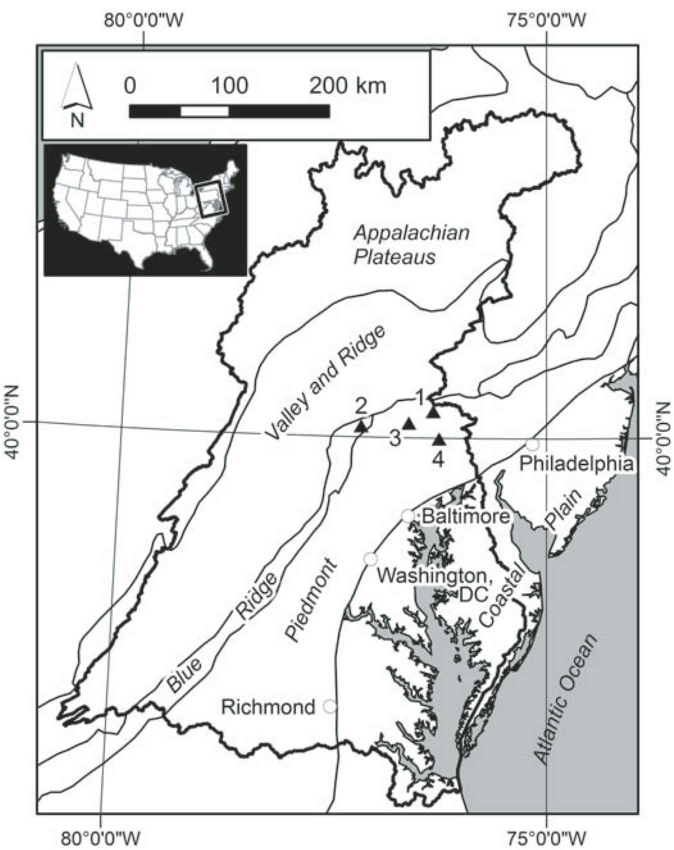

Figure 1. Locations of Mid-Atlantic sites discussed in text, with physiographic provinces and Chesapeake Bay watershed. Sites are as follows: 1—Hammer Creek, Pennsylvania; 2—Mountain Creek, Pennsylvania; 3—Conoy Creek, Pennsylvania; 4—Little Falls, Maryland.

impaired water body under the Clean Water Act (Phillips, 2002). Understanding the sources of sediment in streams is critical to developing successful strategies to reduce erosion and sediment flux to the bay.

Channel Evolution Models

Conceptual channel evolution models (CEM) and geomorphic studies of dam failure provide guidelines to predict the morphological and sedimentological effects of dam removal (Simon and Hupp, 1986; Evans et al., 2000a, 2000b; Evans, 2007; Doyle et al., 2003). When a dam is removed, local base level for upstream reaches is lowered (cf. Schumm et al., 2001; Simon and Darby, 1997). The stream cuts into unconsolidated sediment at the breach site immediately after dam breaching, forming a knickpoint in the stream profile. Vertical incision generally ceases once the stream reaches the base of the dam and the bottom of the original valley. Across this zone of increased grade, the stream has greater scouring capacity than upstream along the stream profile, where it remains perched in reservoir sediment. The knickpoint propagates up the valley through the reservoir sediment as the stream scours its bed. If the sediment is noncohesive and fine grained, the stream is able to erode and transport sediment easily, so the knickpoint propagates rapidly. With continued incision and erosion of the bed, mass movement commonly occurs along incised channel banks near the dam as a result of loss of lateral support (confining pressure) in wet reservoir sediment with high pore pressure (Simon and Darby, 1997; Evans et al., 2000a, 2000b; Evans, 2007; Doyle et al., 2003; Cantelli et al., 2004). Water slope decreases as the stream incises throughout the reservoir and upstream reaches become graded to the new local base level.

Simon and Hupp (1986) and later Doyle et al. (2002, 2003) ascribed these temporal patterns of channel adjustment to stages within a CEM, as follows: A—preremoval; B—lowered water surface; C—bed degradation; D—bed degradation and channel widening; E—bed aggradation and channel widening; and F—quasi-equilibrium. Doyle et al. (2002, 2003) tested this CEM by monitoring two dam removal sites in Wisconsin for a period of 1–2 yr after dam removal (Doyle et al., 2003). After removal of the Rockdale milldam on the Koshkonong River in Wisconsin, Doyle et al. (2003) documented that a headcut migrated upstream at a rate of ~10 m/h for 24 h, but decelerated to an average rate of 40 m/mo over the next 11 mo. Downstream of the headcut, a deep, narrow channel had high boundary shear stresses (up to 20–30 N/m^2) capable of eroding bed and bank material. Upstream of the headcut, however, low boundary shear stresses (<5 N/m^2) were insufficient to erode the bed or banks, and the reservoir sediment surface remained largely undisturbed (see figures 9 and 12c *in* Doyle et al., 2003).

Evans (2007) provided further empirical evidence for the development and duration of each stage of channel evolution by evaluating the response of the Chagrin River to seepage piping failure of the IVEX milldam in 1994. Their 12 yr study found that the general progression of stages of channel evolution was similar to the CEM of Doyle et al. (2003), but stage E was dominated by lateral migration of a single meandering channel rather than by overall bed aggradation and channel widening. Both incision and aggradation occurred as the Chagrin channel migrated through former millpond sediment, with undercutting and slumping at one bank coincident with point-bar deposition on the opposite bank. Furthermore, during stage F, the quasi-equilibrium stage, some bank erosion persisted locally.

Breached Millponds and Bank Erosion

The response of streams to dam breaching became a more prominent problem when Walter and Merritts (2008) documented that late seventeenth to early twentieth-century valley sedimentation in the unglaciated Mid-Atlantic region resulted not only from accelerated upland erosion during post–European settlement land clearing and agriculture, but also from contemporaneous, widespread valley-bottom damming for water power. For centuries, valley damming trapped immense amounts of fine sediment in extensive backwater areas upstream of tens of thousands of low-head milldams. Furthermore, Walter and Merritts (2008) proposed that local drops in base level caused widespread incision into historic reservoir sediment as aging dams breached or were removed during the last century.

For the Mid-Atlantic Piedmont region, Merritts et al. (2011) reported that modern stream-channel entrenchment largely is decoupled from current upland land use. Their case studies demonstrated that a breached dam can lead to incision, stream bank erosion, and increased loads of suspended sediment for streams in forested, rural areas as well as agricultural and urban areas, regardless of whether or not upland land use has altered stormwater runoff or sediment supply.

Pizzuto and O'Neal (2009) concurred with Walter and Merritts (2008) that dam breaching leads to higher rates of stream bank erosion. Of eight millpond reaches along 30 km of the South River, a tributary to the Potomac River in Virginia, all but one of the eighteenth- to nineteenth-century milldams were breached in the 1950s, and the last was breached by 1976. Studying changing bank lines on aerial photos, Pizzuto and O'Neal (2009) found a statistically significant, strong correlation between accelerated rates of bank erosion and dam breach conditions, with normalized estimates of mean bank erosion rates increasing by more than a factor of 3 in the first two decades after dam breaching. Furthermore, they concluded that accelerated erosion could not be explained by climatic factors (e.g., storm intensity or frequency of freeze-thaw cycles) or changes in the density of riparian trees along stream banks. Although the South River study showed that breached reservoirs have higher rates of bank erosion than unbreached reservoirs, it did not provide information on changing rates of postbreach bank erosion over decadal time scales.

Stream bank erosion is the detachment and removal of particles from the surface of the bank. It occurs through three main types of processes (Hooke, 1979; Lawler, 1995; Lawler et al., 1997; Couper and Maddock, 2001; Wynn and Mostaghimi, 2006a; Wynn et al., 2008):

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

The combination of processes of freeze-thaw, wetting and drying, weakening of bank material, mass wasting, undercutting, bank collapse, and removal of material by stream flow causes banks to retreat laterally. At any one site, all three of these processes might occur and contribute to cumulative erosion with time. Freeze-thaw is more frequent at higher elevations and/or higher latitudes, and wetting-drying is more common where precipitation is highly seasonal or where streams are incised and hydrographs are strongly peaked (i.e., flashy) due to high channel banks. Mass wasting is promoted by scour and undercutting, which depend on the nature and erodibility of material at the base of the bank. Fluvial entrainment is directly proportional to shear stress of flowing water, which is proportional to flow depth and water surface slope (see Eq. 1 later herein).

An incised stream with high banks of sediment leads to greater bank instability in a breached reservoir. As sediment is dewatered, gravitational forces and rapidly changing pore pressures result in settling (compaction) and mass wasting. The interaction of gravitational and hydraulic forces acting on bank sediment maintains oversteepened, unstable banks and controls rates of bank erosion (Simon et al., 2000). We have observed rotational slumping, calving, and other types of mass wasting failure at more than 100 breached dam sites in Pennsylvania and Maryland, including sites where dams were breached more than 50 yr ago (Fig. 2).

Figure 2. Mass movement occurred along the left bank of the incised Hammer Creek just downstream of XS-5 as a result of wetting and drying of the banks by high flow from a late June 2006 storm. Double arrow indicates person for scale along tape measure at section. Flat surface at top of bank is the level of sedimentation in the millpond. See Figure 5 for location of cross section.

Erodibility of Stream Bank Sediment and Freeze-Thaw Processes

Stream bank erodibility, k_d (in m^3/N-s), is the rate per unit area at which mass (sediment) is removed from the bank face once it begins to erode. The lateral erosion rate of a stream bank, E_r, (in m/s) is proportional to its erodibility and the amount of available excess shear stress (in Pa, or N/m^2). The excess shear stress is the difference between the shear stress, τ, acting on the

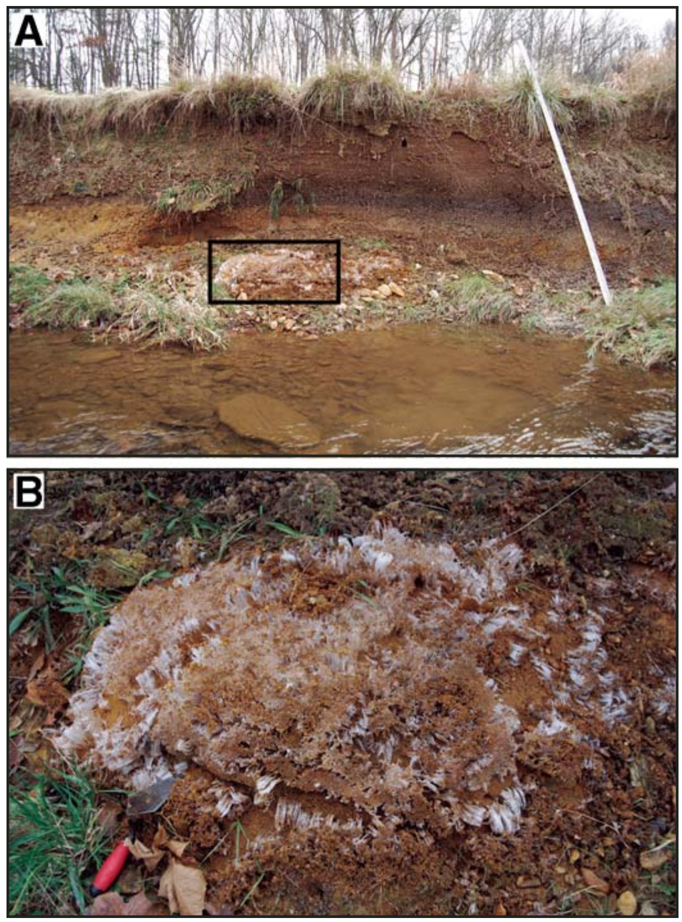

Figure 3. (A) Apron of debris forming on the right bank of a breached millpond on Little Falls, Maryland (see Fig. 1 for location), near the town of Whitehall. Bank height is ~2 m, and downstream is to left. Dark soil at midbank level is the presettlement land surface. The site is close to the valley wall, and the millpond sediment (overlying brown sediment) is thinning toward the original reservoir margin. (B) Freeze-thaw has produced large needles of ice from pore water in bank sediment. As ice needles grew in pores perpendicularly to the bank face (horizontal), a vertical fracture opened parallel to the bank face, causing a large slab of bank to collapse onto the debris apron in the winter of 2008–2009 (photos taken in February 2009). Trowel for scale in lower image.

bank and the critical shear stress, τ_c (in Pa, or N/m^2), needed to entrain material from the bank (Osman and Thorne, 1988; Darby and Thorne, 1996), as follows:

$$E_r = k_d(\tau - \tau_c), \tag{1}$$

Previous work has shown that k_d and τ_c can vary up to four to six orders of magnitude along a given stream reach, and both vary seasonally as a result of soil desiccation (during dry and/or vegetation growth periods) and winter freeze-thaw cycling (Wynn and Mostaghimi, 2006a, 2006b; Wynn et al., 2008). Detailed monitoring of sites along the Ilston River, South Wales, by Lawler (1986, 1993) and along Strouble Creek, Virginia, by Wynn et al. (2008) established that freeze-thaw processes significantly lower the critical shear stress and increase the erodibility of cohesive stream bank sediment. Examination of Equation 1 indicates that lowered τ_c and increased k_d would result in greater rates of bank erosion.

The action of freeze-thaw directly results in bank erosion by the action of needle ice, as observed by us at numerous sites in the Mid-Atlantic region (Fig. 3) and described by Wolman (1959, p. 215) from his observations along banks of sand, silt, and clay at Watts Branch, Maryland, in December 1955: "Particles are heaved out from the bank by ice crystals and upon melting of the crystals the sediment drops into the stream … slabs of sediment perhaps one foot square containing thin ice lenses have been observed. The action of frost appears to be one of preparation of a veneer of sediment for erosion…"

Wolman observed at Watts Branch that most bank erosion occurred during winter months and was associated with freeze-thaw processes (discussed later herein). Bank pins (metal bars), surveyed channel cross sections, and two baselines parallel to the retreating bank edge were used to document up to 0.2 m/yr of bank erosion over a period of several years. Wolman (1959) observed that rises in water stage were more effective at removing bank material after frost-related processes had increased its susceptibility to fluid erosion. In contrast, "little or no erosion was observed" during the highest flood on record at the time in July 1956 (Wolman, 1959, p. 204).

Wolman (1959) concluded that there is an obvious "lack of erosion in summer and marked erosion in winter" and determined that 85% of bank erosion during his 2 yr study occurred during the winter months of December through March. He further noted that lateral channel migration of Watts Branch by bank erosion takes place primarily during the winter (Wolman, 1959, p. 208 and 216). Unbeknownst to Wolman, this reach of Watts Branch was immediately upstream of a recently breached mill dam from a former nineteenth-century (and possibly earlier) grist mill (see supporting online material for Walter and Merritts, 2008).

Lawler's (1986) statistical analysis of data from 230 erosion pins in stream banks consisting of sand, silt, and clay at two meander bends on the Ilston River in South Wales over a 2 yr period (1977–1979) indicated a strong seasonality to stream bank erosion. Nearly all bank erosion took place in the winter, from December to February. The strongest control on average and maximum rates of bank erosion was frost action, and in particular the number of days for which minimum temperatures were below freezing (0 °C). Lawler (1986, p. 230) observed that a "skin of friable, cohesionless" sediment formed on stream banks by needle ice growth and was easily removed by a subsequent rise in stage. Stepwise multiple regression analysis revealed that air frost frequency, the variable most strongly associated with erosion rate, explained 94.2% of the variation in bank erosion rate.

Bank erosion processes are highly dependent upon the nature of the bank material (cf. Julian and Torres, 2006). In all three of the studies cited here (Watts Branch, Maryland; Strouble Creek, Virginia; and the Ilston River, South Wales), the banks varied from 1 to 2 m in height and consisted primarily of sand, silt, and clay. Cohesive silt and clay—with moderate to high critical shear stress when moist to dry, respectively—are particularly susceptible to freeze-thaw, wetting-drying, and mass failure. In contrast, noncohesive material such as sand—with a low to moderate critical shear stress—is more prone to erosion by hydraulic forces (Julian and Torres, 2006). Cohesive sediment (e.g., silt loam) commonly forms vertical banks from which slabs have been observed to slake and calve to the toe of slope or into the stream. Much less cohesive sand and gravel, on the other hand, forms banks that are closer to the angle of repose, generally 35°–40°. Undercutting and bank collapse can reset the slopes of the banks as the stream erodes material from the toe, or base, of the bank.

Vegetation on banks also plays a role, with tree roots and grasses adding various degrees of mechanical reinforcement. For nonplastic stream bank sediment in Virginia, increases in root volume were correlated with reduced K_d (Wynn and Mostaghimi, 2006b). On the other hand, forested stream banks experienced greater diurnal temperature ranges and up to eight times more freeze-thaw cycles than banks with dense herbaceous cover (Wynn and Mostaghimi, 2006b). In addition, fallen trees from bank erosion can obstruct flow and trap debris within incised channels, leading to localized scour and accelerated bank erosion around the obstruction.

Changing Rates of Bank Erosion after Dam Breaching

It is probable that rates of stream bank erosion and mass wasting are highest immediately after a dam breaches. This supposition is supported by the flume experiments of Cantelli et al. (2004, 2007),[1] as well as by post-dam-breach monitoring of Doyle et al. (2003) in Wisconsin and of others in Oregon after removal of the Marmot Dam on the Sandy River (Major et al., 2008, 2012). Based on the previous discussion of the role of freeze-thaw processes in bank erosion, however, it is possible that bank erosion will continue long after dam breaching, provided that banks of sand, silt, and clay are exposed to air temperatures that drop to freezing.

[1]Movies of Cantelli's flume experiments can be downloaded at https://repository.nced.umn.edu/browse.php?dataset_id=28.

Shear stresses at the stream bed are much higher downstream of a knickpoint that is propagating through a breached reservoir than upstream of the knickpoint (e.g., Doyle et al., 2003). Basal shear stress, τ, acting on the channel bed is the product of fluid density, flow depth, and water surface slope:

$$\tau = \gamma RS, \tag{2}$$

where γ is the specific weight of water (9800 N/m^3), R is hydraulic radius, calculated as A (channel area) divided by P (wetted perimeter), and S is the energy slope. Both hydraulic radius and slope increase as a result of post-dam-breach channel incision.

We posit several scenarios for the relation between stream bank erosion and time since dam breach. Erosion rates might remain constant with time or diminish gradually until the majority of reservoir sediment is eroded. It is more likely, however, that the rate decelerates with time. About 9%–13% of the reservoir sediment of the IVEX dam was eroded during and immediately after dam breaching in 1994, and a laterally migrating stream channel has continued to erode reservoir sediment since then (Evans et al., 2000a, 2000b; Evans, 2007). Average monthly rates of sediment removal from two millponds in southern Wisconsin indicate a rapid decline in volume of sediment removed, from 0.7% to 1.7% per month within the first 8–10 mo after dam removal, to 0.2%–0.5% per month from 8 to 13 mo after dam removal (Doyle et al., 2003).

Upstream of the breached Marmot Dam, the rate of removal of sediment decelerated rapidly during the first year after dam breach. About 17% of the volume of reservoir sediment was eroded within 3 wk, 28% after 5 wk, 39% after ~2 mo, and 51% after 11 mo (Major et al., 2008, 2012; C. Podolak, 28 April 2011, personal commun.).

Once the geometry of an incised channel is established and adjusted for upstream runoff conditions, substrate resistance, and other factors, it is possible that a lower rate of stream bank erosion will continue until most or all of the reservoir sediment is gone. The long-term trend might correspond to a negative power function, as with the rate of removal of sediment from the Marmot Dam reservoir. It also is likely, however, that sporadic, stochastic events, such as high-magnitude floods, or tree falls that lead to localized scour, could cause short-term deviations in this long-term signal. In subsequent sections, we present data that enable us to quantify the trend in long-term sediment removal from three breached reservoirs. In the discussion section, we compare the observed trend to the scenarios posited here.

BACKGROUND

Mid-Atlantic Region Streams and Milldams

Tens of thousands of grist mills, sawmills, furnaces, forges, and other industries relied upon hydropower from first- to fourth-order Mid-Atlantic streams throughout the seventeenth to early twentieth centuries (Walter and Merritts, 2008; cf. U.S. industrial censuses of 1840, 1860, 1870, and 1880 [U.S. Bureau of the Census, 1841, 1865, 1872, and 1884, respectively). Such streams comprise greater than 70% of stream length in the region, and damming them had a substantial impact on a large portion of watersheds, including upstream tributaries. Hydropower was dominant when the Mid-Atlantic region was one of the world's leading suppliers of wheat and iron, and mills were particularly abundant in areas close to major shipping ports, including Philadelphia, Pennsylvania, and Baltimore, Maryland.

Few historic milldams are included in the U.S. Army Corps of Engineers National Inventory of Dams, which lists only 1546 dams in Pennsylvania. Of these, only 833 are listed as being less than ~7.6 m in height. In contrast, the Pennsylvania Department of Environmental Protection has an inventory of ~8400 low-head milldams (generally <5 m) in Pennsylvania, of which 4100 are breached, and it estimates that 8000–10,000 more might exist (J. Hartranft, Pennsylvania Department of Environmental Protection, 19 September 2007, personal commun.). These estimates result in an average density of 1 dam per 6–7 km^2 for the state of Pennsylvania. Considering that mill and dam building continued throughout the nineteenth century, the possibility of 16,000–18,000 dams in Pennsylvania is consistent with the ~10,000 mills listed for Pennsylvania in the U.S. census of 1840 (U.S. Census Bureau, 1840).

Our research of township-scale maps in southeastern and central Pennsylvania indicates that at least 1200 milldams existed in Chester, Lancaster, and York Counties, 153 in Cumberland County, 205 in Huntingdon County, and 186 in Centre County (Walter and Merritts, 2008; Merritts et al., 2011). Similar to Pennsylvania, adjacent states in the Mid-Atlantic region had ubiquitous milldams, with at least 211 in Baltimore and Montgomery Counties of Maryland (Walter and Merritts, 2008; Merritts et al., 2011). From detailed historic records, we have calculated the mean height of milldams in Lancaster County, Pennsylvania, as ~2.4 m (n = 246). Historic dams ranged in height from as low as 1.5 m to as high as ~9 m (Lord, 1996). Nineteenth-century U.S. census reports indicate that milldams in other Mid-Atlantic counties had similar heights (U.S. Census Bureau, 1840, 1870, 1880).

Milldams commonly lined Mid-Atlantic streams in series, forming chains of slack-water pools that enabled millers to maximize the potential energy of falling water. For example, at least 13 milldams operated on the lower 21.3 km of one of the streams investigated here, Hammer Creek, during the eighteenth and nineteenth centuries (Fig. 4; Bridgens, 1858, 1864; Lord, 1996). This number yields a milldam spacing of ~6 km along Hammer Creek.

High trap efficiencies in historic millponds are corroborated by large volumes of historic sediment stored along stream corridors upstream of milldams (Walter and Merritts, 2008; Merritts et al., 2011). Previous work has shown that low-head dams built across small (first- to third-order) stream valleys have high sediment trap efficiencies of >40%–80% (Brune, 1953; Gottschalk, 1964; Dendy and Champion, 1978; Petts, 1984; Evans et al., 2000a; Doyle et al., 2003). A reservoir's trap efficiency, a measure of its ability to trap and retain sediment, is expressed as a ratio of sediment retained by settling to incoming sediment (Brune, 1953; Verstraeten and Poesen, 2000).

High-resolution topographic data from airborne laser swath mapping (LiDAR) provides a means of tracing the tops of millpond sediment fill surfaces to the crests or spillways of milldams. Such analyses indicate that wedges of sediment exist upstream of thousands of milldams in Pennsylvania and Maryland (Walter and Merritts, 2008; Merritts et al., 2011). These wedges thicken downstream toward the dams that formed the slack-water reservoirs.

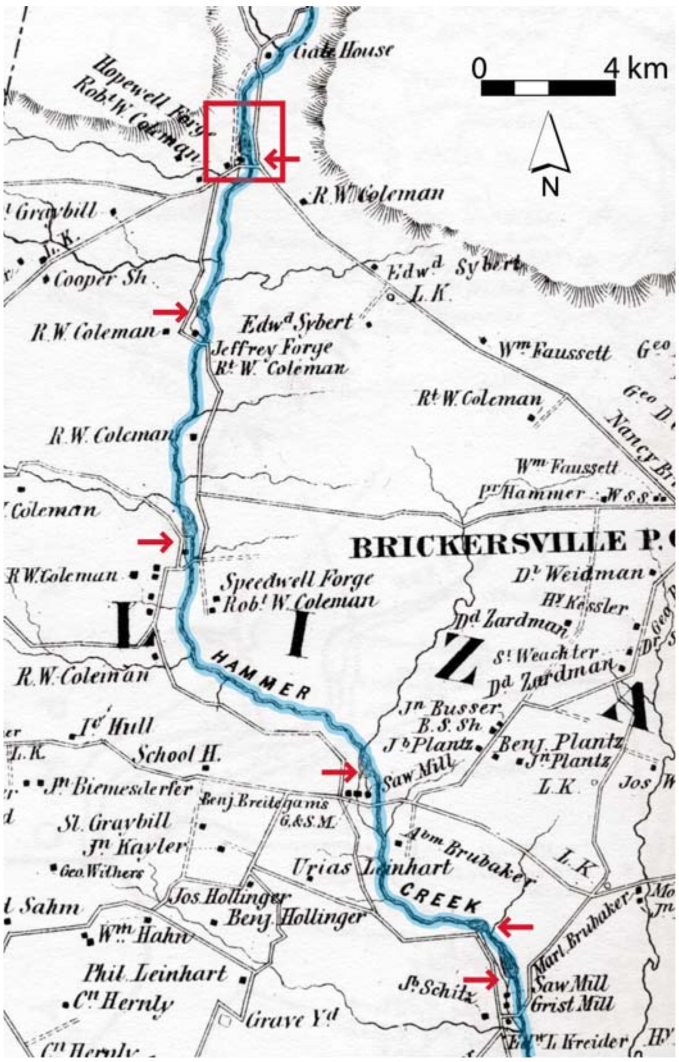

Figure 4. Historic township maps indicate that at least 13 milldams were located along a distance of ~28 km on Hammer Creek in the mid-nineteenth century (Bridgens, 1858). Inset box is area of Figure 5. Earliest milldams were built in the early seventeenth century, and many ponds were partly or nearly filled with sediment by the late nineteenth century. Milldams located in six counties in Pennsylvania and two in Maryland for the nineteenth century, as well as a number of mills per county in the eastern United States as of the 1840 U.S. census, can be viewed at the following website: http://www.fandm.edu/x17479.

Site Descriptions

Our three study sites are located within the Piedmont and the Ridge and Valley physiographic provinces of the Mid-Atlantic United States. The headwaters of Hammer and Conoy Creeks, both third-order streams in the Piedmont, consist of a low-relief undulating landscape formed in Triassic- to Cretaceous-age rift basin sedimentary rocks. Conglomerates and sandstones form the hills, whereas valley bottoms are underlain by shale. A thick cobble- to boulder-size weathered residuum with sandy matrix occurs in relict periglacial slope deposits that bury the shale, so it rarely is exposed along valley bottoms. Upstream drainage area is 47 km^2 at the Hammer Creek site and 20 km^2 at the Conoy Creek site. Hammer Creek drains southward into the Conestoga River, which, in turn, drains westward into the Susquehanna River and ultimately Chesapeake Bay. Conoy Creek flows westward directly into the Susquehanna River. Mountain Creek is located along the easternmost edge of the Ridge and Valley physiographic province (see Fig. 1). This fourth-order stream has a drainage area of 120 km^2 and flows northeastward into Yellow Breeches Creek, which, in turn, drains into the Susquehanna River and ultimately to Chesapeake Bay.

Hammer Creek

Hammer Creek was named during the Colonial period for the constant hammering of iron at forges and mills along the stream. In 1901–1902, a 2.4-m-high concrete and block dam was built within the incised stream channel of Hammer Creek at the approximate site of an older, breached milldam (40.2421°N, 76.3359°W). This older dam was associated with an iron forge on nineteenth-century maps (see Fig. 4). Slack water from the twentieth-century pump station dam extended upstream at least 500 m, but the thickness of historic sediment from the older reservoir indicates that the impact of the original dam extended even farther upstream. Assuming an upstream-thinning wedge for the reservoir and a trapezoidal valley shape over a length of 0.5 km, we estimate ~22,300 m^3 of reservoir sediment. The slack-water reservoir formed by the Hammer Creek pump station dam four decades after the dam was built is shown in an historic air photo from 1940 (Fig. 5A). A digital orthophoto acquired in 1993, just 8 yr before dam removal, shows that sedimentation had narrowed the stream channel substantially.

An 11 m section of the Hammer Creek dam was removed in September 2001. The upper 1 m of the dam was removed in September 2001, leaving a rock ledge with concrete ~0.5 m in height that forms a local base-level control. The post-dam-breach gradient of Hammer Creek in the former reservoir is 0.0015. A digital ortho-image acquired in 2005 shows an incised stream channel 3.5 yr after dam removal (Fig. 5B). Photographs taken by state officials at the time of partial dam removal show the channel during and shortly after breaching (Figs. 6A–6D). A narrow incised channel produced a knickpoint that propagated rapidly upstream more than 500 m within the first few days, and a substantial amount of fine-grained sediment (sand, silt, and clay) exposed in

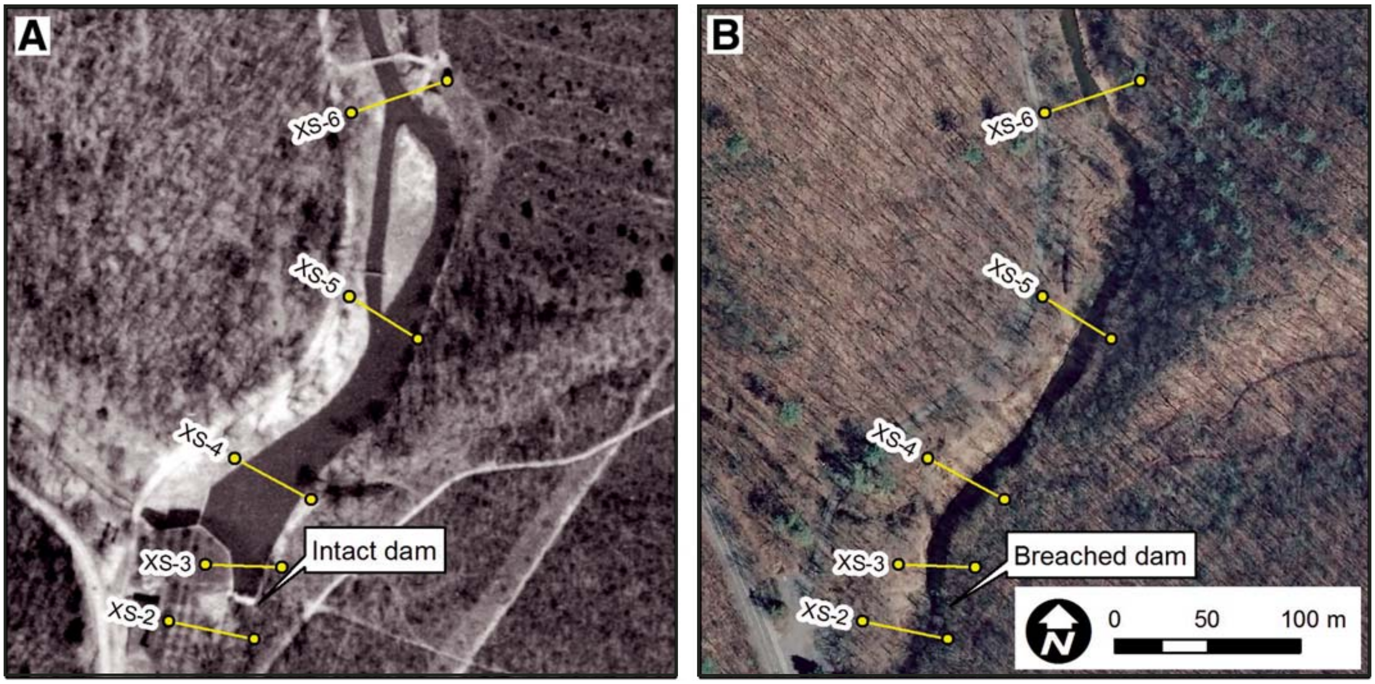

Figure 5. (A) Historic (1940) aerial photo of the Hammer Creek pump station dam showing the reservoir upstream and wing wall connecting the main-stem dam to that on a small tributary (Walnut Run) from the west. The pump station dam was built in 1901–1902 and had substantial sedimentation by the time of this photo. (B) Digital ortho-image from 2003, acquired by the state of Pennsylvania (horizontal resolution 0.6 m), showing the incised stream channel and remnant paired fill terraces from the millpond 2 yr after dam breaching. The dam on Walnut Run is not breached, so this tributary has not yet incised to adjust to the lowered base level on the main stem.

the reservoir was removed by bank erosion within several weeks. Some thin beds of pebble-sized quartz gravel derived from local Mesozoic conglomerates also occur in the uppermost part of the historic reservoir sediment.

Conoy Creek

At the Conoy Creek site, a 1.2-m-high dam (40.1327°N, 76.6212°W) was built for local water supply in 1930 near a breached 1.8-m-high dam originally built to power an eighteenth-to nineteenth-century sawmill (see Fig. 1). This second-generation dam was constructed within the older, incised millpond reservoir. A 1940 air photo shows the intact twentieth-century dam set within the valley flat (the older millpond fill surface). A state inspection report from 1959 indicates that the reservoir upstream of the dam was "silted up," with no remaining capacity, and the stream banks around the wing walls were eroded. Our field mapping indicates that the younger inset fill forms a prominent bench along the valley ~0.3 to 0.6 m lower than the larger valley flat formed by the older millpond sediment. Assuming an upstream-thinning wedge for the millpond reservoir and a trapezoidal valley shape for the ~1 km of stream impacted by the millpond, we estimate ~29,240 m^3 of historic reservoir sediment.

A 1971 air photo shows the Conoy Creek dam as intact, although erosion can be seen along the left (southeastern) bank between the masonry wall and the valley margin, and some water appears to be passing through this eroded area. Air photos from the late 1970s indicate that the channel had completely bypassed the dam along this margin, effectively causing a dam breach without breaching the actual structure. We estimate the timing of complete dam bypass as 1972, the year that Hurricane Agnes caused severe flooding in the region and damaged many old dams. Digital ortho-images acquired since the 1990s show a channel with significant meander migration and a more sinuous channel at multiple locations, in marked contrast to the limited channel migration prior to 1971. Modern channel gradient in the former millpond is 0.002.

Mountain Creek

Ridges adjacent to Mountain Creek consist of early Paleozoic quartzite, and the valley is underlain by early Paleozoic dolomite. As at Hammer Creek, hillslopes adjacent to the valley bottom are mantled with unconsolidated Pleistocene periglacial deposits. Our mapping along the valley slopes indicates that these deposits consist of thick sheets (~1 to 4 m thick) of quartzite cobbles and boulders within a sandy loam matrix. Exposures of these colluvial deposits in quarries, and light detection and ranging (LiDAR) analysis of landforms on the slopes of South Mountain indicate that many are gelifluction sheets and lobes. Periglacial slope deposits also underlie the historic millpond sediment along Mountain Creek.

The Mountain Creek study site extends from the 4-m-high Eaton-Dikeman paper mill dam (40.1015°N, 77.1834°W) to the

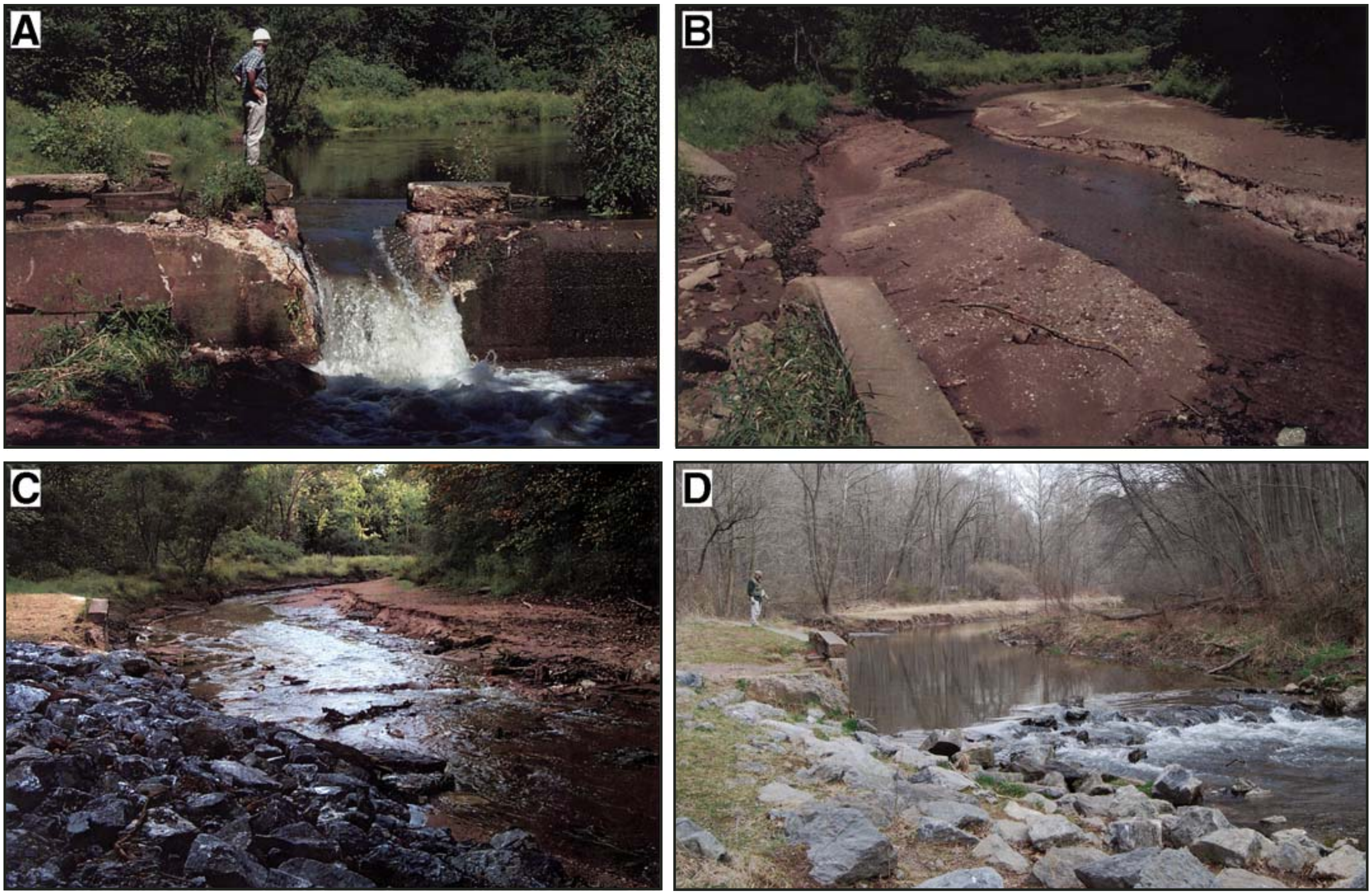

Figure 6. Photos, taken by staff of the Pennsylvania Department of Environmental Protection, document dam breaching and subsequent channel incision at Hammer Creek. All views are looking north, upstream. (A) 5 September 2001, just after the dam was breached. Note person standing on wing wall that attaches this dam to a small dam on a tributary from the west just out of view on the left. Note that historic millpond sediment is graded to the original dam crest. (B) 6 September 2001, showing exposed and eroding fine-grained reservoir sediment. Mesozoic rift basin sedimentary rocks in the watershed, including red shales and sandstones, produce sediment with strong red hues. (C) 27 September 2001, showing the breached reservoir after rocks were placed near the breach and the surface just upstream of the dam was graded. (D) The breached reservoir in April 2011. Note exposed banks upstream of the breach and remnant millpond surface forming paired terraces on each side of the incised stream channel. About 0.5 m of the base of the dam remains in place, as do the ends of the dam on each side of the breach, and rubble from the breached dam was used by anglers to create a pool for fishing.

upstream end of the reservoir, a distance of ~1.2 km. Built in 1855, the milldam was ~213 m long, but field evidence indicates that an older dam might have existed in the vicinity (within 10 m upstream) of this structure. Pennsylvania state dam inspections reported that the reservoir was substantially filled with sediment by 1914 and the reservoir volume was ~173,000 m^3. The Eaton-Dikeman reservoir as shown in an historic air photo from 1968 reveals a deltaic lobe of sediment crossing the valley from southeast to northwest near the dam (Fig. 7A). Bathymetric surveying by Dickinson College students in 1976 determined that the greatest water depth near the dam was ~1 m, and the majority of the reservoir had water depths less than 0.3 m. By assuming a trapezoidal valley shape, we estimate that the reservoir volume might have been as large as 250,000 m^3.

In 1985, an ~15 m section of the northern end of the 213-m-long Eaton-Dikeman dam was removed. An incised channel formed immediately at this breach, and the modern channel gradient is 0.003. State records and photos from 1985 to 1986 indicate that the channel incised and then widened rapidly after dam breaching. Digital ortho-images from 2003 show the incised channel of Mountain Creek 18 yr after dam removal (Fig. 7B), and our photographs of the site show the widened stream corridor 25 yr after dam breaching (Fig. 8).

At all three sites, the contact between historic reservoir sediment and the original valley bottom is marked by a thin stratum of Holocene organic-rich wetland soils (mucks) and fine-grained sediments. At Mountain Creek, tree stumps, logs, and forest soils rich in bark, nuts, and leaves are exposed by the incised channel at valley margins, indicating that the reservoir buried forested toe-of-slope as well as valley bottom landforms and soils. At Conoy Creek, weathered toe-of-slope colluvium is exposed where the incised channel has cut into the valley margins. Such

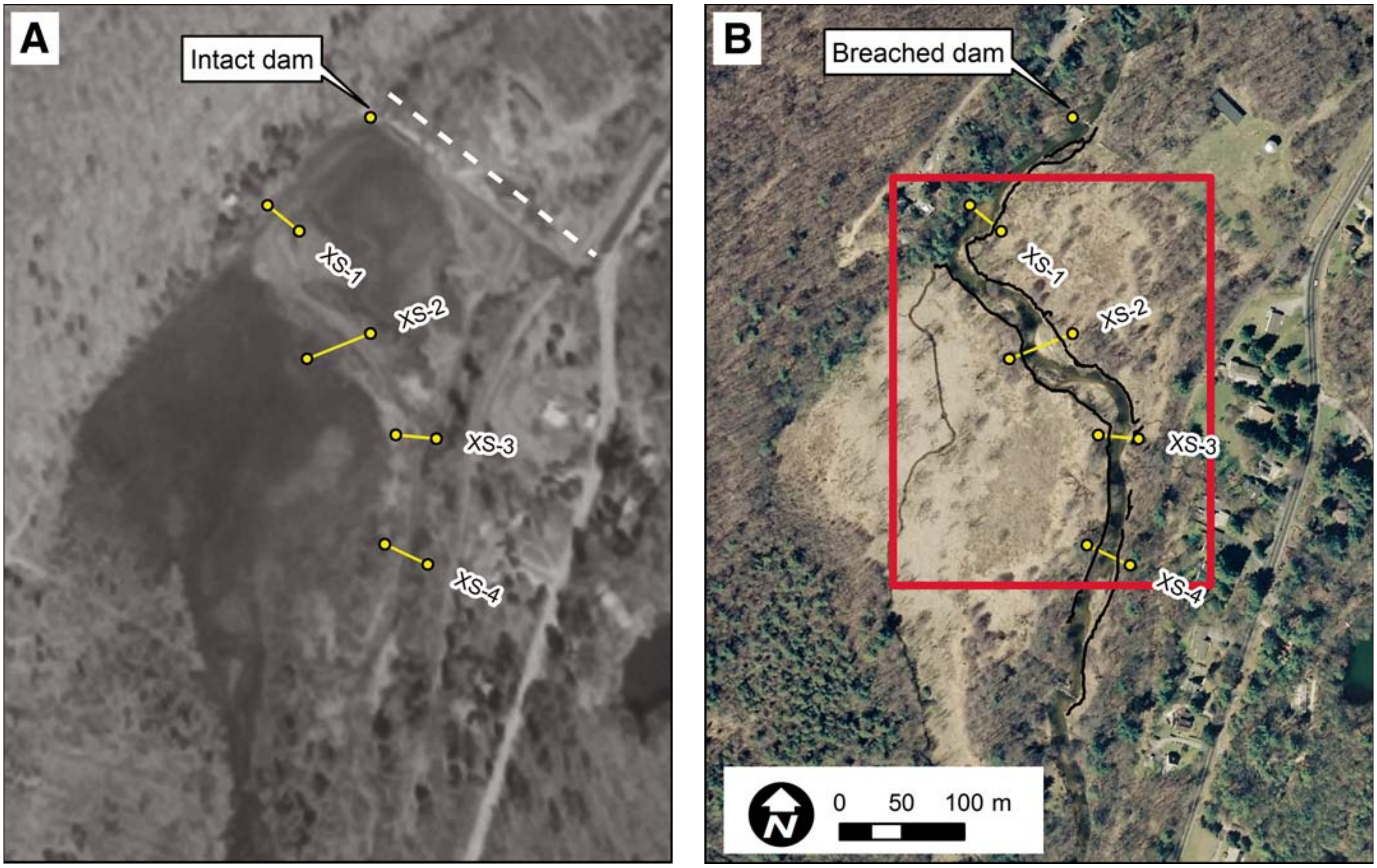

Figure 7. (A) Historic (1968) aerial photo of the Mountain Creek Eaton-Dikeman milldam (213 m long) showing the reservoir and deltaic lobes of sediment filling in the reservoir. The dam was built in 1855, and was reported as having substantial sediment infilling by the early twentieth century (see text). (B) Digital ortho-image from 2003, acquired by the state of Pennsylvania (horizontal resolution 0.6 m), showing the incised stream channel and remnant paired fill terraces from the millpond 18 yr after dam breaching. Channel cross sections for this study are shown. Solid black lines represent millpond fill-terrace edge break lines surveyed in 2008; note substantial retreat of the terrace edge from 2003 to 2008 in many places. Red box is area of Figure 13.

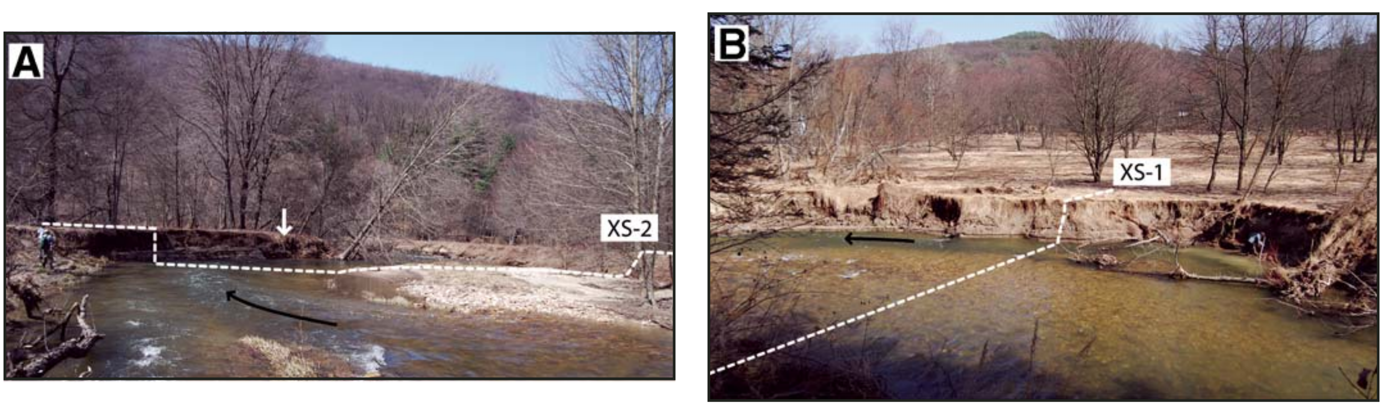

Figure 8. (A) Downstream view of XS-2 at the breached Eaton-Dikeman reservoir on Mountain Creek. Note the point bar on right bank prograding to the left (northwest) within paired fill terraces from the original millpond level. White arrow on left bank indicates exposure of Pleistocene periglacial gravel at base of bank, beneath millpond sediment. This sediment is interpreted as part of a toe-of-slope deposit of South Mountain in the background. (B) View of XS-1 at the breached Eaton-Dikeman reservoir looking across (southeast) the original reservoir surface, toward Piney Mountain in distance. Right bank height is ~3 m at this location, and left bank has eroded into colluvium (periglacial) at the toe of South Mountain (behind and to left of photographer).

exposures have not been observed at Hammer Creek, as it has not yet incised to the predam valley bottom nor has it eroded into the margins of the reservoir fill.

METHODS

Standard methods (cf. Wolman, 1959; Lawler, 1993) were used to estimate bank erosion rates for Hammer, Conoy, and Mountain Creeks. Erosion was measured as lateral retreat at a point (one-dimensional horizontal) with bank pins or as lateral retreat perpendicular to the stream bank face (two-dimensional vertical) with surveyed cross sections, and then converted to volume removed (three dimensions) by multiplying erosion from the incised stream corridor over a given length interval of stream. In addition, plan-view changes in bank edges and bar were determined for the breached Eaton-Dikeman reservoir on Mountain Creek. Stream bank and bar edges were digitized on two sets of color digital ortho-images (orthorectified) acquired by the state of Pennsylvania (PA MAP) during late spring leaf-off conditions in 2003 (0.6 m ground resolution) and 2006 (0.3 m ground resolution). Our mapping of break lines (water edge, bar edge, and terrace edge) with a Trimble GeoXH global positioning system (GPS) unit in 2008 and 2009 was interpreted in combination with high-resolution topographic data from LiDAR (PA MAP). We also determined particle size distributions for sediment of different ages within the Eaton-Dikeman reservoir and compared grain size of point-bar sediment to estimates of predicted particle size mobility based on flow depth and the Shields parameter. Each of these methods is discussed in more detail next.

Particle Size Analysis

Standard sieve methods were employed for particles greater than or equal to very fine sand, and a laser particle analyzer (Micromeritics Saturn Analyzer) was used to estimate particle sizes less than 300 µm (50 mesh). Particle size distribution was determined for four different ages of sediment at the Eaton-Dikeman reservoir on Mountain Creek. From oldest to youngest, these are (1) coarse presettlement substrate buried beneath millpond sediment, probably Pleistocene in age; (2) fine-grained presettlement substrate, probably Holocene in age; (3) historic millpond sediment probably dating from the eighteenth to early nineteenth centuries in age; and (4) sediment deposited in an actively migrating, unvegetated point bar within the incised channel corridor. Examination of digital ortho-images from 2003 and 2007 indicates that sediment on the bar at the sample site is likely to have been deposited within the past 6–8 yr. The historic and underlying presettlement sediment eroding from banks generally is much finer grained than the older coarse substrate or sediment deposited in point bars, and grain-size analysis was used to evaluate these differences.

Sediment particle size was evaluated at XS-1 and XS-2 in the breached Eaton-Dikeman reservoir (see Fig. 8). Samples were collected at ~10–40 cm increments, following stratigraphic boundaries, from top to bottom of the incised stream channel bank. Total sample depth was 280 cm at XS-1 and 245 cm at XS-2. Air-dried, lightly crushed (for disaggregation) samples were sieved to 0.6 mm grain size, and particle size for the fraction finer than 0.6 mm was analyzed with a Micromeritics Saturn laser diffraction particle size analyzer. Sieve data were merged with laser diffraction data to produce a complete grain-size distribution.

The coarse layer of sediment that underlies the historic sediment exposed in stream banks was exhumed as the bank of historic sediment retreated by lateral erosion. A fresh exposure of this pebbly-cobble substrate was provided after high flows in the vicinity of XS-2, where the average annual lateral erosion rate on left bank is ~0.3 m/yr. This coarse substrate is winnowed after exhumation, so the grain size estimate presented here represents the coarse fraction of the presettlement substrate that remained after being exposed to stream flow for several years. A pebble count was performed in the exposed bed substrate on 13 August 2008, using the standard "Wolman pebble count" method and a grain-size template (Wolman, 1954).

Sediment in the active point bar on the right bank at XS-2 was sampled on 25 September 2008. The sample was wet sieved in the field to the 2 mm fraction, and each fraction was dried and weighed. Wash water with particles finer than 2 mm was collected in a bucket and dry sieved in the laboratory. Some fine sediment <0.5 mm possibly was lost during wet sieving. Total mass sampled was 30.4 kg.

Shields Parameter and Particle Mobility in an Incised Reservoir

The Shields parameter (τ^*) for particle entrainment is the ratio of driving forces (τ_b, the basal shear stress acting on the sediment particles) to resisting forces (buoyant weight of sediment particles), given as

$$\tau^* = \tau_b / ([\rho_s - \rho] g D), \tag{3}$$

where ρ_s is the density of sediment (2650 kg/m^3), ρ is the density of water (1000 kg/m^3), g is acceleration from gravity, and D is particle diameter (in m). The basal shear stress, τ_b, is estimated as shown in Equation 2. Assuming that particle entrainment occurs when $\tau^*_c = 0.03$–0.07, as reviewed in Buffington and Montgomery (1997), we estimated a range in predicted D_{50} values for given flow depths in the breached Eaton-Dikeman reservoir on Mountain Creek.

Bank and Bed Erosion Measurements

Repeat surveys of channel cross sections at all three sites and of the long profile at Hammer Creek, done with either a laser level or total geodetic station during various surveys, enable the calculation of change in cross-sectional area during intervals between surveys, as well as cumulative change in channel geometry and erosion. Channels were surveyed perpendicular to stream flow between section end points marked with concrete monuments at Hammer and Mountain Creek, and with rebar embedded 0.6 m in the ground and marked with survey caps at Conoy Creek. Measurement errors for cross-section surveys are ±0.5 cm and ±1 cm for horizontal and vertical dimensions, respectively. Estimates of uncertainty for erosion volume from repeat cross-section surveys are on the order of ±26%–32% for typical measurements (Table 1).

Two monumented cross sections (XS-1 and XS-2) downstream and three upstream (XS-3, XS-4, and XS-5) of the dam were installed and surveyed with a total geodetic station on Hammer Creek during the summer of 2001, just prior to dam removal in September. Two more sections (XS-0 and XS-6) were added and surveyed with a laser level during the summer of 2006, with XS-0 downstream of XS-1, and XS-6 upstream of XS-5. Locations of five sections are shown in Figure 5. In addition, the long profile of the water surface and bed along the thalweg were surveyed before and after dam removal. All cross sections upstream of the dam were located in historic reservoir sediment, but the right bank at XS-3 was lined with a stone block wing wall connecting the pump station dam with a dam and gate on a small tributary from the west (see Fig. 5A).

Four cross sections were installed with a total geodetic station upstream of the Conoy Creek dam by LandStudies, Inc., an engineering firm in Lititz, Pennsylvania, in 2005. All were located within historic reservoir sediment. We resurveyed these cross sections several times with a laser level between February 2005 and July 2008, but we used only the total change during the entire time period to estimate an average rate of bank erosion.

Two cross sections were installed on Mountain Creek upstream of the breached dam in the winter of 2007–2008 (XS-1 and XS-2), and two more were added upstream of these (XS-3 and XS-4) in the summer of 2008 (see Fig. 7). The first two sections were surveyed with a total geodetic station, and the more recent two were surveyed with a laser level. At XS-1, the left channel bank has eroded into the steep colluvial slope along the south side of South Mountain (see Fig. 7B), but all other cross sections are located within historic, unconsolidated reservoir sediment.

At Mountain Creek, bank pins (1 m metal rebar rods) were inserted horizontally into stream bank faces at the top, middle, and bottom of the bank at all four cross sections. Rod exposure at different times was measured to determine the cumulative amount of linear bank erosion, the average erosion rate, and seasonal variations in rates of erosion. Pins were installed on the left bank on all but XS-1, where pins were installed on the right bank. All pins were located within historic, unconsolidated millpond sediment. Measurement error for bank pins is ±1 cm, and estimates of uncertainty for erosion volume from bank pins are on the order of 15%–18% for typical measurements (see Table 1).

Channel-Normalized Sediment Production

We quantify erosion of sediment along the stream corridor as "channel-normalized sediment production." This parameter is useful in addition to the lateral erosion rate of a specific bank because (1) bank height varies with distance upstream of a dam; (2) both erosion and deposition occur along incised channels; and (3) one or both banks can erode at a given reach. We calculated channel-normalized sediment production in m^3/m/m/yr, a parameter for volume of sediment eroded per unit stream length per unit bank height per year. Normalizing to volume/height/length/time provides comparative numbers with the same units for different methods of measurement as well as for different bank heights.

For two-dimensional channel cross sections, we measured net area removed in m^2 and multiplied by one unit of stream length to get m^3, which then is presented as m^3 per meter of height per meter of stream length. This method accounts for changes in bed elevation as well as erosion and deposition within the stream corridor.

For the one-dimensional bank pin method, we measured lateral retreat at a point and converted this value to volume by

TABLE 1. UNCERTAINTY ESTIMATES FOR DIFFERENT METHODS, CALCULATED FROM TYPICAL MEASUREMENT ERRORS FOR TYPICAL MEASURED VALUES

				Typical measured values			Uncertainty		
Methodology	Dimension	Half-range (cm)	Source	Measured value (m)	Period (yr)	Change value (m^3)	Limits (m^3)	1σ, assumed triangular distribution (%)	1σ, assumed normal distribution (%)
Pins	Horizontal	2	Pin measurement	0.30					
	Vertical	4	Bank height measurement	1.8	1	0.17	±0.073	±18.0	±14.6
	Vertical, longitudinal	4	Extrapolation to unit stream length on irregular surface	0.30					
Cross sections	Horizontal	1	Kinematic survey horizontal RMSE	15.2					
	Vertical	2	Kinematic survey vertical RMSE	1.8	1 to 2	0.85	±0.66	±32.0	±25.8
	Vertical, longitudinal	4	Extrapolation to unit stream length on irregular surface	0.30					

Note: RMSE—root mean square error.

multiplying lateral retreat and bank height (m) for one unit length of stream (m). This value is presented as m^3 of sediment eroded per meter of bank height per meter of stream length. It does not account for deposition at point bars that form opposite of eroding banks, or for bed aggradation or degradation.

The following example illustrates the concept of a sediment production unit (SPU) for a given stream corridor using the two methods described here. Consider a stream reach of 100 m with left and right bank heights of 2.4 m. One of the two banks is eroding at a rate of 0.3 m/yr, and the other is not eroding. Bank pins and repeat channel cross sections could be used to quantify rates of bank erosion and net channel change. Over the 100 m length of channel, 0.3 m/yr of bank erosion would produce 72 m^3/yr of sediment. This volume yields 72 m^3/100 m/2.4 m/yr = 0.3 SPU. If both banks were eroding at 0.3 m/yr, sediment production from the 100 m reach would be 144 m^3/yr of sediment, or 144 m^3/100 m/2.4 m/yr, or 0.6 SPU. If the banks were 1.2 m high instead of 2.4 m, then for a bank retreat rate of 0.3 m/yr at only one bank, the rate of sediment eroded would be 0.3 m^3/m/m/yr, or 0.3 SPU, and the total annual amount of sediment produced would be 36 m^3/yr. Note that these estimates could be presented in units of m/yr, but SPU indicates the procedure by which we estimated the rate, as it is not merely a lateral rate of retreat measured at a point.

Temporal variability also is captured in the different methods of measuring bank erosion rates. A measure of the total volume removed along a channel corridor 25 yr after a dam breach yields a long-term, 25 yr average rate of erosion. However, bank pins installed 23 yr after dam breaching and measured for 2 yr yield a post-dam-breach, short-term average rate from years 23–25. If bank pins or channel cross sections are monitored over a lengthy period, it is possible to compare short-term rates from different intervals within the longer measurement period, and to compare these short-term estimates to the long-term average rates.

RESULTS

Here, we present the results of particle size analysis of stream bed, bank, and bar sediment and of particle size mobility calculations from the Shields parameter equation for the breached Eaton-Dikeman reservoir on Mountain Creek. We compare stream bank erosion rates measured from repeat surveys of cross sections in the three breached reservoirs and evaluate changes with time since dam breach. To determine plan-view changes at Mountain Creek from 2003 to 2009, we compared bank and bar edges from digital ortho-images from 2003 and 2007 with our 2008 and 2009 surveys of bank and bar edges over a distance of 600 m upstream of the dam. Finally, we consider the role of freeze-thaw processes in bank erosion by examining seasonal variations in bank erosion from bank pin measurements at Mountain Creek, and compare these variations to those measured 50 years earlier by Wolman (1959) at a breached millpond on Watts Branch, Maryland.

Sediment Size in the Eaton-Dikeman Reservoir

Particle size data are presented for XS-2 in the Eaton-Dikeman reservoir on Mountain Creek (Fig. 9). Our particle size analysis indicates that grain sizes are similar at XS-1 and XS-2, and field observations indicate they are similar at XS-3, but the historic reservoir sediment is coarser at XS-4, the upstream-most cross section. At XS-2, the historic reservoir sediment consists of 2%–23% clay, 8%–76% silt, and 30%–55% sand, with minor (<1%–25%) amounts of fine gravel. The fine gravel occurs as low-density, porous slag in thin beds with a quartz sand matrix in the uppermost 1 m of reservoir sediment. This slag most likely is from the eighteenth–nineteenth-century Pine Grove and Laurel Forge iron workings located 12 km upstream.

With exception of the uppermost 40 cm, the upper 155 cm section of historic sediment is much sandier than the lower

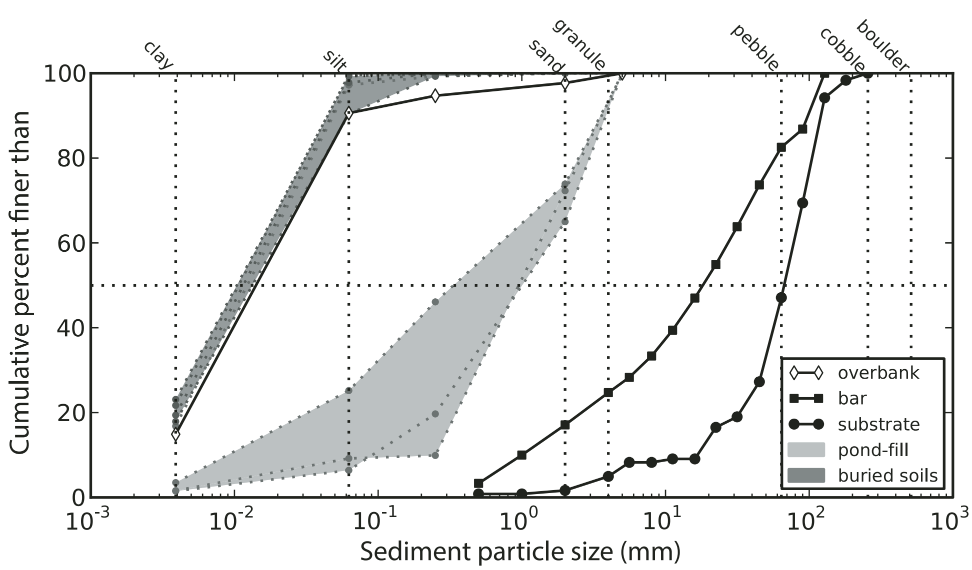

Figure 9. Cumulative grain-size distribution curves for XS-2, with cumulative percent finer on y-axis and grain size on x-axis, for the following sediments: basal gravel substrate exposed in the channel bed by bank erosion, the point bar on right bank, millpond (pond fill) sediment sampled at 10–40-cm-depth increments, and buried fine-grained presettlement sediment between gravel substrate and pond fill. Overbank sediment is uppermost 40 cm of pond fill deposited in shallow pond as overbank deposits (see Fig. 7A).

90 cm of organic-rich prehistoric sediment (from 155 to 245 cm depth, measured from top of reservoir fill). The latter is mostly silt and has a D_{50} particle size of ~0.01 mm. For the millpond sediment above 155 cm, the D_{50} particle size ranges from ~0.03 mm to 1 mm.

Coarse sediment underlying millpond strata throughout the reservoir is exposed at the base of the stream banks and in the channel bed along most of the incised channel. The uppermost part of this exhumed substrate is winnowed of finer sediment along the actively migrating stream bed. As noted earlier herein, this sediment is poorly sorted and can be traced to the hillslope of South Mountain. It is interpreted as exhumed toe-of-slope, late Pleistocene periglacial deposits (e.g., gelifluction sheets). This exhumed and winnowed substrate was sampled at the channel bed just downstream of XS-2, and yielded 2% sand, 3% granules, 65% pebbles, and 30% cobbles. The D_{50} particle size is ~68 mm. The two largest clasts were embedded, and their intermediate axes were estimated at 210 and 220 mm. Both upstream and downstream of the sample site, we measured boulders in the channel with diameters up to ~600 mm.

The inset historic bar forming on the right bank at XS-2 is much coarser than historic millpond sediment, but finer than the periglacial substrate beneath the historic sediment. It consists of 17% sand, 8% granules, 62% pebbles, and 13% cobbles. The D_{50} particle size is ~19 mm.

In sum, the different-aged sediments exposed in the breached Eaton-Dikeman reservoir range in mean grain size from pebbles and cobbles for the Pleistocene periglacial substrate exposed in the channel bed, to clay for prehistoric (Holocene) sediment, silt to sand for millpond sediment, and sand- to cobble-sized sediment for the inset point bar forming within the incised channel corridor. Note that the finest 10% of the point-bar sediment is coarser than 50% of the millpond sediment, and coarser than nearly all of the Holocene sediment between the historic millpond and lower periglacial sediment. The coarsest 70% of sediment in the channel bed is larger than all but the coarsest ~30% of sediment in the point bar.

We interpret the periglacial substrate—exhumed from beneath the eroding banks and exposed as colluvium along valley margins—as the source of most coarse sediment forming point bars within the incised stream corridor of the Eaton-Dikeman reservoir. This interpretation is consistent with the grain-size distributions shown in Figure 9. Some of the coarser parts of the historic millpond sediment probably are mixed and stored with sediment in the point bar. This interpretation is consistent with the grain-size distributions.

Shields Parameter and Particle Mobility in an Incised Reservoir

A review of particle entrainment in flume and field studies indicates that τ^*_c, the critical Shields stress for entrainment of the D_{50} size particle, generally ranges from 0.03 to 0.07 (Buffington and Montgomery, 1997). Assuming that particle entrainment occurs within this range of τ^*_c, we estimate a range in predicted D_{50} values of 34–79 mm for high flow (basal shear stress = 38 N/m^2) at the point bar on the right bank at XS-2 in the breached Eaton-Dikeman reservoir on Mountain Creek. For these estimates, we use bankfull flow depth of 1.3 m and slope of 0.003 (water surface slope measured from LiDAR). High flow depths at XS-2 have been observed to be at least 1.3 m. This flow depth is consistent with the height of the active point bar, ~1 m, on the right bank at XS-2. Values of 34–79 mm are higher than the D_{50} of 19 mm measured at the point bar.

If, on the other hand, we predict flow depth based on the D_{50} of 19 mm measured at the point bar, and again assume that particle entrainment occurs when τ^*_c = 0.03–0.07, we estimate a range in predicted flow depths of 0.3–0.7 m. The point bar was sampled just after Hurricane Hanna occurred in 2008 (September 6–8), and water depth was at least 1.3 m during that event. It is possible that our measurements of grain size done on 25 September 2008 would be different if we had sampled before rather than after a large storm.

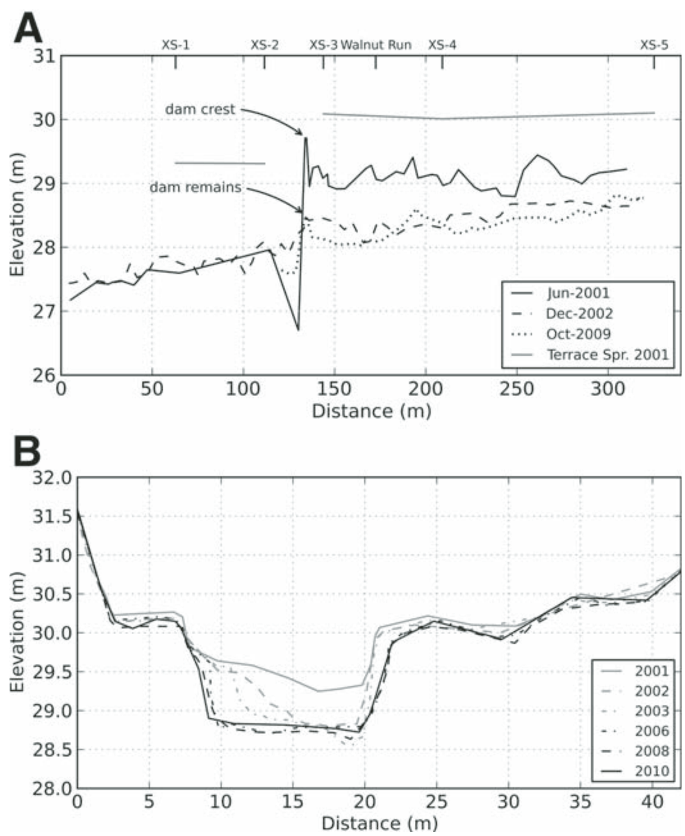

Figure 10. (A) Long profile of Hammer Creek before and after dam breaching. About 0.5 m of the base of the dam remains, forming a grade control that prevents further bed lowering. Terrace surface represents the fill terrace formed by sedimentation to the level of the original dam crest. (B) Repeat surveys of XS-5 showing post-dam-breach vertical incision (2001–2002) followed by channel corridor widening as a result of bank erosion (2002–2010).

Erosion along Incised Streams in Breached Millponds

The four cross sections upstream of the Hammer Creek dam showed similar patterns of incision during the first year after dam breaching, followed by bank erosion and channel widening for the 10 yr since breaching. In 2002, a year after dam breaching at Hammer Creek, the channel bed had degraded ~1 m just upstream of the dam; bed lowering diminished to ~0.5 m ~300 m upstream of the breach (Fig. 10A). With exception of a slightly high part of the bed 200 m upstream of the dam, the bed was lowered an additional 0.2 m between 2002 and 2009. Upstream of the dam, the surface of the historic sediment settled and subsided during the first 5 yr after dam breach, probably as a result of dewatering of the sediment-filled reservoir. Although bank retreat and channel widening occurred at all sections, no prominent point bars formed upstream of the breached pump station dam (Fig. 10B). Downstream of the dam, changes in the bed and banks were insignificant from 2002 to 2009, although the bed was slightly elevated by deposition of sandy gravel immediately after dam breaching.

A plot of cumulative net increase (erosion minus deposition) in channel area for XS-4 and XS-5 on Hammer Creek versus time since dam breach is logarithmic (Figs. 11A and 11B). Cross section 6 has only 1 yr of data (from 2006 to 2007), as it has not been resurveyed since 2007, so a long-term trend cannot be discerned. The stone wall on the right bank of XS-3 prevents its use for monitoring long-term trends in bank erosion. The majority of the increase in channel area for XS-4 and XS-5, where both banks are in historic reservoir sediment, has been the result of lateral bank erosion since 2001.

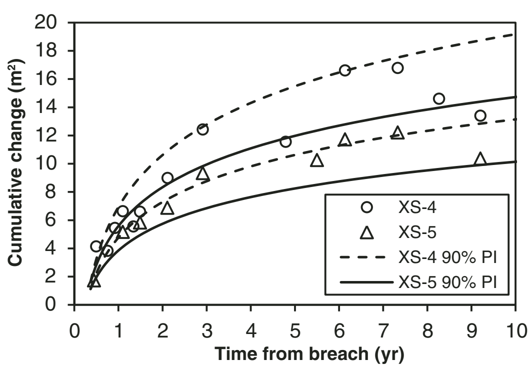

Figure 11. Net channel enlargement of XS-4 and XS-5 at Hammer Creek modeled as a function of the natural log of time. For XS-4, $n = 13$, $y = 4.48\ln(x) + 5.85$, $R^2 = 0.89$, and $p = 1.139 \times 10^{-6}$, with residuals normally distributed. For XS-5, $n = 9$, $y = 3.35\ln(x) + 4.72$, $R^2 = 0.94$, and $p = 1.826 \times 10^{-5}$, with residuals normally distributed. The 90% prediction interval (PI) is shown for each cross section and its model. Most channel enlargement is the result of bank erosion and widening, as little vertical change in the bed has occurred since 2002. Instances of recent vertical aggradation at Hammer Creek result from construction, by anglers, of a low rubble dam (~0.5 m height) immediately downstream of the former dam to create a pool for fishing.

The four cross sections in the breached Eaton-Dikeman reservoir on Mountain Creek are characterized by bank erosion with little change in bed elevation (Fig. 12). The channel has incised to the level of periglacial pebbles, cobbles, and boulders along the entire length of the reservoir. As a result, most erosion is lateral rather than vertical. Post-dam-breach inset point bars are prominent in the reach of stream between XS-1 and XS-3, where the channel crosses the breached reservoir from the southern to northern sides of the valley (see Fig. 7B). Along this channel reach, both banks consist of historic fine-grained millpond sediment. Scour winnows the underlying periglacial gravel and has produced several prominent point bars within the incised stream banks (see Figs. 7B and 8A). Digitizing bank and bar edges (break lines) on repeat digital ortho-images from 2003 to 2006 and LiDAR (PA MAP) from 2007 reveal that these bars are migrating rapidly downstream at a rate of several meters per year (Fig. 13). Bar migration occurs as upstream ends of the bars are eroded, and deposition occurs on the downstream ends of the bars.

Rates of sediment production for XS-4 and XS-5 at Hammer Creek have decreased since dam breaching, from as high as 7.6 SPU in 2001–2003 to ~0.2–0.5 SPU in 2006–2008 (Table 2, Fig. 14). Sediment production rates calculated from repeat channel cross-section surveys along Mountain Creek in the breached Eaton-Dikeman reservoir varied from –0.5 to 1.0 SPU over a period of 1–1.4 yr from 2008 to 2009. Transient negative values occur when the volume of point-bar growth is greater than volume of bank eroded over short measurement intervals. As discussed earlier herein, however, the point bar consists of much coarser material than the eroded bank sediment. Comparison of digitized bank and bar edges (break lines) from digital ortho-images for 2003 and 2006, and of LiDAR for 2007, yields a reach-averaged sediment production rate of 0.3 SPU for the 2003–2007 time period. Note that comparison of digital ortho-images and LiDAR elevation models yields an average rate of bank erosion over a greater length of channel than do surveys of individual cross sections.

The four cross sections at Conoy Creek yield sediment production rates that ranged from 0.1 to 0.4 SPU during 2.4 yr of repeat surveys in 2006–2008 (Table 2). The second lowest rate of 0.1 SPU at Conoy Creek is for XS-4, located along the southeastern valley margin near the bypass that eroded behind the masonry wall of the dam. At this location, a large amount of rubble, including masonry and concrete, existed in the channel bed, probably as a result of deterioration of the dam. This cross section did not experience the deep incision and scour that occurred upstream at the other three cross sections, which were not limited by the grade control of remnants of the dam.

Bank pin measurements at Mountain Creek yield sediment production rates of 0.3–0.6 SPU, and reveal that more lateral bank erosion occurs in late winter to early spring than during other

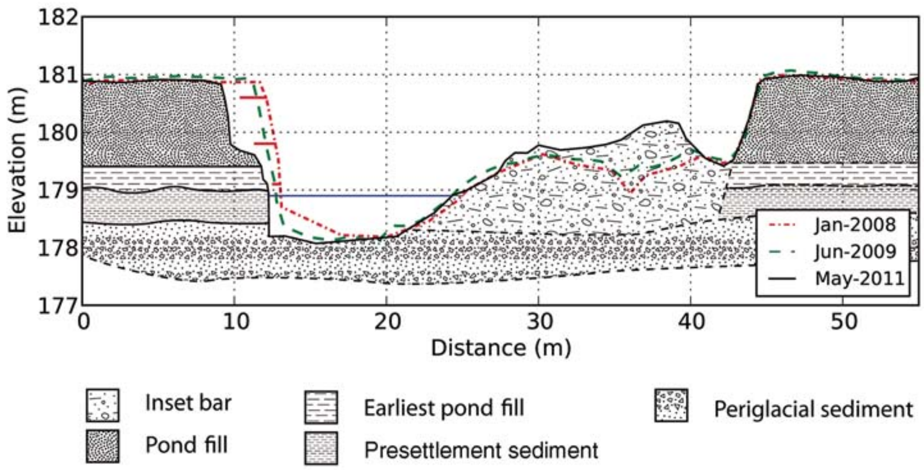

Figure 12. Repeat surveys of channel cross section 2 at Mountain Creek in 2008 (total geodetic station), 2009 (laser level), and 2011 (total geodetic station) reveal erosion of left bank and bar deposition on right bank. Red lines indicate positions of bank pins. Pins are reset periodically to keep pace with erosion. Cumulative erosion of the top pin from 2008 to 2010 was >1.6 m, as the pin was removed during bank erosion in March 2010, and replaced immediately after. Stratigraphic data indicate different age deposits, from Pleistocene periglacial gravel at the base of the section, to fine-grained, organic-rich presettlement sediment, to fine-grained historic millpond sediment, to point-bar sand and gravel on right bank within the incised stream corridor. A thin, dark, organic-rich wetland soil is found at the contact between Pleistocene gravel and millpond sediment at most sites in the Mid-Atlantic region, and it has been dated at numerous localities as Holocene in age (Walter and Merritts, 2008; Merritts et al., 2011).

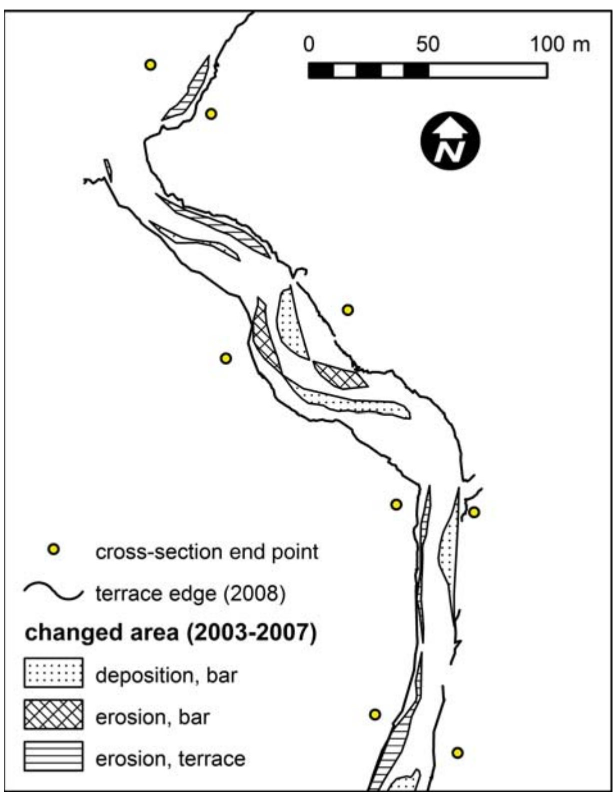

Figure 13. Ortho-images from 2003 and 2006 were mapped and compared with light detection and ranging (LiDAR) elevation data from 2007 and global positioning system (GPS) surveys in 2008 to identify areas of change (erosion and deposition) during the 4 yr interval. Point bars migrated along the channel reach between XS-2 and XS-3 at several meters per year, with upstream tips eroding and downstream tips prograding with time. In addition, incised channel banks eroded laterally, and the stream channel corridor widened with time.

seasons (Table 2; Fig. 15). The majority of bank retreat occurs in March and April. Similar observations were made by Wolman at Watts Branch in Maryland during the 1950s (Wolman, 1959), and by Lawler in his studies of stream banks in England (cf. Lawler, 1986). Data from Wolman (1959) are plotted here for comparison with our data from Mountain Creek (see Fig. 15). Remarkably, the rates and seasonal timing of bank retreat measured with bank pins and survey lines along the bank edge by Wolman (1959) on Watts Branch, Maryland, are nearly identical to those we measured at Mountain Creek with similar procedures from 2007 to 2010, half a century later. The distance between the two sites is ~140 km, with Mountain Creek due north of Watts Branch.

We observed freeze-thaw processes and needle ice in the incised banks of all three reservoirs during winter months since observations began in 2007. Winter freeze-thaw processes weaken and disaggregate bank sediment by freeze-thaw, and spring flow events are able to remove much of the apron of debris that accumulated on the banks during the preceding winter. Prominent notches form at various levels in the apron of disaggregated debris throughout the spring until it is removed completely. We observe that it takes 1 to 3 mo to remove this apron at most localities. Subsequently, warming, evaporation, and plant growth during summer months lead to drying and desiccation of banks.

DISCUSSION: POST-DAM-BREACH STREAM BANK EROSION

A primary objective of the research presented here was to evaluate decadal changes in rate of erosion of reservoir sediment for incised stream channels in breached reservoirs. Channel cross-section data for Hammer Creek, for which we have the longest record (9 yr) of repeat cross-section data, demonstrate that

TABLE 2. SITE, MEASUREMENT METHOD, TIME PERIOD, AND ESTIMATE OF SEDIMENT PRODUCTION BY BANK EROSION PER UNIT METER OF CHANNEL LENGTH

Site	Station	Method	Start date	End date	Period (yr)	Change	Unit	Length (m)	Bank height (m)	Production (SPU* or m/yr)
Hammer Creek	XS-4	Cross section	26-Jun-2001	23-Oct-2008	7.33	16.8	m^2	1	0.8	2.9
Hammer Creek	XS-4	Cross section	26-Jun-2001	2-Aug-2002	1.10	6.6	m^2	1	0.8	7.6
Hammer Creek	XS-4	Cross section	2-Aug-2002	8-Aug-2003	1.02	2.4	m^2	1	1.0	2.2
Hammer Creek	XS-4	Cross section	8-Aug-2003	25-May-2004	0.80	3.4	m^2	1	1.4	3.0
Hammer Creek	XS-4	Cross section	25-May-2004	11-Apr-2006	1.88	–0.9	m^2	1	1.1	–0.4
Hammer Creek	XS-4	Cross section	11-Apr-2006	14-Aug-2007	1.34	5.1	m^2	1	1.0	3.7
Hammer Creek	XS-4	Cross section	14-Aug-2007	23-Oct-2008	1.19	0.2	m^2	1	0.8	0.2
Hammer Creek	XS-4	Cross section	23-Oct-2008	1-Oct-2009	0.94	–2.2	m^2	1	1.2	–1.9
Hammer Creek	XS-4	Cross section	1-Oct-2009	8-Sep-2010	0.94	–1.2	m^2	1	1.2	–1.1
Hammer Creek	XS-5	Cross section	26-Jun-2001	2-Aug-2002	1.10	5.2	m^2	1	1.0	4.5
Hammer Creek	XS-5	Cross section	2-Aug-2002	6-Aug-2003	1.01	1.7	m^2	1	1.1	1.5
Hammer Creek	XS-5	Cross section	6-Aug-2003	25-May-2004	0.80	2.5	m^2	1	1.1	2.9
Hammer Creek	XS-5	Cross section	25-May-2004	26-Dec-2006	2.59	0.9	m^2	1	0.9	0.4
Hammer Creek	XS-5	Cross section	26-Dec-2006	14-Aug-2007	0.63	1.5	m^2	1	0.9	2.5
Hammer Creek	XS-5	Cross section	14-Aug-2007	23-Oct-2008	1.19	0.5	m^2	1	0.9	0.5
Hammer Creek	XS-5	Cross section	26-Jun-2001	23-Oct-2008	7.33	12.2	m^2	1	0.9	1.8
Hammer Creek	XS-5	Cross section	23-Oct-2008	8-Sep-2010	1.88	–1.8	m^2	1	1.2	–0.8
Mountain Creek	XS-1	Cross section	15-Jan-2008	23-Jun-2009	1.44	2.0	m^2	1	2.2	0.6
Mountain Creek	XS-2	Cross section	15-Jan-2008	23-Jun-2009	1.44	–1.4	m^2	1	2.0	–0.5
Mountain Creek	XS-3	Cross section	13-Aug-2008	7-Aug-2009	0.98	1.8	m^2	1	2.0	0.9
Mountain Creek	XS-4	Cross section	13-Aug-2008	7-Aug-2009	0.98	2.0	m^2	1	2.1	1.0
Conoy Creek	XS-1	Cross section	15-Feb-2006	18-Jul-2008	2.42	0.2	m^2	1	1.8	0.1
Conoy Creek	XS-2	Cross section	15-Feb-2006	25-Jul-2008	2.44	0.9	m^2	1	1.7	0.2
Conoy Creek	XS-3	Cross section	15-Feb-2006	18-Jul-2008	2.42	1.4	m^2	1	1.6	0.4
Conoy Creek	XS-4	Cross section	15-Feb-2006	25-Jul-2008	2.44	0.6	m^2	1	1.6	0.1
Mountain Creek	XS-1	Bank pin	18-Dec-2007	7-Aug-2009	1.64	0.3	m	1	2.7	0.2
Mountain Creek	XS-2	Bank pin	18-Dec-2007	7-Aug-2009	1.64	0.4	m	1	2.6	0.3
Mountain Creek	XS-3	Bank pin	13-Aug-2008	7-Aug-2009	0.98	0.3	m	1	1.9	0.3
Mountain Creek	XS-4	Bank pin	13-Aug-2008	7-Aug-2009	0.98	0.4	m	1	2.1	0.4
Mountain Creek	XS-2	Bank pin	18-Dec-2007	22-May-2008	0.43	0.5	m	1	2.6	1.2
Mountain Creek	Reach	Bank edge digitization	1-Apr-2003	23-Apr-2007	4.06	1539	m^3	611	2.0	0.3

*SPU—sediment production unit.

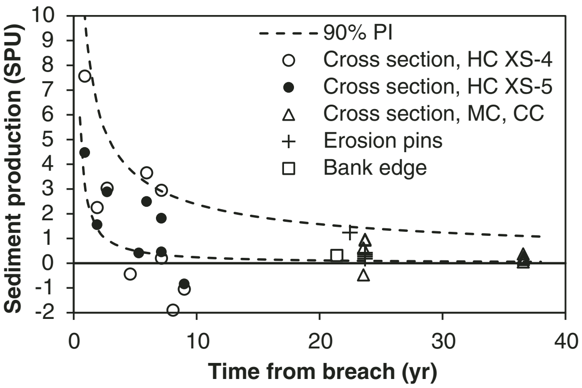

Figure 14. Channel-normalized rate of sediment production from the stream corridor with time is modeled with a negative power function for Hammer (HC), Mountain (MC), and Conoy (CC) Creeks. Data sources include channel cross sections for all three breached reservoirs (n = 20), and bank pins (n = 5) and repeat digital ortho-images (n = 1) for Mountain Creek. Each data point represents 1 to 2 yr measurement intervals, with the exception of the single data point from repeat digital ortho-images, which represents 3 yr. In some years and at some locations, net change is negative, indicating no change or deposition; however, these values are transient. At Hammer Creek, recent negative values result from construction, by anglers, of a low rubble dam (~0.5 m height) in 2007 and subsequent aggradation in the bed upstream from the dam. We therefore fit a power function to the positive data (n = 21) and indicate a 90% prediction interval [PI] for those data. The negative power function indicates that erosion rates slowly diminish with time after an early period of rapid erosion. SPU (sediment production unit): This estimate of sediment produced along a given length of stream channel by stream bank erosion takes into account bank height and erosion rate.

the cumulative increase in cross-sectional area is a function of the natural log of time (see Fig. 11A). This increase in channel area is largely an increase in width of the incised stream corridor, as most of the vertical incision occurred soon after dam breaching. Although some bed scour and deposition continue to occur, the 0.5 m of unremoved dam at Hammer Creek and the coarse periglacial substrate beneath historic sediment prevent substantial bed erosion. Similarly, the coarse periglacial substrate at Conoy and Mountain Creeks limits bed degradation (cf. Figs. 8 and 12). For the remaining discussion, we make the assumption that the majority of decadal-scale erosion from the breached millponds studied here is due to lateral bank retreat and that the rate of enlargement of the incised stream corridor width is proportional to the rate of bank erosion, E_r.

We proposed earlier that the rate of erosion in a breached reservoir might decelerate with time after dam breach, as was observed with the Marmot Dam removal on the Sandy River in Oregon (Major et al., 2008, 2012). All cross section (n = 25), bank pin (n = 5), and bank edge digitization (n = 1) data from Hammer, Mountain, and Conoy Creeks indicate that decadal rates of sediment production, proportional to linear bank retreat rates, do indeed diminish with time (Fig. 14). We model this decrease in rate of bank erosion as a power function, with time as the independent variable and sediment production rate as the dependent y variable.

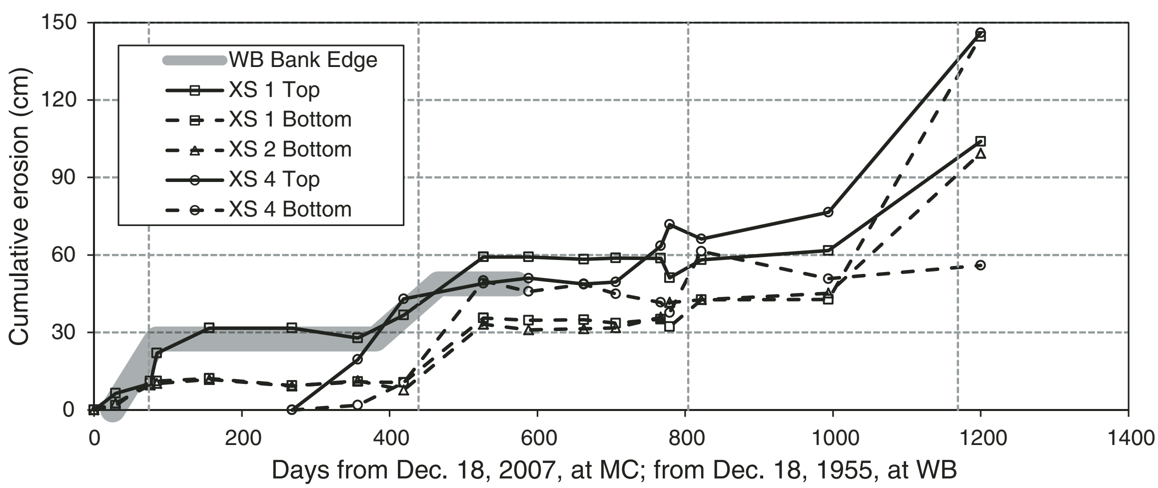

Figure 15. A record of erosion for ~1220 d (3.3 yr) for bank erosion pins at XS-1, XS-2, and XS-4 on Mountain Creek reveals that the majority of bank retreat occurs during mid- to late winter and early spring (December through early April). This same phenomenon was observed by Wolman (1959) for Watts Branch (WB), Maryland, also upstream of a breached milldam and in historic reservoir sediment. Watts Branch data from Wolman (1959) are shown as black squares. Wolman collected data from 5 December 1955 to early 1957. For comparison here, the Watts Branch and Mountain Creek (MC) records are plotted versus time since 18 December 2007, the start date for our measurements at XS-1 and XS-2. Pins at the middle of the bank commonly were buried by an apron of debris from above, and were not as frequently swiped clean as the lower bank, and they do not yield as clear a seasonal signal of erosion as top and bottom pins. Vertical lines indicate 1 March for each year.

A best-fit power function for all positive values of sediment production ($y = 5.1356x^{-0.832}$, $n = 26$, $R^2 = 0.6008$; $p = 3.326 \times 10^{-6}$) can be used to predict that erosion rates will be 0.2 SPU some 50 yr after dam breaching, and 0.1 SPU after 100 yr. These numbers, though seemingly small, can produce ~400–220 m^3/yr of sediment, respectively, per kilometer of incised channel length from a breached reservoir with 2-m-high banks, yielding tens of thousands of cubic meters of sediment over decadal time spans.

We propose that the rate of increase in channel width subsequent to dam breach might decelerate more slowly, leading to a smaller exponent in the power function, in regions where freeze-thaw is an important process compared to in warmer climes. Freeze-thaw processes occur winter after winter regardless of land-use change or increased width of the stream corridor. An exposed bank is weakened and disintegrated each year and prone to removal by flow depths sufficient to reach the debris that accumulates in a freeze-thaw apron. Greatest rates of erosion occur where stream flow has access to this debris, as on the outside banks opposite point bars. Wetting and drying from variable flow depths are likely to accelerate freeze-thaw processes by pumping more water into stream banks.

CONCLUSIONS

An important implication of the results presented here is that incised stream banks in breached milldam reservoirs continue to be sources of fine-grained sediment for decades after dam breaching. Within the first 10 yr of dam breaching, rates of sediment production from breached reservoirs are highest, but they decelerate with time. Even 50–100 yr after dam breaching, however, millponds with typical bank heights of 2 m can produce hundreds of cubic meters of sediment per kilometer of stream length per year.

Freeze-thaw processes are significant in weakening the banks of incised streams and are most effective where banks have a large component of silt, as is the case in Mid-Atlantic region millpond reservoirs. Lawler (1986) determined that bank erosion rates from freeze-thaw processes are proportional to the number of days with air frost (air temperature ≤0.0 °C). Furthermore, bank erosion rate corresponds more strongly with this parameter than any of the other 16 meteorological and hydrologic variables examined for the Ilston River by Lawler (1986). For southeastern Pennsylvania, air temperature dropped below 0 °C at least 100 d in both 2008 and 2009. Lawler's statistical regression equation for erosion rate as a response to number of days of frost (see Table IV *in* Lawler, 1986) yields a predicted value of bank erosion of 0.6 m/yr, similar to rates measured at the sites discussed here, including Watts Branch, Maryland (see Fig. 15).

These implications and the results presented here have substantial portent for evaluating sources of fine-grained sediment to impaired water bodies, such as the Chesapeake Bay (see Fig. 1). Thousands, perhaps tens of thousands, of milldams exist throughout this large watershed in the states of New York, Pennsylvania, Maryland, and Virginia (Walter and Merritts, 2008). An unknown number, but probably thousands, were breached in the last century. Each is in different stages of post-dam-breach channel incision. We estimate that typical milldams contain 50,000–250,000 m^3 of sediment, depending on dam height and the geometry and gradient of the valley upstream of the dam. Freeze-thaw processes are common throughout the Mid-Atlantic region, as are stream banks incised into historic sediment associated with post–European settlement and milling (Wohl and Merritts, 2007; Walter and Merritts, 2008; Merritts et al., 2011). Nevertheless, watershed models typically do not take into account stream bank erosion as a source of sediment. Even less recognized are the significance of time of dam breaching and the role of freeze-thaw processes in rates of bank erosion. Instead, watershed models use modern land use as a predictor of sediment loads in streams.

Linking upland soil erosion with sediment loads in streams has substantial uncertainties at present. The values of soil erosion predicted by empirical relations such as the Revised Universal Soil Loss Equation, referred to as "edge-of-field" estimates, are inadequate for predicting sediment delivery to streams (Boomer et al., 2008), despite their common use for such purposes. Widely used watershed models (e.g., HSPF [Hydrological Simulation Program–FORTRAN] and SWAT [Soil and Water Assessment Tool]) predict sediment loads in streams based on empirical relations among modern land use, land cover, and soil erosion (cf. Nasr et al., 2004). The Chesapeake Bay Watershed Model, for example, estimates the delivery of sediment and nutrients to the bay, which drains most of the Mid-Atlantic Piedmont, by simulating hydrologic and nutrient cycles for given land-use and land-cover conditions.

The limitations of models that simulate only upland sediment sources and modern land use can be illustrated with an example of a forested watershed such as Mountain Creek (nearly 100% forest cover), for which such models would predict low sediment yields. Recent breaching of milldams with reservoirs of fine-grained historic sediment, however, might result in high suspended sediment loads. In this case, causality is assumed to be a function of modern land use and upland soil erosion, rather than changes in stream channel slope due to base-level fall and the transient storage and release of historic sediment. Breached millponds with historic sediment are the source of sediment that originated from upland erosion during prior land-use conditions over a period of decades to centuries, representing decadal to centennial lag times in different components of the system. These legacy effects and inherent lag times are missing from a watershed model that relies upon current land use to estimate sediment sources.

Breached historic reservoirs are sources of fine sediment loads to Mid-Atlantic streams, and, as more obsolete dams breach and channels become incised with time, that source could grow. As a result of the deliberate, close spacing of milldams to maximize waterpower on streams even as small as first order, the potential for trapping significant amounts of fine-grained sediment has historically been substantial throughout the Mid-Atlantic region. The corollary is that the potential for releasing significant amounts of sediment after dam breaching and channel incision is likewise substantial. The results of this study indicate that fine-grained reservoirs continue to be sediment sources for at least several decades after dam breaching and most likely for at least a century.

ACKNOWLEDGMENTS

Funding for this work was provided by the Pennsylvania Department of Environmental Protection, the Chesapeake Bay Commission, Franklin and Marshall College, the U.S. Environmental Protection Agency, and the National Science Foundation (EAR-0923224). We are particularly grateful to the Masonic Villages, The Nature Conservancy, and the Pennsylvania Game Commission for granting us permission to work on their property. This work benefited from discussions with W. Oberholtzer, D. Altland, and E. Wohl. Reviews by Tess Wynn and Jason Julian were helpful in improving the presentation of various concepts and data.

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Manuscript Accepted by the Society 29 June 2012

Printed in the USA