PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

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Anthropocene streams and base-level controls from historic dams in the unglaciated mid-Atlantic region, USA

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Recently, widespread valley-bottom damming for water power was identified as a primary control on valley sedimentation in the mid-Atlantic US during the late seventeenth to early twentieth century. The timing of damming coincided with that of accelerated upland erosion during post-European settlement land-use change. In this paper, we examine the impact of local drops in base level on incision into historic reservoir sediment as thousands of ageing dams breach. Analysis of lidar and field data indicates that historic milldam building led to local base-level rises of 2–5 m (typical milldam height) and reduced valley slopes by half. Subsequent base-level fall with dam breaching led to an approximate doubling in slope, a significant base-level forcing. Case studies in forested, rural as well as agricultural and urban areas demonstrate that a breached dam can lead to stream incision, bank erosion and increased loads of suspended sediment, even with no change in land use. After dam breaching, key predictors of stream bank erosion include number of years since dam breach, proximity to a dam and dam height. One implication of this work is that conceptual models linking channel condition and sediment yield exclusively with modern upland land use are incomplete for valleys impacted by milldams.

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With no equivalent in the Holocene or late Pleistocene sedimentary record, modern incised stream-channel forms in the mid-Atlantic region represent a transient response to both base-level forcing and major changes in land use beginning centuries ago. Similar channel forms might also exist in other locales where historic milling was prevalent.

Keywords: Anthropocene; geomorphology; surface processes; base level

1. Introduction

Walter & Merritts [1] proposed that late seventeenth to early twentieth century valley sedimentation in the unglaciated mid-Atlantic US 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 milldams. Furthermore, Walter & Merritts [1] proposed that local drops in base level have caused widespread incision into historic reservoir sediment as thousands of ageing dams have breached or been removed during the last century. The phrase 'Anthropocene[1] stream' as used here refers to a stream characterized by deposits, forms and processes that are the result of human impacts, in this case, reservoir sedimentation in response to base-level rise (dam building) and subsequent channel incision in response to base-level fall (dam breaching).

In this paper, we propose that the modern phenomenon of stream-channel entrenchment is largely decoupled from the modern upland land use. As documented herein, a breached dam can lead to incision, stream bank erosion and increased loads of suspended sediment in streams, even with no increase in stormwater runoff. Incision occurs in forested, rural areas as well as agricultural and urban areas. Given that milldams and their upstream impacts were so prevalent throughout the mid-Atlantic region, this finding has substantial import. One implication of this work is that conceptual models linking channel condition and sediment yield exclusively with modern upland land use, sediment supply and runoff are incomplete for valleys impacted by milldams. Significant changes have occurred in valley-bottom, not only upland, boundary conditions.

The geomorphic history of stream channels in the mid-Atlantic US is not only important to understanding channel evolution, but also has significant land-management implications. Currently, fine-grained sediment and nutrients are the leading pollutants in the Chesapeake Bay, the largest estuary in the United States [3]. The US Environmental Protection Agency is charged with enforcing regulations to manage the total maximum daily loads of sediment and nutrients in watersheds draining to this estuary. Understanding the sources of sediment in streams is critical to developing successful strategies to reduce erosion and sediment flux to the Bay. Furthermore, characterization of the pre-impacted nature of valleys and streams is fundamental for determining potential ecological restoration goals.

Three streams in the mid-Atlantic region of Pennsylvania—Mountain Creek, Valley Creek and Big Spring Run—are presented as examples of typical incised streams that were produced by a series of similar human impacts over the course

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[1] The term 'Anthropocene' is not formally recognized by the US Geological Survey as a description of geologic time. We use it here informally. The origins of the term are discussed in [2].

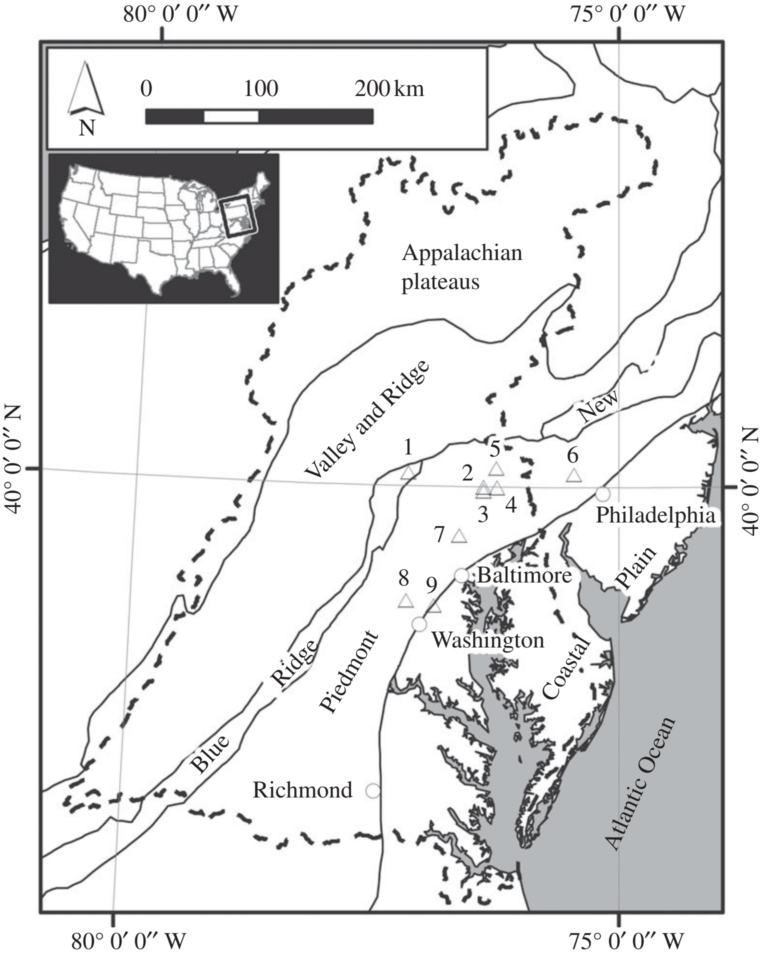

Figure 1. Locations of mid-Atlantic sites discussed in text, with physiographical provinces and Chesapeake Bay watershed. Sites are as follows: 1, Mountain Creek; 2, Little Conestoga Creek West Branch; 3, Indian Run; 4, Big Spring Run; 5, Lititz Run; 6, Valley Creek; 7, Gunpowder Falls; 8, Watts Branch; and 9, Indian Creek.

of several centuries (figure 1). Four other incised streams (Indian Creek, MD; Watts Branch, MD; Indian Run, PA; and West Branch Little Conestoga, PA) are discussed more briefly to illustrate key elements of this suite of processes. All streams are located within approximately 100–200 km south of the border of the last full-glacial, or Wisconsinan ice-sheet advance and probably were subject to periglacial processes during glaciation (cf. [4–6]). Representative of mill-dammed valleys and incised streams throughout the mid-Atlantic region, these seven examples provide context for evaluating ecological restoration goals as well as current efforts to stave off stream bank erosion and reduce high loads of suspended sediments. Before examining these streams and the anthropogenic impacts that led to their formation, we first describe the stratigraphy of valley-bottom deposits into which modern streams have incised, and the typical forms of incised streams channels.

2. Anthropocene stream forms and stratigraphy

Modern channels in the low-relief, unglaciated mid-Atlantic US have a characteristic form, repeated throughout the region, as the result of a similar history of anthropogenic activities [1] (figure 2*a*). Cut deeply into historic sediment, stream channels have steep eroding banks of cohesive clay, silt and sand. Fresh exposures and stratigraphy reveal lamina, graded bedding and historic materials such as logs with axe marks, various iron objects and bits of brick and ceramic (cf. [7–11]).

Between the historic deposits and underlying bedrock of incised mid-Atlantic streams is a polygenetic veneer of pre-Holocene sediment, including toe-of-slope fine-grained colluvium and coarser grained debris fans, tributary junction fans and a quartz-rich, long-term denudational gravel lag. Because of the region's periglacial history, often the basal gravel is cobble to boulder in size. When exposed beneath fine-grained historic sediment in banks of incised streams, it sometimes is misinterpreted as point bar gravel. This sediment is generally poorly sorted and angular to sub-angular, however, and the small streams where it is commonly found could not generate sufficient shear stresses to move such large gravel as bed load. Our field mapping indicates, instead, that coarse (cobble to boulder) pre-Holocene deposits beneath historic sediment in mid-Atlantic valley bottoms are colluvial, and in at least some cases, periglacial (e.g. gelifluction), rather than fluvial in origin. This conclusion is consistent with results of geomorphic and soil mapping on hillslopes of Maryland and Pennsylvania [12–14].

Our research shows that Holocene spring-fed wetlands in a low-energy fluvial environment existed upon this gravel substrate for thousands of years prior to European settlement, gradually filling low spots with organic matter in the form of a dark (black, 10YR 2/1), fine-grained (sandy to silty loam), hydric soil [1,15,16]. Beaver damming is likely to have played a role in the evolution of these Holocene wetlands. Today, this buried Holocene hydric soil is commonly exposed beneath the historic sediment at the base of incised streams in the mid-Atlantic region (figure 2*b*). Radiocarbon dates ($n = 87$) from this organic rich, hydric soil at multiple sites in Pennsylvania and Maryland range in age from 10 500 years BP to approximately 300 years BP ([1], and more recent unpublished data).

At some locations along the margins of first, second- and third-order valleys, a thin, laterally discontinuous, fine-grained, light-coloured, gleyed deposit occurs between the dark, organic-rich hydric soil and overlying historic sediment. From its age (approximately AD 1200–1750 based on six radiocarbon dates), stratigraphical position, seeds and association with Native American and early Colonial artefacts, our preliminary interpretation is that this sediment encroached upon valley-bottom wetlands as a result of human activities (e.g. land clearing or burning), perhaps in conjunction with climatic events such as drought, hurricanes, wetter periods or colder periods with more freeze–thaw. The geometry of these pre- and early Colonial deposits, the surfaces of which have low-amplitude down-valley undulations, indicates that they were shed from the adjacent toe-of-slope environments and deposited near the sediment source. These deposits differ from later millpond sedimentation. Once valleys were ponded by historic damming, the

Figure 2. (*a*) Indian Creek, MD, has the typical characteristics of an anthropogenically formed stream as characterized in this paper. Historic, fine-grained (predominantly silt, clay and sand) sediment overlies a pre-settlement (Holocene), organic-rich, hydric soil (*b*). Vertical incision, followed by lateral channel migration, exposes high banks to erosion. Confined flows result in high flow depths and shear stresses that, in turn, are capable of transporting gravel as bed load in addition to fine sediment as suspended load. Gravel scoured from beneath the Holocene wetland soil is typically polygenetic in origin, including a quartz-rich denudation lag and various periglacial deposits such as debris fans. Note large cobble-sized clasts of low-density pre-settlement peaty material on the gravel bar. In this case, some of the underlying bedrock consists of Cenozoic conglomerate, which might also be a source of gravel. (Photographs taken by D. Altland and F. Bubczyk.)

sediment eroded from uplands was transported farther into valley bottoms as well as down-valley, and deposited by lacustrine and fluvial rather than colluvial processes.

Fine-grained historic (post-contact) sediments exposed in the banks of incised mid-Atlantic stream channels are unusually thick relative to modern amounts of overbank deposition of fine sediment [10,11,17]. They form broad surfaces referred

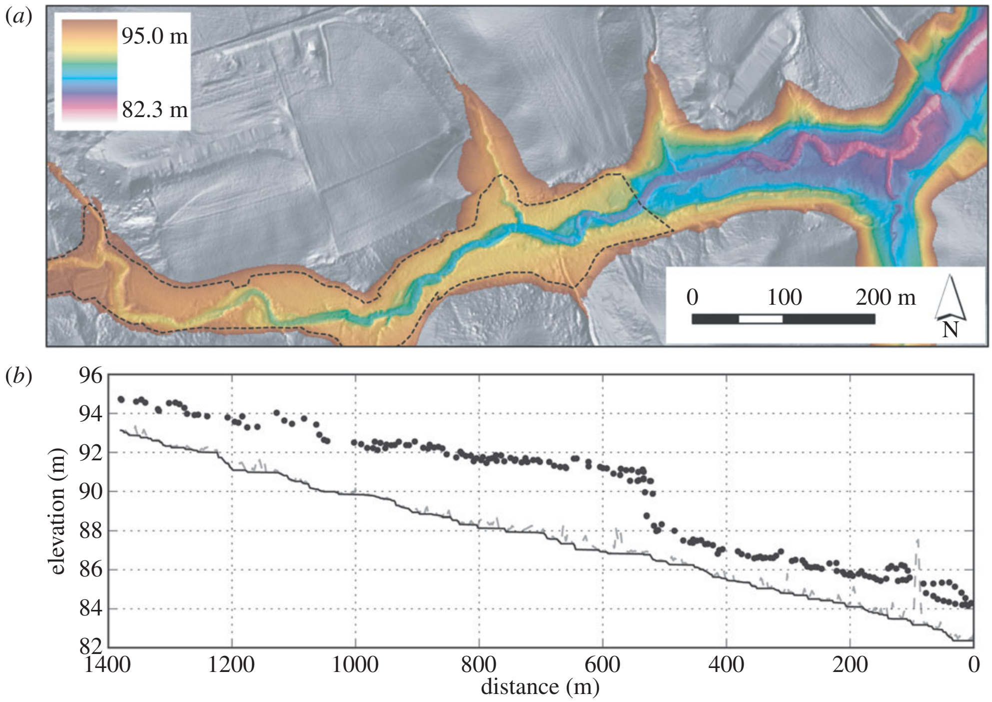

Figure 3. Lidar reveals an approximately 3.5 m dam that raised local base level on Indian Run, a tributary to the Little Conestoga Creek in southeastern Pennsylvania. One of at least two milldams on this small, relatively steep stream, the dam trapped sediment for greater than 1 km upstream, resulting in a wedge of sediment that can be seen in (*a*) plan view and (*b*) the longitudinal stream profile. The stream has incised to the original valley-bottom level at a slope about two times that of the reservoir fill surface. Note the marked drop in the elevation of sediment fill surface just downstream of dam. (Lidar acquired at 1200 m above mean terrain with horizontal accuracy of 0.6 m and nominal point spacing of 0.9 m. Vertical r.m.s.e. better than 0.15 m relative to the North American Vertical Datum of 1988.)

to as ‘valley flats’ that are higher than the level associated with bankfull discharge along incised channels [10]. These valley flats, too, are anthropogenic in origin. Using lidar, Walter & Merritts [1] documented that the crests of breached, historic milldams merge with valley-flat surfaces along multiple streams throughout the mid-Atlantic piedmont (figure 3). Valley flats are abandoned terraces—the former surfaces of millponds—that diminish in height upstream of milldams. Prior to this work, valley-flat surfaces in the mid-Atlantic region were interpreted as floodplains formed by a combination of laterally migrating meandering stream channels and overbank deposition of silt and clays [9,11,18].

Gravel and medium to coarse sand are transported as bed load in modern, incised streams and deposited within the channel corridor at locations of decreased channel slope, sharp bends and inside (convex) banks at meander bends (figure 2) [9]. Post-dam breach incision and lateral migration exhume and winnow the older basal and toe-of-slope gravels, leaving a coarse cobble to boulder lag. Finer gravels (granule to cobble size) transported and deposited on this exhumed surface are subject to further erosion and reworking as incised meandering channels migrate laterally across the resistant substrate of coarse sediment (cf. [7]).

In addition to transporting coarse bed load, modern incised streams in the Appalachian Piedmont carry suspended-sediment loads that are anomalously high, comparable to suspended loads of tectonically active regions with higher relief [19–21]. The incised streams have ready access to a supply of suspended-sediment load from the fine-grained banks. The low channel width-to-depth ratios produce water depths sufficient to carry large suspended loads, and basal shear stresses sufficient to transport gravel as bed load.

Observations of the migration of one stream channel in particular, Watts Branch, MD, over several years were used to infer that 'lateral migration of meanders by the erosion of the concave banks and deposition on the convex banks over many years results in a river channel's occupying every possible position between the valley walls' ([22], p. 68). Our research indicates, however, that the reach of Watts Branch studied by earlier workers, with an upstream drainage area of only 10 km^2, is incised into historic millpond deposits upstream of a previously unrecognized dam, and these deposits overlie a late-Holocene hydric soil and older colluvium (see supporting online material in [1]). The pre-Holocene, Holocene and historic deposits did not form by lateral migration of a meandering stream over a prolonged time period. Indeed, we have found no stratigraphical evidence of a buried, pre-settlement, meandering stream channel within the incised stream corridor of Watts Branch.

3. Human impacts on geomorphic processes

(a) *Causality or coincidence*

Our identification of the anthropogenic controls on the origin of historic landforms and deposits raises questions about how causality is determined for changes in geomorphic processes. The geometry of single-channel meandering streams generally is viewed as the result of self-adjusting hydraulic variables in response to changing sediment load and discharge or to base-level lowering [23,24]. The cause of a change in channel conditions is commonly determined by searching for contemporary perturbations in upland sediment load or runoff, downstream base-level controls or the crossing of a threshold [8,9,18,24–27].

Most workers focus on external factors other than base-level change when examining causes of change for streams in the mid-Atlantic, a region of very low tectonic activity and long-term slow denudation [28]. Instead, agriculture and urbanization are cited widely as the causes of historic aggradation and degradation, with aggradation presumed to be owing to an increase in sediment supply (cf. [8]). Degradation is attributed to a decrease in sediment supply, an increase in stormwater runoff or a combination of the two forcing factors (cf. [9,27]).

Other common causes of aggradation and degradation are dam building and breaching that trigger the base-level rise and fall, respectively. Base-level rise leads to a decrease, and base-level fall to an increase, in water surface slope (figure 4) [23,29–31]. The ubiquity of dams and dam breaching in the mid-Atlantic

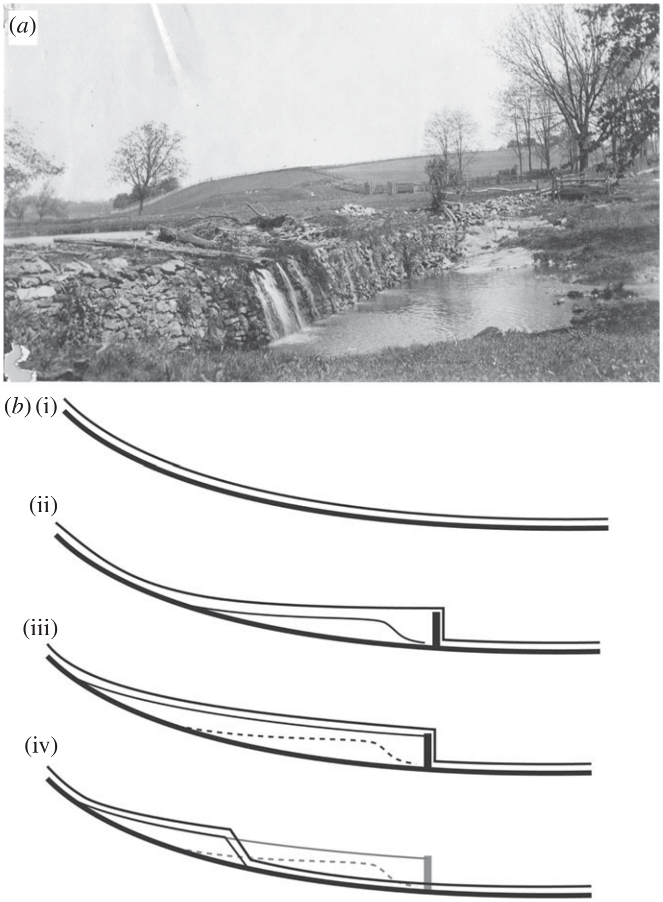

Figure 4. (*a*) Lancaster County mill dam (2.7 m high) photographed on 13 May 1919 (PA Department of Environmental Protection Dam Safety inspection files). The modern stream is incised deeply to bedrock at this location. (*b*) Dam building on a stream with a graded valley profile (i) results in base-level rise and aggradation (ii). Dam breaching results in base-level fall and vertical incision (iii). Whereas aggradation occurs with progradation of a wedge of deltaic sediment from up to downstream, degradation begins as a knickpoint that propagates upstream through the reservoir sediment, and continues as lateral retreat of eroding banks in the wake of the knickpoint (iv). The remaining reservoir fill persists as paired terraces that are eroded by the migrating incised stream.

region was not recognized until recently [1], so the possibility of large-scale, short-term (10^0–10^2 yr) changes in water surface slope and channel behaviour were not considered. Furthermore, previous models of channel change focused on upstream changes in sediment supply and runoff, not on historic, anthropogenic changes to valley bottoms (cf. [27]).

Upland soil erosion has long been recognized as a source of suspended sediment in modern streams through the processes of sheet wash, rilling and gully erosion, which can be initiated and accelerated by deforestation and agriculture (cf. [32–34]). Aerial photos of the US from the early twentieth century often show extensive rilling and gullying on farm fields, and the advent of mechanized ploughing in the late nineteenth century is cited as a contributor to increased upland soil erosion. Human activities associated with construction are also thought to be a source of sediment during the period of construction activity [35]. As a consequence, many land-use management practices have been implemented to mitigate upland soil erosion, including contour ploughing and terracing.

Linking upland soil erosion with sediment loads in streams has substantial uncertainties at present. The amount 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 [36], despite their common use for such purposes. Widely used watershed models (e.g. the HYDROLOGIC SIMULATION PROGRAM—FORTRAN (HSPF) and the SOIL AND WATER ASSESSMENT TOOL (SWAT)) predict sediment loads in streams based on empirical relations among modern land use, land cover and soil erosion (cf. [37]). 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 hydrological and nutrient cycles for the given land-use and cover conditions. Field methods, such as the caesium-137 technique, can be used to quantify agricultural erosion and delivery, but data collection needs and costs limit this approach [21,38].

The limitations of models that simulate only upland sediment sources and modern land use can be illustrated with an example of a forested watershed, for which such models would predict low sediment yields. Recent breaching of milldams with reservoirs of fine-grained historic sediments, however, might result in high suspended-sediment loads. If causality were assumed to be a function merely of modern land use and upland soil erosion, rather than changes in stream-channel slope owing to base-level fall, then the transient storage and release of historic sediments would be overlooked. Decadal to centennial lag times in different components of the system, and inherent transient conditions, are missing from models that rely upon current land use to estimate sediment sources.

If upland soil erosion were the dominant source of sediment to streams, and if the resultant sediment loads were the predominant control on channel geometry, then stream channels should be more stable after many decades of soil-conservation practices. Yet, many streams in the mid-Atlantic Piedmont continue to be unstable and degrading, with both bed scour and bank erosion observed as widespread phenomena [1,7,25,26,39–41].

Conceptual models that link upland land use to channel condition (aggradation, degradation and stability) and sediment yield predict that upland soil erosion and sediment yields in streams should diminish after urbanization (cf. [27]). After nearly a century of soil-conservation implementation and substantial reforestation, however, Appalachian Piedmont streams continue to have high sediment yields [20,21]. Neither causality nor a coincidence between land use and timing of high sediment loads is justified or evident. Furthermore, continued high sediment loads should preclude incision according to such models, and yet incision is widespread.

In response to this incongruity, some have argued that increased stormwater runoff from urbanization, possibly in combination with a decrease in upland sediment supply, is the cause of widespread modern channel incision and stream bank erosion [18,26,42,43]. As with associating the coincidence in the timing of agriculture with high sediment yields, linking incision and bank erosion with either stormwater runoff or reduced sediment supply is done by association with upstream, contemporaneous land use. Although increased stormwater has been documented to accelerate channel widening in developed areas (cf. [44]), incision and bank erosion also occur in rural areas with little or no development and nearly 100 per cent forest cover, as in the Mountain Creek, PA, example discussed below. Furthermore, some reaches of the same stream are incised much more deeply than others and have higher rates of bank erosion, even though all are downstream from the same sub-urbanized areas, as in the Valley Creek, PA, example discussed below.

4. Anthropogenic base-level forcing and geomorphic change

Here, we provide evidence that, for valleys impacted by mill damming, rates of valley-bottom sedimentation and erosion are decoupled from modern upland land use in the mid-Atlantic region. Although mills became obsolete with the advent of fossil fuels, the base-level forcing that led to reservoir sedimentation remains as long as dams exist.

Our analysis of lidar and field data in Pennsylvania and Maryland indicates that dam building on relatively low-gradient valley bottoms (typically 0.001–0.006) led to local base-level rises of 2–5 m (typical range of milldam height) and reductions in valley-bottom slopes of roughly half. Subsequent base-level fall with dam breaching led to an approximate doubling in slope, a significant base-level forcing. Until dam breaching occurs, sediment storage in the reservoir continues regardless of land use and rates of erosion on upland slopes. The important factors for sediment accumulation are dam height, reservoir trap efficiency (TE), reservoir age (i.e. degree of filling) and the frequency and severity of storms that might flush some sediment from the reservoir.

After dam breaching, factors more important than land use for predicting stream-bank erosion include number of years after dam breaching, proximity to a dam and dam height, the last two of which control the height of incised stream-channel banks (figure 3). Similar to Pizzuto & O'Neal [41], we find that number of years elapsed since dam breaching is the most important factor in identifying causes of increased stream-corridor erosion upstream of breached dams.

The causes and effects of mill damming and breaching are not immediately coincident in time, as it takes decades to centuries for reservoirs to fill and for incised channels to erode reservoir sediment once dams breach [45]. Importantly, the perturbation is downstream of the apparent change in channel condition when a milldam is built or breaches, not upstream as in the case of land-use change. Looking for the source of stream impairment downstream of the impaired area is counter-intuitive to the long-term bias towards privileging upland land use as the primary source of stream impairment. As shown in §5, water-powered milling was widespread and ubiquitous, so the regional impact on base level was significant, and continues to be so.

5. The ubiquity of water-powered milling

In colonial and post-revolutionary America, low-head dams, typically 1–3 m high, were built across numerous small (first- to third-order) valley bottoms for water-powered milling that propelled the Industrial Revolution [1,46–48] (figure 5).

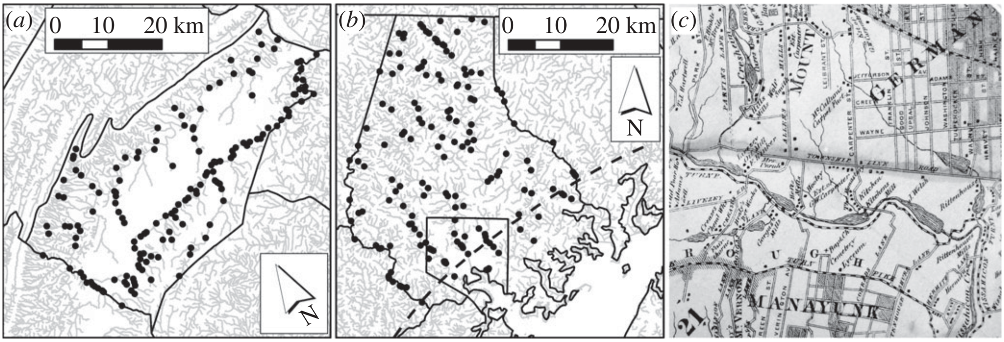

Figure 5. (*a*) At least 153 milldams were located in Cumberland County, PA, based on an 1858 historic map [52]. Mountain Creek is the southeastern-most tributary, with 10 milldams. Milling on this stream was associated with iron mining, iron forge and paper-mill industries. The fifth dam on this stream supplied water to the Eaton-Dikeman millpond, one of the case studies presented here. (*b*) At least 160 milldams were located in Baltimore County, MD, in the mid-nineteenth century based on historic maps [53,54]. (*c*) Eleven milldams and ponds are shown on Wissahickon Creek, PA, and its tributaries on the Barnes 1868 Philadelphia County Atlas [55]. Dams located for six counties in Pennsylvania and two in Maryland for the nineteenth century, as well as a number of mills per county in the eastern US as of the 1840 US Census, can be viewed at the following website: http://www.fandm.edu/x17479.

Milling was vital for grinding grain, fulling wool, producing textiles and paper, cutting wood, stamping and melting ores, pounding metals, making gunpowder, and squeezing oil and juice from seeds and fruit. Dams were also built in conjunction with mining operations, particularly for iron and chromite, in the mid-Atlantic region during the Colonial to Civil War period. Early American settlers brought milling technologies from Europe, where thousands of water-powered mills lined streams as early as AD 1100 [1,49].

Milling intensified with economic growth in early America, and dozens of mill acts crafted to promote economic development were passed in every early American colony and state east of the Mississippi River throughout the late seventeenth to mid-nineteenth centuries [50,51]. By 1840, more than 65 000 water-powered mills existed in the 26 states of the eastern US ([1]; see US industrial censuses of 1840, 1870 and 1880). Our analysis of historic records in Lancaster County, PA, indicates that peak mill development was 1790–1850, but widespread water-powered milling extended from 1710 to 1940, with a few mills operating throughout the twentieth century (figure 5*a*; [56]).

Prior to adoption of steam engines (late nineteenth century), milldam reservoirs supplied a relatively constant head and reliable supply of water to mills. Early American mill acts that regulated the raising of dams and compensation for upstream landowners of flooded lands clearly indicate that milldams had well-known backwater effects on streams and valley bottoms [50]. A review of legal history demonstrates that mill acts probably were the 'most common uses of the eminent domain power during the colonial and Revolutionary periods ... [and] ... authorized riparian landowners to construct dams to build up heads of water that were necessary for the operation of mills' [57, p. 370]. Because of these backwater effects, later mill acts were passed to control mill-crowding [58].

Milldams commonly lined mid-Atlantic valleys in series, forming chains of slackwater pools that enabled millers to maximize the potential energy of falling water in a watershed (figure 5). Valley Creek and Mountain Creek in Pennsylvania, for example, have main stem lengths of only 20 km, but each had at least 10 milldams during the eighteenth and nineteenth centuries (see discussion below).

6. Reservoir trap efficiency and sedimentation

Walter & Merritts [1] documented that considerable amounts of historic sediment are stored in valley corridors upstream of relict milldams that once supplied waterpower to the industry. The combination of soil erosion induced by widespread deforestation and agriculture in a deeply weathered landscape, and the close spacing of milldams to maximize waterpower, resulted in substantial trapping of fine-grained sediment in elongate millponds throughout the mid-Atlantic region.

Gradients along first- to third-order Piedmont valleys generally are relatively low (0.001–0.006), so backwater effects from milldams extended as much as several kilometres upstream. Valleys were filled with mud and sand for long distances upstream of milldams, producing a local rise in base level for upstream tributaries as well. Our analysis of lidar data, field mapping and backhoe trenching indicate that margins of millponds continued to serve as sediment traps for soil moving down slope, even after ponds had filled. In sum, all conditions requisite for significant trapping of sediment were met during the period dominated by water-powered milling: base-level rise, a large sediment flux, low-gradient valleys and relatively high reservoir TEs. For 2 km upstream of a 3 m milldam in a 60 m wide valley with a trapezoidal shape and gradient of 0.002, for example, approximately 180 000 m^3 of sediment would be stored.

Previous work has shown that low-head dams (generally < 7 m high) built across small (first- to third-order) valleys have high sediment TEs of greater than 40–80 per cent [59,60]. A reservoir's TE, a measure of its ability to trap and retain sediment, is expressed as a ratio of incoming sediment that is retained by settling to total sediment influx [59,61],

$$\mathrm{TE} = \frac{S_{\mathrm{settled}}}{S_{\mathrm{inflow}}}, \tag{6.1}$$

where S_{settled} is the mass of sediment deposited within the reservoir and S_{inflow} is the mass of sediment entering the reservoir. This TE is dependent upon the amount of water inflow, the characteristics of the inflowing sediment, the retention time of water in the pond. Retention time is controlled by run-off characteristics and pond geometry, both of which are related to reservoir age.

Data for 44 reservoirs indicate a close correlation between the ratio of reservoir capacity to inflow (C/I ratio) and the TE ([59]; see also [61]). The greater the capacity of a reservoir relative to the inflow of water, the higher is its TE. A large reservoir on a small stream, for example, would have high-sediment TE, whereas a small reservoir on a large stream would have low-sediment TE.

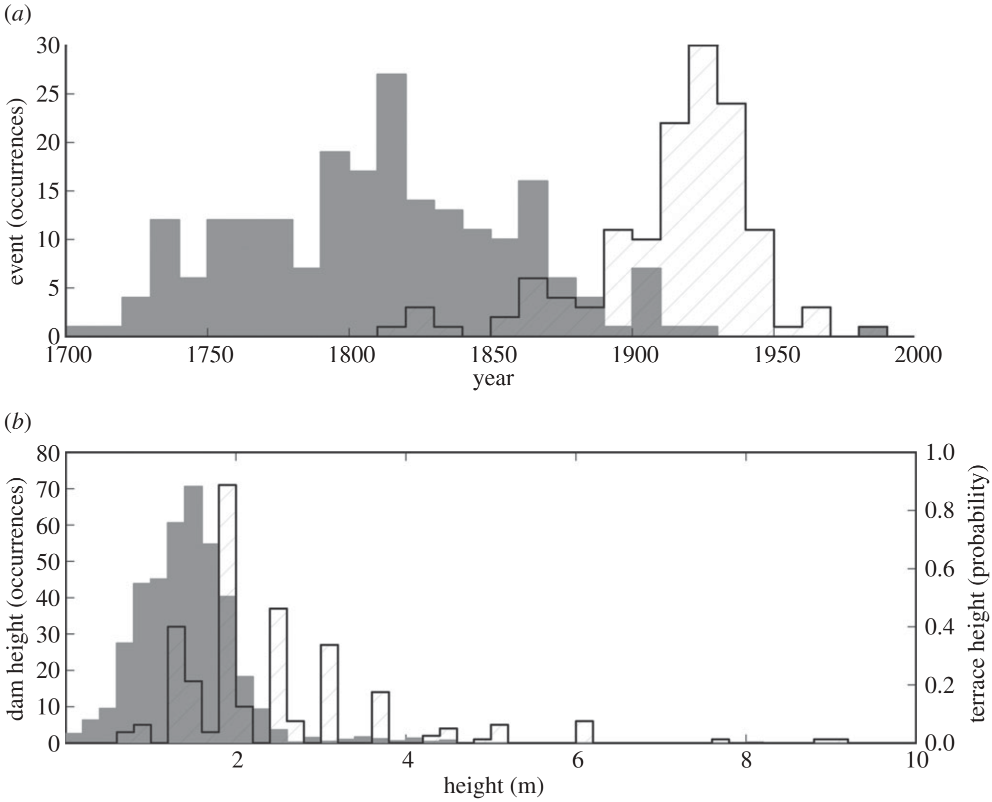

Figure 6. (a) According to historic records, at least 215 mills were built in Lancaster County, PA, from the early eighteenth to mid-twentieth century with peak mill building in the early nineteenth century. The peak period of mill closing was approximately 110 years later, in the early twentieth century. Early mills relied solely on water power from milldams, but later mills also used steam and other energy sources. Grey bars, mill built; white bars, mill closed. (b) At least 246 dams were built to power mills in Lancaster County by the late nineteenth century and the median dam height was 2 m (mean was 2.4 m). Bank height, in this case equivalent to terrace height, was sampled every 20 m along the stream from lidar data for Indian Run, Little Conestoga Creek, West Branch Little Conestoga and the Conestoga River, all located in the Piedmont of southeastern Pennsylvania. The terrace (bank) height probability density function (right y-axis) reveals that median bank height is slightly less than that of median dam height, and all bank heights are less than the corresponding dam heights. Grey bars, terrace height; white bars, dam height.

Dam height provides a measure of reservoir capacity, in that higher dams have larger reservoirs (figure 6b). From detailed historic records, we have determined that the height of milldams in Lancaster County, PA, typically was 1.2–3.7 m ($n = 246$), although some dams were as high as approximately 9 m [56]. Nineteenth century US Census records indicate that milldams in other mid-Atlantic counties had similar heights. Given the generally small size of the streams in this region (see figure 5, for example), we infer that this range in dam heights was sufficient to produce relatively high TEs. Furthermore, as reservoirs were filled, the TE diminished and approached zero.

7. Reservoir trap efficiency: example of Mountain Creek, PA

Using modern US Geological Survey stream gauge flow data for the Pine Grove Furnace station on Mountain Creek and historic state inspection reports of reservoir capacity and filling, we calculate a capacity to inflow ratio of 0.003–0.004 for the Eaton-Dikeman millpond in Cumberland County, PA (figure 5). The corresponding TE for mixed grain sizes varies from 14 to 21 per cent for the 4 m high, 213 m long milldam that powered a paper mill from 1855 to the mid-twentieth century. Within approximately 60 years of construction, the reservoir was 57–64% full according to Pennsylvania state inspections. Inspectors also reported that the total reservoir capacity was about 173 000 m^3. Historic aerial photographs dating to the 1930s and bathymetric surveys by Dickinson College students and faculty in the 1970s indicate that the reservoir was filled to capacity, with water depths less than 0.3 m, before it was breached in 1985. Modern water surface slope for the incised channel is approximately 0.0030, and the reservoir fill surface slope is approximately 0.0016.

Several factors indicate that this reservoir probably had a sediment TE greater than 20 per cent before dam breaching. The amount of time during which a reservoir fills with sediment depends not only on the ratio of reservoir capacity and inflow of sediment, but also on factors such as duration of time during which the pond surface does not reach the level of the spillway. When the water in a millpond drops below the level of its spillway, retention time increases greatly and TE approaches 100 per cent. At Eaton-Dikeman, the 1914 state inspection report noted that the water in the pond did not reach the level of the spillway during inspection in June. It is probable that this millpond, like others in the region, often was below the level of the spillway—even during relatively wet months—because water was removed from the pond via a head race in order to supply power to the mill. Mills typically operated around the clock and rarely shut down.

In addition, stream-flow values are so low during late summer to autumn months in this region that it is likely that many millponds often did not reach the level of dams and spillways during low-flow months. Gauge data throughout the region consistently indicate high monthly stream flow from January to July, and low flow from August–December. Numerous historic accounts of milling and photographs of milldams support the conclusion that water in millponds sometimes was below the level of the spillway. Thick beds of clay, silt and leaves in millpond reservoir sediment also support the interpretation of high TE. For low-flow months (August–December), we estimate capacity to inflow ratios as high as 0.048, and corresponding TEs of 77–86% [61].

Finally, iron mining and charcoaling for iron forges were widespread upstream of the Eaton-Dikeman papermill dam from approximately 1760 to 1890, and historic records indicate that upstream milldams breached repeatedly during storms. It is likely that sediment fluxes were particularly great during this time period, and would have increased the reservoir TE. Iron and other mining, forges and charcoaling were prevalent throughout the mid-Atlantic region during the early American to Civil War era; their reliance on water power and wash ponds probably played a substantial role in higher sediment fluxes and reservoir sedimentation during that time.

8. Dam breaching, incision and stream bank erosion

When a dam is breached, the local base level for upstream reaches is lowered, leading to reservoir incision at the breach (figure 4*b*) [62,63]. As a result, channel slope and bank height increase at the site of dam breach, leading to higher boundary shear stresses, bed degradation and lowering of the water surface. As reservoir sediment dewaters, it also becomes more compacted and settles. With continued incision and erosion of the bed, mass movement commonly occurs along banks near the dam because lateral support (confining pressure) is removed from wet reservoir sediment with high pore pressure.

Doyle *et al.* [64], building on the research of previous researchers [62,63,65,66], developed a conceptual model for the evolution of a stream incised into a breached, sediment-filled reservoir. They tested this model by monitoring two dam removal sites in Wisconsin for a period of 1–2 years after dam removal [64]. According to this conceptual model, a stream cuts into the unconsolidated sediment at the site of the breach immediately after dam breaching, forming a knickpoint, or head-cut, in the stream profile. Across this zone of increased grade, the stream has greater scouring capacity than upstream along the stream profile, where it remains perched in the reservoir sediment. This head-cut propagates up-valley through the reservoir sediment as the stream scours its bed. If the sediment is non-cohesive and fine grained, the stream is able to cut into and transport sediment easily, so the knickpoint propagates rapidly.

After removal of the Rockdale milldam on the Koshkonong River, for example, Doyle *et al.* [64] documented that a head-cut migrated upstream approximately $10\,\mathrm{m\,h^{-1}}$ for 24 h, but decelerated to an average rate of 40 m per month over the next 11 months. Downstream of the head-cut, a deep, narrow channel had high boundary shear stresses (up to $20–30\,\mathrm{N\,m^{-2}}$), capable of eroding bed and bank material. Upstream of the head-cut, however, low boundary shear stresses (less than $5\,\mathrm{N\,m^{-2}}$) were insufficient to erode the bed or banks, and the reservoir sediment surface remained largely undisturbed (fig. 9 and fig. 12 in [64]).

Many incising channels in the mid-Atlantic Piedmont and Ridge and Valley region access pockets of gravel along valley margins, much of it talus or periglacial toe-of-slope deposits that date to the last full glacial conditions of approximately 15 000–50 000 years ago. With high banks and shear stresses, incised streams are able to transport some of this gravel as bed load. At Big Spring Run, PA, a small headwater stream (drainage area $4\,\mathrm{km^2}$, average gradient approx. 0.005), for example, we have documented bedload transport of tracer gravel (*b*-axis 5 cm) at basal shear stresses calculated to be $12–29\,\mathrm{N\,m^{-2}}$ for water depths of 0.25–0.6 m, respectively, during moderate to large flow events. In contrast, as discussed below, this area was a low-energy, wet meadow prior to down valley mill damming, sedimentation and post-breach incision.

Both bed scour from incision and subsequent bank erosion contribute to post-dam breach erosion from the stream corridor. Bed scour is particularly important at the onset of dam breaching, which initiates a period of stream incision to the level of the breach. Once a stream has incised, stream banks retreat along eroding faces. Both bed and bank erosion contribute to total erosion from the stream corridor, but the sediment stored in eighteenth to nineteenth century millponds generally is fine grained (clay, silt and sand), so bank erosion is largely a process of removing fine sediment and leaving winnowed coarse sediment behind.

Bars of sand and gravel accumulate at the inside banks and upstream ends of channel bends of incised stream corridors, as well as at locations of reduced slope, flow expansion and engineering infrastructure such as culverts, at-grade bridges and road crossings (figure 2). Overbank deposition, which could store some of the eroded fine sediment, generally is uncommon along deeply incised channels, particularly where banks are highest near dams and water depth rarely is sufficient to go over bank. Some fine sediment is deposited in the stream corridor as flood flows wane and wetted banks collapse, as in the case of fine-grained channel margin deposits associated with debris trapping, but residence times of fine sediment are short (days to years) in comparison with those of gravel in deeply incised channels with low width–depth ratios.

Fine sediment production from an incised reservoir is largely the result of mass movement, freeze–thaw, wetting and drying, and fluvial entrainment from exposed stream banks [45,67]. Our investigations of sites where dam breaching occurred up to 100 years ago indicate that erosional processes along incised reservoirs continue over a period of more than 100 years after a milldam breaches. Low- to moderate stream flow within high banks results in the removal of toe-of-bank sediment. This removal leads to collapse of overlying bank sediment during subsequent wetting–drying events [68].

Banks are prone to freeze–thaw because sediment is exposed to lower air temperatures during the winter. Needle-ice formation and erosion during melting are more likely for banks with high contents of silt [69,70]. Channel flow at the base of near-vertical banks can sweep away material shed by freeze–thaw or collapse processes, as discussed below, resetting the banks for future erosion.

9. Case studies of three post-dam breach-incised streams

Our primary field sites number more than 100 on 23 first- to third-order valleys in the Piedmont and Ridge and Valley physiographical provinces of PA and MD, and we have visited similarly impacted, milled valleys in Virginia, New Jersey, Delaware, New York and Massachusetts. In Pennsylvania, state records indicate that thousands of the estimated 8000–16 000 milldams that once existed are breached. Here, we present three case studies: Mountain Creek, Valley Creek and Big Spring Run, Pennsylvania, which are representative of the suite of geomorphic forms and processes produced over a period of centuries by mill damming and breaching in this region. We examine the history of dam-induced sedimentation and breach-induced incision and bank erosion for these three case studies.

Upstream of the study reaches Mountain Creek drains 114 km^2, Valley Creek approximately 61 km^2 and Big Spring Run approximately 4 km^2. Located in the easternmost Ridge and Valley physiographical province, the Mountain Creek valley is underlain by carbonate rocks, primarily dolomite, and adjacent ridges consisting mostly of quartzite with some phyllite. Along Valley Creek in the Piedmont, metamorphosed carbonate rocks underlie the valley floor; adjacent hills consist of quartzite and/or schist. The entire Big Spring Run watershed in the Piedmont is metamorphosed silty limestone with minor phyllite and prominent quartz veins. Mountain Creek was the locus of extensive deforestation for charcoaling to supply iron furnaces from the 1700s to late

1800s, and for wood to supply paper mills from the 1800s to early 1900s. Since approximately 1910, the watershed has been reforested and much of it is state park and forest. Historic land use in Valley Creek was primarily agricultural until the mid-twentieth century. The watershed has experienced some recent reforestation and suburbanization, with 18 per cent impervious surface [71]. Big Spring Run remains largely agricultural, with some recent suburbanization in its headwaters.

10. Methods for estimating rates of bank erosion and sediment production

Rates of bank erosion and sediment production from the stream corridor are compared for each case study using a variety of methods to measure the amount of sediment eroded by incised streams. We calculate *channel-normalized sediment production* in $m^3\ m^{-1}\ m^{-1}\ yr^{-1}$, a parameter for the volume of sediment eroded per unit stream length per unit bank height per year, in order to compare erosion rates at breached reservoirs with different dam heights. For a 1 m high bank over a distance of 1 m that is eroding along only one side of the channel and has no deposition, for example, the rate of lateral bank retreat is equivalent to this sediment-production parameter. This sediment-production parameter is used in addition to lateral erosion rate of a specific bank because (i) bank height varies with distance upstream of a dam, (ii) both erosion and deposition occur along incised channels, and (iii) one or both banks can erode at a given reach. Because erosion can be measured in different ways, as lateral retreat, plan-view area removed or volume removed over a given length interval, we are able to compare different sites and methods of measurement by normalizing to volume/bank height/stream length/time.

The same units are used for four different methods of measuring sediment erosion. For the one-dimensional bank-erosion pin method, for example, we measure lateral retreat at a point where a 1 m metal rod is installed, and convert this value to volume by multiplying lateral retreat and bank height (m) for one unit length of stream (m). This value is presented as channel-normalized sediment production in cubic metres of sediment per metre of bank height per metre of stream length per unit time or $m^3\ m^{-1}\ m^{-1}\ yr^{-1}$. For two-dimensional channel cross sections surveyed at different times, we measure net area removed in square metres and multiply by one unit of stream length to get cubic metres, which is then presented as cubic metres per metre of bank height per metre of stream length per unit time. From plan-view digital orthophotos (horizontal resolution approx. 0.3–0.5 m), we measure net area of bank retreat and multiply this area by bank height to get volume of eroded sediment. This estimate, in cubic metres, is presented as cubic metres per metre of bank height per metre of stream length over which the aerial change was measured per unit time. Finally, from lidar, we calculate the volume of the channel corridor incised within the historic sediment-filled reservoir, assuming that the fill formed a continuous subplanar surface just prior to dam breaching. We then normalize this volume with respect to average bank height for the entire length of reach over which the volume change was measured. This estimate of erosion is a measure of how much sediment (of all sizes) is gone since dam breaching occurred, and is not a measure of a contemporary, short-term erosion rate.

All of these values are minimum estimates of the actual rate of erosion of historic reservoir sediment because some of the eroded stream-corridor volume has been filled with coarser grained, inset sand and gravel bars in the wake of incised, migrating stream channels. The amount of infill generally increases with time after dam breach as the incised stream migrates laterally in the breached reservoir. However, we have also documented that this second generation of reworked reservoir sediment, mixed with toe-of-slope colluvium from valley margins and basal gravel that underlies the historic sediment, is itself eroded by laterally migrating streams within the incised stream corridor.

11. Eaton-Dikeman Reservoir, Mountain Creek, PA

The breached Eaton-Dikeman milldam on Mountain Creek discussed above illustrates the magnitude of sediment-production rates and decadal-scale trajectory of change. The 213 m long Eaton-Dikeman dam was breached by the deliberate removal of 15 m of the span of the dam along its northwestern edge in 1985. Immediately afterwards, Mountain Creek incised approximately 3 m, equivalent to the breach height. Lidar and field surveying reveal that stream banks are graded in height downstream to the spillway crest, corresponding to the downstream thickening wedge of reservoir sediment. The pre-reservoir valley bottom is exposed along the length of the incised channel.

Our repeat surveys (Trimble GeoXH global positioning system (GPS)) of stream-bank edges and monumented stream-channel cross sections indicate that near-vertical to vertical banks continue to erode and retreat laterally 25 years after this dam breached. During our 3 year study period from 2007 to 2010, we observed marked bank erosion by freeze–thaw (needle-ice) processes and mass movement of blocks of bank up to $5 \times 5 \times 3$ m in size after wetting and drying events. Four cross sections yield rates of lateral bank erosion that varied from 0.6 to 1.2 $\mathrm{m\,yr^{-1}}$ from 2008 to 2009. Comparison of GPS breakline surveys done in 2008 and 2009 with digital orthophotos from 2003 and 2006 yields a mean lateral bank-erosion rate of 0.3 $\mathrm{m\,yr^{-1}}$ from 2003 to 2006. Using the rates of bank-edge retreat (planform) and repeat cross-section surveys to determine volume, we estimate that the amount of sediment eroded from the 366 m reach of stream between surveyed cross sections was approximately 1543 $\mathrm{m^3}$ between 2003 and 2006, or approximately 514 $\mathrm{m^3\,yr^{-1}}$. The channel-normalized sediment-production rates from eroding banks within the breached Eaton-Dikeman reservoir ranged from 0.22 to 0.95 $\mathrm{m^3\ m^{-1}\ m^{-1}\ yr^{-1}}$ for 2003–2009. Note that, as discussed above, the channel-normalized sediment-production rates are presented in units of $\mathrm{m^3\ m^{-1}\ m^{-1}\ yr^{-1}}$ for the length of stream investigated, in this case 366 m, and provide a number that can be compared for different measurement methods and bank heights.

Using lidar topography (acquired in 2007), we estimate that approximately 38 228 $\mathrm{m^3}$ of sediment was eroded over a distance of 1183 m since dam breaching in 1985, yielding a long-term average sediment-production rate of approximately 1738 $\mathrm{m^3\ yr^{-1}}$, about three times greater than the short-term rate of 514 $\mathrm{m^3\ yr^{-1}}$ from 2003 to 2006. Comparing this estimate to the volume of sediment that we estimate was stored in the reservoir over this distance, about 10–15% of the reservoir sediment has been removed by the incised stream channel. It is likely that the erosion rate was much higher during the years immediately after breaching, and has diminished with time. Because eroding banks remain vertical and expose fine-grained sediment, they continue to erode by mass movement associated with freeze–thaw and wetting–drying processes.

12. Valley Creek at Valley Forge, PA

Similar to other Piedmont streams, Valley Creek has a long history of milling that included iron forges, paper mills, grist mills, slitting mills and textile (wool and cotton) mills [72] (figure 7*a*,*b*). The stream is about 19 km in length and drains into the Schuylkill River near the Revolutionary War era Valley Forge. Historic maps and documents, including unpublished maps and photographs at the Valley Forge National Historical Park, indicate that at least 10 dams and associated mills existed along Valley Creek in the eighteenth and nineteenth centuries, and at least one inset, second-generation dam was built within the incised channel of an older, breached millpond in the 1920s (cf. Map of Chester County, Pennsylvania, Painter and Bowen, 1847; and Breou's Official Series of Farm Maps, Chester County published by Kirk [73]).

As with most first-generation milldams in this region, the earliest dams spanned the valley. Today, remnants of older breached dams are exposed in the stream banks and bed of the incised Valley Creek, and extensive deposits of laminated, fine-grained millpond sediment can be traced upstream from the dams (figure 7*c*,*d*). These reservoir sediments form wedges that are thickest near the breached dams, where they are graded to the dam crest or spillway, and thin upstream towards what once were the upper ends of millponds.

The Valley Creek study area focused on here encompasses a distance of about 4 km along the lowermost part of the main stem of the creek within Valley Forge National Historical Park. This part of the stream, with a slope of 0.003–0.007, was investigated by previous workers from 2003 to 2006 [39,40,71]. In June and July of 2004, Fraley *et al.* [40] installed and surveyed three channel cross sections within each of 12 reaches of the lowermost 3658 m of Valley Creek, for a total of 36 cross sections. These sections were resurveyed with a total geodetic station after major storm events and at the end of the study period from April to June of 2005. The area of change was calculated by comparing repeat surveys. In addition, the bank tops and bottoms throughout the study period were resurveyed at 10 locations where significant bank instability was observed. Fraley *et al.* [40] calculated the area of bank retreat and then divided by the length of bank surveyed in order to determine the average lateral distance of bank retreat. They combined this estimate with the average bank height to get the net volume of sediment eroded from the stream bank. Seven of ten of the stream banks analysed for particle-size distribution consisted of 59–90% silt and clay, and eight consisted of more than 80 per cent sand, silt and clay (see table 3 in [40]). Calculations of the volume of eroded stream bank for each of the 12 reaches assessed are presented in table 4 of Fraley *et al.* [40].

Seven of the reaches studied by Fraley *et al.* [40] and Fraley [39] lie within a pond formed upstream of a 5 m high milldam that was built in 1789 and filled to the brim with historic sediment in the early twentieth century (pond and dam shown in figure 7*b*). Historic photographs and maps of the 1789 dam and

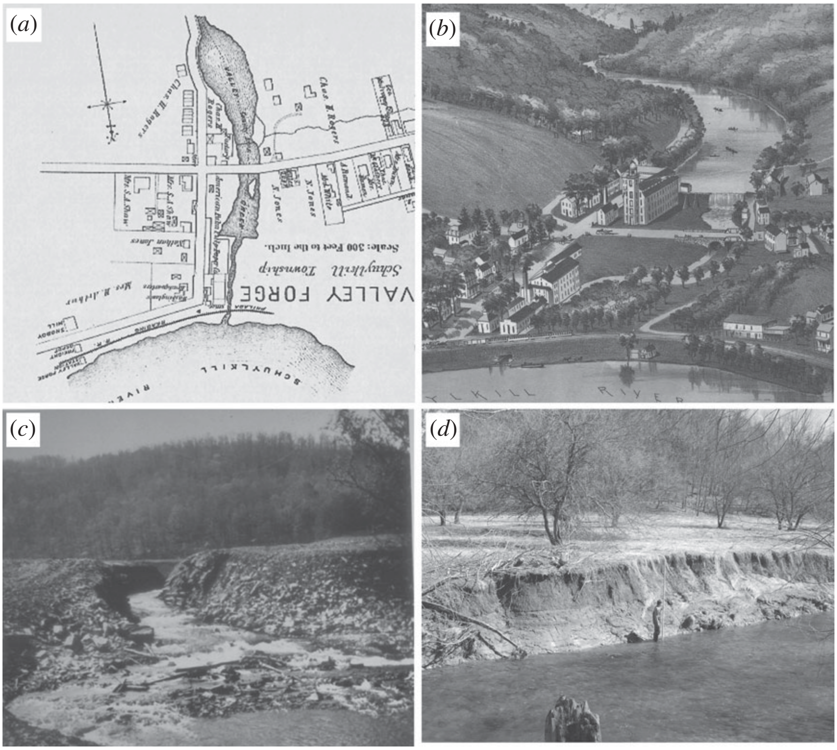

Figure 7. (*a*) An 1883 map [73] and (*b*) 1890 bird's eye view [74] of the mouth of Valley Creek, near Valley Forge and General Washington's Revolutionary War headquarters, illustrate mill dams, ponds and buildings and their changes with time. Two dams appear on the 1883 map, but only one on the 1890 bird's eye view. The pond upstream of the remaining dam, built in 1789, buried an older milldam associated with an iron forge. (*c*) The 1789 milldam was breached in 1920. (Image from Valley Forge National Historic Park, courtesy of Kristina Heister.) (*d*) View upstream of right bank Valley Creek, illustrating the collapse of fine-grained laminated sediment deposited in the slackwater millpond reservoir upstream of the 1789 dam. Note person with a 2 m stadia rod for scale in the centre of photograph. (Photograph taken 17 April 2010 by Cheryl Shenk.)

millpond date to the late nineteenth century and there exist photographs of the dam just after breaching (figure 7*c*). This pond actually buried an older, smaller millpond that supplied water to an early Colonial iron forge. The 1789 dam was breached in the 1920s, and subsequent stream incision exposed the early American forge 3 m below the surface of the younger millpond sediment in the 1930s. Aerial photographs, historic photographs at the site and maps indicate that deep incision and lateral migration of the stream channel began immediately after dam breaching and have continued since then (figure 7*d*).

Using estimates of volume of erosion and measurements of average bank height and stream length from Fraley [39] and Fraley *et al.* [40], we calculate channel-normalized sediment production for the seven reaches within the former millpond. The calculation requires the division of volume of erosion by bank height and channel length and then dividing by the time period of measurement. In this way, using only the data reported by Fraley [39] and Fraley *et al.* [40], we are able to compare their erosion data with those from other post-dam breach-incised streams. Our calculated channel-normalized sediment-production rates for lower Valley Creek, upstream of the breached dam, diminish from 0.54 to 0.16 $\mathrm{m^3\ m^{-1}\ m^{-1} yr^{-1}}$ over a distance of approximately 2000 m, the extent of the former millpond. Lateral bank-retreat rates at these reaches, as measured by Fraley [39] and Fraley *et al.* [40], varied from approximately 0.2 to 0.8 m $\mathrm{yr^{-1}}$ from 2004 to 2005.

Bed scour and bank erosion are greatest nearest the 5 m breached dam at lower Valley Creek. We interpret these processes to be a response to the local base-level fall. An exception is a short reach just at and upstream of the dam, where resistant bedrock and remnants of the stone block dam—anchored in a prominent bedrock rib—cause reduced erosion rates. Bed deposition is greatest immediately upstream of an inset twentieth century dam that was built within the incised channel shortly after downstream dam breaching. The inset dam is lower than the height of the incised banks. We interpret this deposition as a response to the local base-level rise. Despite this deposition, bank erosion continues to occur on the incised banks of the older millpond that are exposed above the bed of the inset pond. Although urbanization upstream has increased stormwater runoff, the variation in the rates of bank erosion and bed scour can be explained by examining the local base-level controls from the breached and existing dam.

13. Big Spring Run, PA

Draining 15 $\mathrm{km^2}$, Big Spring Run begins at multiple springs and seeps along the valley floor and flows north into Mill Creek, a tributary to the Conestoga River in Lancaster County, southeastern Pennsylvania (figure 8). The Conestoga drains into the Susquehanna River, a tributary to the Chesapeake Bay. Many segments of the Conestoga River, including Big Spring Run, are included on the Environmental Protection Agency's Clean Water Act (303d) impaired water body list for high loads of suspended sediment and nutrients. Land use for the majority of the Big Spring Run watershed is agricultural. Big Spring Run is the location of a multi-year (2008–2012), multi-agency (PA Department of Environmental Protection, United States Geological Survey, and United States Environmental Protection Agency) and multi-institutional research investigation to assess a floodplain, stream and riparian wetland restoration approach to ecological restoration.

The Big Spring watershed was one of the first parts of Lancaster County settled by European immigrants in 1709. A wedge of fine-grained sediment that thickens downstream towards a breached milldam near the confluence with Mill Creek has buried the valley bottom and many springs. The milldam, shown on the 1864 Atlas of Lancaster County [52], was used to operate a machine shop near the mouth of Big Spring Run. Today, remnants of the 2.5 m high stone dam are found at the location shown on the historic map, where the dam once spanned the entire valley. Fine-grained, laminated sediment is stacked to the level of the top of the dam on the upstream side. The dam appears breached on the earliest historic aerial photographs (late 1930s), and aerial photographs from 1940, 1957 and 2005 (digital orthoimage) reveal that the stream has been incised (and laterally migrating) during this time period. Local farmers (including H. Keener 2008, personal communication) report that the mill operated on waterpower until the

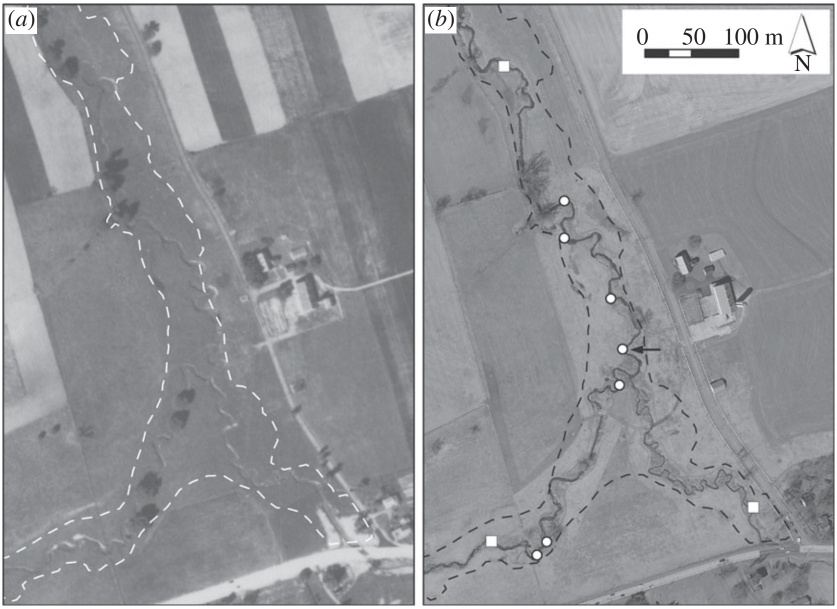

Figure 8. (*a*) Aerial photographs from 1957 illustrates straight-row ploughing along the sinuous Big Spring run, flowing south to north, which was incised and migrating laterally at this time. Dashed white lines are boundaries of historic fine-grained sediment in valley bottom, mapped from lidar, field mapping and trenching. (*b*) Sample sites (circles) for dark, buried, Holocene hydric soil at Big Spring Run are shown on an April 2005 digital orthophoto. Squares are United States Geological Survey stream gauge stations. Note the differences in sinuosity of the eastern tributary (*b*) and main stem in 1957 and 2005. Approximate extent of restoration area described in the text is the area between the southwest and northeast trending fence line at upper left and road at bottom of the image. Arrow in (*b*) marks location of photographs in figure 9.

early 1900s, so dam breaching must have occurred between about 1900 and 1930. It is likely that other structures built on the stream between the headwaters and mouth had similar effects on sedimentation during the past three centuries. Indeed, historic photographs from local farmers (particularly the collection of R. Houser) reveal ice ponds, stock ponds and bridge crossings that served as small dams and local grade-control structures. Some were built within the incised channel in the twentieth century, after downstream dam breaching.

Big Spring Run currently is an incised channel that has cut deeply into several generations of historic sediment along its entire length (figure 9). The study and restoration area encompass two headwater tributaries and the main stem beginning about 1.5 km upstream of the breached dam. Most of the post-settlement sediment in the study area is laminated and fine grained ($> 95\%$ silt and clay, as determined by sieving and laser-diffraction particle-size analysis). Our mineralogical analysis indicates that the clay-sized particles are quartz and not clay minerals. This fact is important because clay minerals have much higher cohesion, and hence critical shear strength, than clay-sized quartz. The underlying pre-settlement soil is composed of dark gray to black (10YR 2/1) organic matter, sand and locally abundant angular to sub-angular quartz gravel derived from long-term weathering of the Paleozoic limestone bedrock with quartz veins. The pre-settlement organic-rich soil generally varies in thickness from 20 to 50 cm.

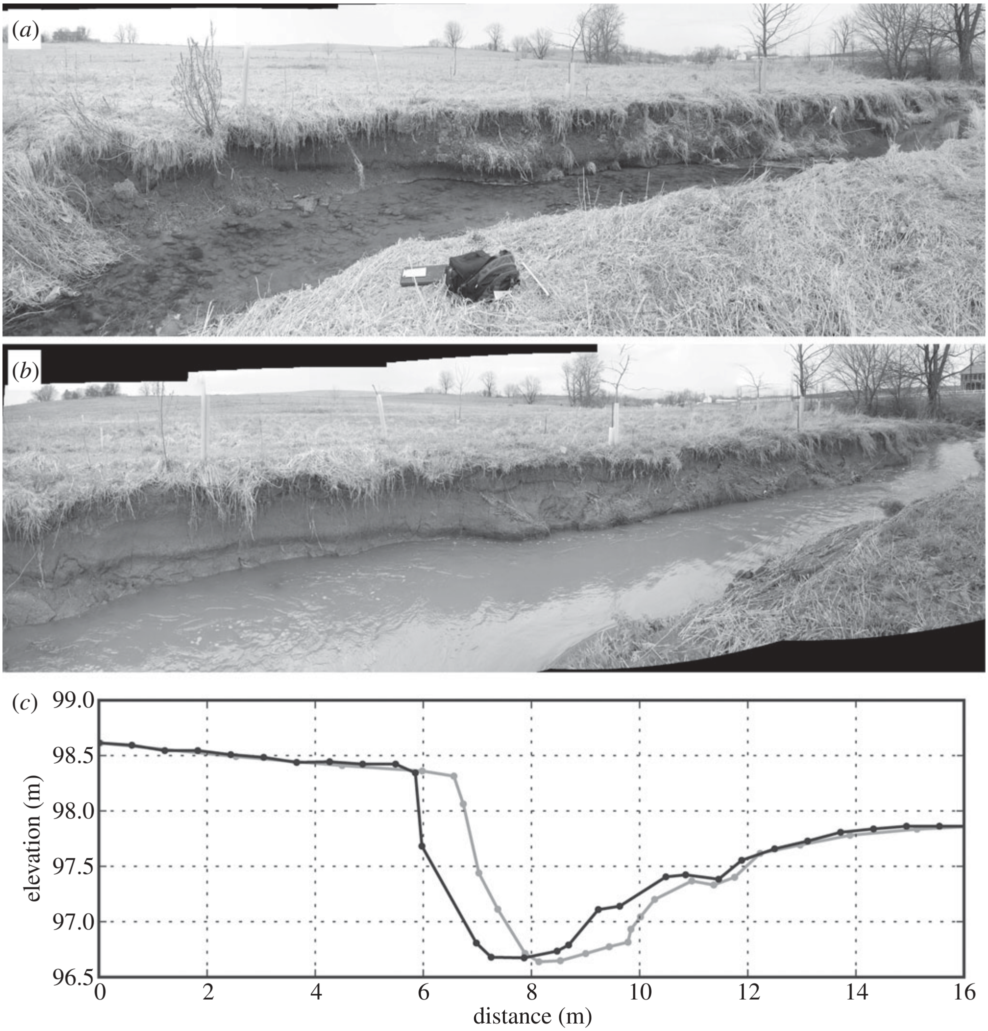

Figure 9. (*a*) Freeze–thaw processes and needle ice in the banks of Big Spring Run generated an apron of debris during the winters of 2008–2010 (photograph taken 26 February 2009; see arrows in figure 8 for location; flow is left to right). (*b*) This apron was washed away during spring thaw and spring to summer rains (3 April 2009). Dark, buried hydric soil is original valley-bottom topography that predates historic sedimentation. (*c*) Channel cross section at this location reveals approximately 1 m of lateral bank retreat on left bank from 2004 (grey line) to 2009 (black line). Surveying done with total geodetic station. Eroded sediment from high left bank of incised channel is greater than 90% silt and clay. Deposited sediment on lower, inset right bank is greater than 60% sand and gravel.

A thin (<5–30 cm), laterally discontinuous gleyed hydric soil that dates from approximately AD 1200–1750 occurs locally between the dark hydric soil and historic millpond deposits along valley margins (see discussion above).

Twelve cross sections were surveyed along the study reach with a total geodetic station in 2004 and again in 2010 with a real-time kinematic GPS survey unit. In 2008–2009, we installed 20 sets of erosion pins to monitor bank

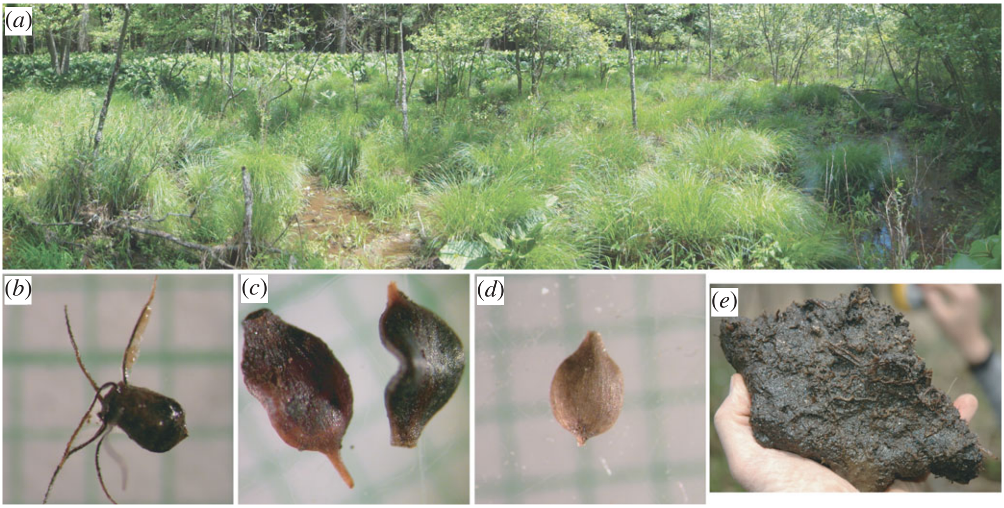

Figure 10. (*a*) Rare patches of historic valley-bottom wetlands not covered by millpond sediment include tussock sedge meadows with low-energy streams, as shown here along Gunpowder Falls, MD, that contain species identical to palaeoseeds found in buried hydric soils beneath millpond sediment elsewhere in the Piedmont region. Microscope photos of seeds from pre-settlement hydric soil include (*b*) *Eleocharis ovata* (ovate spikerush), (*c*) *Carex crinita* (fringed sedge) and (*d*) *Carex stricta* (tussock sedge), all of which are obligate wetland species in this region. Grid markings are millimetre spacing. (*e*) Organic-rich hydric palaeosoil typically contains 10–30 palaeoseeds per 30 cm^3 of sediment.

erosion, with three to four pins aligned vertically on the bank at each site. Our repeat surveying of the cross sections yields rates of channel-normalized sediment production from lateral bank erosion that ranged from 0.04 to 0.27 $\mathrm{m}^3\ \mathrm{m}^{-1}\ \mathrm{m}^{-1}\ \mathrm{yr}^{-1}$ between 2004 and 2009 (figure 9*c*). The pin data yielded lateral bank-erosion rates that ranged from 0.05 to 0.64 $\mathrm{m\ yr}^{-1}$ during the period of 2008–2009. The equivalent rates of channel-normalized sediment production are 0.04–0.65 $\mathrm{m}^3\ \mathrm{m}^{-1}\ \mathrm{m}^{-1}\ \mathrm{yr}^{-1}$.

The bank pins at Big Spring Run reveal that more lateral bank erosion occurs in the winter than in other seasons. This same phenomenon was observed in the 1950s at Watts Branch in Maryland [75], and in studies of stream banks in the UK [69]. Detailed monitoring of sites along the Ilston River, UK [69,70] and Strouble Creek, Virginia [76] established that freeze–thaw processes significantly lower the critical shear strength and increase the erodibility of cohesive stream-bank sediment. We observed freeze–thaw processes and needle ice in the stream banks of Big Spring Run during the winters of 2008–2009 and 2009–2010. An apron of debris from freeze–thaw processes accumulated during winter months, and subsequent spring rains and snow melt removed the apron (figure 9*a*,*b*).

In addition to the role of freeze–thaw in bank erosion, we noted that bank slumping and calving are frequent and typically occur immediately after a rise and fall in stage. Other workers have noted that high stages cause banks to be wetted, and the rapid drop in pore pressure in wet banks after a high-stage event is conducive to failure, particularly in banks composed of large amounts of silt and clay [68]. For Big Spring, we documented that such failure occurred throughout the year, but was especially notable in the autumn during long-duration high-flow events that wetted the banks over a period of days. For stream banks consisting of more than 40 per cent silt and clay, as is the case at Big Spring Run (and all other sites discussed here), flow duration is more important than flow depth in bank erosion [77].

During summer months, we observed that the stream banks desiccate and fracture. Grasses and other vegetation growing on the fill terrace accelerate stream-bank desiccation as the growing season progresses. Summer drying and fracturing prime the banks for failure during the autumn, when the decline in vegetation activity and the increased frequency of storms in the mid-Atlantic region increase bank moisture content.

Radiocarbon dating of wood and seeds from the buried organic-rich soil exposed beneath historic sediment throughout the Big Spring study area yield ages ranging from approximately 300 to 3300 BP (figure 10; seed location sites in figure 8). Nearly 1000 seeds have been extracted from this stratigraphical unit, with typical yields of 10–30 seeds per 30 cm^3 of sample [16]. Of those identified, the most common seeds are *Carex* spp. (*prasina*, *crinita, stipata*, *stricta* and multiple unknowns), *Polygonum* spp., *Eleocharis* spp. (including *Eleocharis ovata*) and *Scirpus* spp. [16]. Additionally, we have found several seeds of *Najas flexilis* (nodding water nymph) and *Brasenia schreberi* (watershield) at a buried spring site along the southern valley margin [16].

The majority of the species found are those of obligate wetland species, but near the valley margin, nuts and seeds have been identified from facultative upland species, including *Liriodendron tulipifera* (tulip tree) and *Juglans cinerea* (butternut). Because these nuts and seeds are embedded within dark, organic-rich soil that contains primarily obligate wetland species, we interpret their occurrence to indicate that they fell into the wetland from an adjacent hillslope.

Macrofossil analysis of buried pre-settlement soils provides a palaeoecological record of wetland vegetation across the entire valley bottom of the headwaters of Big Spring Run [16]. Species are representative of plants that grow in organic-rich wetland mucks (i.e. hydric soils) or pools of water, as at springs. Rare patches of wet meadows with similar plant communities occur in the mid-Atlantic Piedmont and Ridge and Valley regions where historic sediment is thin, as at valley margins near springs or at the upstream ends of millponds (figure 10*a*).

The modern incised stream of Big Spring Run crosses the valley at several locations (figure 8), but no distinct buried stream channels or fluvial bedforms are observed. Across the valley bottom, the buried hydric soil exists at the current level of baseflow, which is the seasonal groundwater level, indicating that the modern hydrology is not substantially altered from the pre-settlement conditions.

Species from the buried plant communities at Big Spring Run and other buried wetland soils prevalent throughout the region can be assigned to wetland classification systems that illuminate the palaeoenvironment just prior to European–American settlement [78,79]. Buried wetlands at Big Spring Run are best classified as persistent emergent wetlands in palustrine systems. Cowardin's description of the vegetation that occurs in a persistent emergent wetland includes an array of *Scirpus* spp., *Carex* spp. and *Polygonum* spp. Fike [79] further classifies persistent emergent wetlands in Pennsylvania into 18 separate wetland communities. The persistent emergent wetland that best describes the buried wetlands at Big Spring Run is the wet-meadow wetland.

We conclude that a wet-meadow wetland existed at Big Spring Run from at least 3300 years ago until the time of its burial beneath historic sediment *ca* AD 1710–1720. In such wetlands, the entire valley bottom is wet throughout much or all of the year, supplied predominantly by groundwater.

As a result of reservoir sedimentation and subsequent incision, a highly unstable channel is currently migrating rapidly across the Big Spring Run valley bottom, eroding both historic sediment and the pre-settlement wetland soil. A planting of approximately 3000 riparian trees on the historic silt and clay in 2002 had a high mortality rate ($>95\%$). A possible cause of this high mortality is the height of the plant roots above the groundwater table. Typical thickness of historic sediment above groundwater (base flow level for the incised stream) at the Big Spring Run headwaters is approximately 0.9–1.2 m.

14. Restoring Anthropocene streams and wetlands

The current condition of milldam-impacted streams in the mid-Atlantic region has significant implications for restoration strategies for incised streams. The presence of groundwater at the level of a buried, organic-rich hydric soil is widespread (figures 2, 9 and 10), and the predominance of seeds of obligate wetland species of sedges in this Holocene to pre-settlement age palaeosol indicates that valley bottoms once had extensive wetlands in or near permanently saturated soil. By contrast, modern plants commonly growing on the surface of historic sediment fill in this region include quackgrass (*Agropyron repens*), Canada thistle (*Cirsium arvense*), orchard grass (*Dactylis glomerata*) and poison hemlock (*Conium maculatum*), species characteristic of mesic wastelands and roadsides [80,81].

Isolated patches of obligate wetlands with similar species to those of the buried hydric soil occur near springs at valley margins, where the wedge of historic sediment thins, and in a few isolated valley-bottom areas with limited millpond impacts (figure 10*a*) [82]. We interpret these to be remnant ecosystems that provide an analogue for the original valley-bottom wetlands.

A possible implication of this study is that restoring the naturally occurring riparian wetlands buried beneath historic sediment, rather than restoring incised stream channels or planting riparian trees upon the elevated historic sediment surface, could be a more effective and sustainable approach to increasing wetland biodiversity and improving riparian habitat and function (figure 11). In addition, it might reduce downstream sediment and nutrient loads. These findings are likely to be particularly significant for those sites closest to the recently breached dams, where the historic sediment is thickest and banks of incised streams highest.

Wetland restoration via removal of historic millpond sediment was implemented in Lititz Creek in southeastern PA, in 2002, and will be implemented at nearby Big Spring Run in 2011. At the site of a breached milldam on Lititz Creek, approximately 1 m of historic sediment was removed from about two-thirds of the original area of the millpond reservoir by an engineering firm, LandStudies, Inc. (figure 11*a*). Within several years, the same obligate wetland

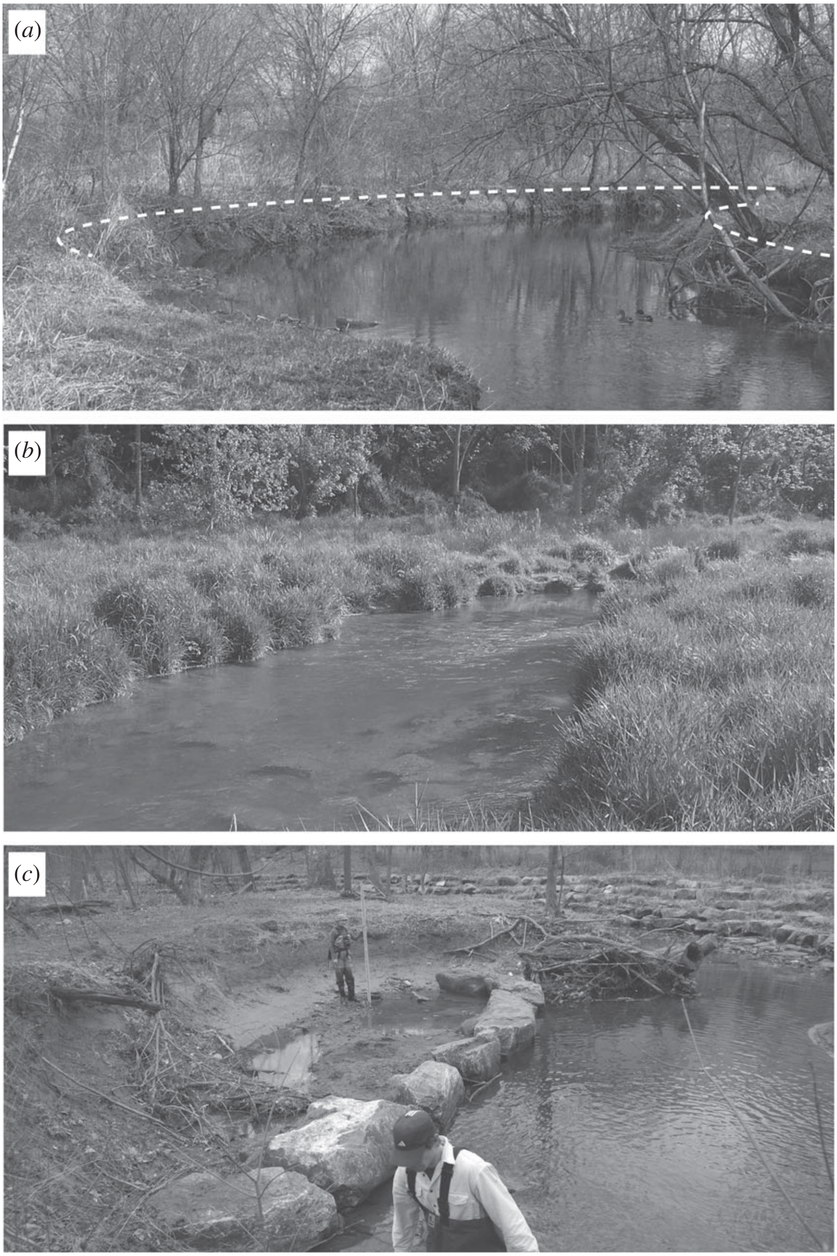

Figure 11. (*a*) Lititz Run before restoration, in 2001, with high banks of millpond sediment exposed along the incised stream upstream of a breached milldam (photograph by Ward Oberholzer). (*b*) Lititz Run in 2007, after approximately 23 000 m^3 of historic sediment was removed to a depth of about 0.5 m above the pre-settlement valley bottom along the stream corridor. Note wetland sedges and other plants that grew in the exhumed wetland conditions soon after restoration. (*c*) Conventional approaches to stream restoration generally consist of attempts to stabilize meander bends with hard structures, even on incised streams near breached milldams in small headwater areas of streams, as here at Woottens Mill park restoration (completed 2006) along Watts Branch, MD. (Photograph taken March 2008.)

species as those of seeds that are common in the buried hydric palaeosol (various *Carex*, and *Eleocharis*, for example) were growing throughout the restoration reach (figure 11*b*). The ongoing Big Spring Run scientific investigation is designed to fully evaluate the pre- and post-restoration conditions of surface and groundwater, sediment and nutrient loads, and ecological change for a similar approach to restoration.

15. Discussion

The incised streams presented here span the full spectrum of modern land use, but their forms and processes dominantly reflect anthropogenic base-level rise during damming, followed by base-level fall from dam breaching. More recent infrastructure, including dams and bridges set within incised channels, has caused additional base-level forcing and complexities. All of the streams, however, are similar in terms of the overall geomorphic forms and processes of Anthropocene streams as characterized here.

For the three case studies detailed here, the origin of sediment in the banks and the dominant causes of incision and bank erosion are the same, and are largely decoupled from modern land use. Mountain Creek is a fully re-forested watershed, Big Spring Run is mostly agricultural with some suburbanization and Valley Creek has mixed land use (see Fraley *et al.* [40]). Yet in all three cases, incised streams formed in fine-grained reservoir sediment after dam breaching and continue to have active bank erosion and lateral retreat up to a century later.

All three examples have substantial amounts of stream-bank erosion that can be related directly to former reservoir sedimentation, time of dam breach and location within the former reservoir. The channel-normalized sediment-production rates from eroding banks at the Eaton-Dikeman reservoir on Mountain Creek, where the dam breached 25 years ago, range from 0.22 to $0.95\,\mathrm{m^3\ m^{-1}\ m^{-1}\ yr^{-1}}$ for 2003–2009. For the milldam on lower Valley Creek removed 80 years ago, erosion of fine sediment continues long after dam breaching, with channel-normalized sediment-production rates that range from 0.16 to $0.54\,\mathrm{m^3\ m^{-1}\ m^{-1}\ yr^{-1}}$ for 2004–2005. With exception of the reach at the former dam, sediment-production rates increase downstream towards the dam. More recent dam breaching might explain the higher rates of sediment production at Eaton-Dikeman, despite greater forest cover, than Valley Creek. For Big Spring Run, in which the primary milldam breached approximately 80–110 years ago, rates of channel-normalized sediment production at the upstream end of the millpond were $0.04\text{–}0.65\,\mathrm{m^3\ m^{-1}\ m^{-1}\ yr^{-1}}$ from 2004 to 2010.

Erosion associated with freeze–thaw is significant decades after dam breaching, as noted here and at a breached millpond on Watts Branch [18,75]. Just upstream of a previously unrecognized breached dam for the former Wootten mill on Watts Branch, where aerial photographs and historic records indicate that an incised channel existed by at least the 1940s, Wolman [75] measured erosion rates of $0.2\text{–}0.4\,\mathrm{m\ yr^{-1}}$ for the predominantly silt and clay banks from 1953 to 1958. These rates are similar to those for the three case studies of breached dams presented here: $0.3\text{–}1.2\,\mathrm{m\ yr^{-1}}$ for Mountain Creek, $0.2\text{–}0.8\,\mathrm{m\ yr^{-1}}$ for Valley Creek and $0.1\text{–}0.6\,\mathrm{m\ yr^{-1}}$ for Big Spring Run.

Similar rates of bank erosion at multiple breached millponds can be explained by freeze–thaw processes, and need not be the result of urbanization and increased runoff. Wolman observed that 'rates of erosion appear to be unexpectedly high' [75, p. 216] at Watts Branch from 1953 to 1958, and determined that 85 per cent of bank erosion occurred during winter months of December through March as a result of freeze–thaw processes that weaken the banks. At that time, Watts Branch was still largely an agricultural, rural watershed. Leopold observed that erosion of banks at Watts Branch was 'not the result of erosion by high-velocity water', but rather the result of formation and melting of ice crystals in winter, which extrudes grains of silt from the bank to form 'a loosely structured debris cone at the base of the bank … major floods occur in summer … and are not effective in lateral erosion. Small rises in flow, separated by periods of freeze and thaw, are effective agents in channel migration' [18, p. 1850]. These observations, made prior to significant urbanization of Watts Branch, indicate that causes of channel incision and bank erosion can be explained by anthropogenic base-level forcing from dam breaching, without the need for accompanying changes in land use, soil erosion and stormwater runoff.

Prior to mill damming, sedimentation and post-dam breach incision, the valley bottoms described here were substantially different throughout Holocene time, with a key pre-settlement difference being the abundance and ecological persistence of sedge wet meadows for thousands of years. We propose that as wetlands developed upon a low-relief periglacial rubble substrate during the Holocene, plants that populated the spring-fed valley bottoms might have increased resistance to, and hence attenuated, water flow. Some of the species listed above, particularly certain *Carex* spp., form prominent mounds that would add microtopographical flow resistance as well as bed and bank roughness elements.

We further propose that the reason we have not found distinct palaeochannel forms buried beneath historic millpond sediment is that streams in wet meadows were likely to be similar to those characterized by Nanson & Knighton [83] as the cohesive-sediment anabranching type. Such laterally stable channels would have been multiple and small, with low stream power ($< 10\,\mathrm{W\,m^{-2}}$) and cohesive banks. Because sediment loads to the Chesapeake Bay were low prior to Colonial settlement [84], these streams probably transported little sediment. As a result, buried channel forms are not distinctive in exposures of the valley-bottom stratigraphy for first- to third-order valleys in the mid-Atlantic region. Although anabranching channels are considered relatively uncommon today [85], a review of archaeological, historic and geomorphological evidence indicated that anastomosing channels and floodplain wetlands 'were formerly of considerable significance' in lowlands of England and Wales [86, p. 267]. We posit that they were similarly of considerable significance in low-relief areas of the mid-Atlantic region prior to European settlement and anthropogenic impacts.

16. Conclusions

The streams presented here raise questions about how causality is determined for changes in geomorphic processes. We show that incised, post-dam breach streams and fine-grained banks in the mid-Atlantic region are anthropogenic in origin, and the causes of both the accumulation of sediment in valleys and subsequent incision and erosion are not directly related to modern upland land use or cover. Conceptual and computer models that link channel condition and sediment yield exclusively with contemporaneous upland land use, sediment supply and runoff are incomplete because anthropogenic forcing has impacted valley bottom, not only upland, boundary conditions, and has done so for centuries. Determining cause and effect relations more accurately might require geomorphologists to examine past as well as current processes, deposits and landforms (cf. [87–90]).

Modern incised stream-channel forms in the mid-Atlantic region, with no equivalent in the Holocene or late Pleistocene sedimentary record, represent a transient response to base-level forcing and major changes in historic land use that led to widespread valley-bottom sedimentation. Similar forms might also exist in other locales where historic milling was prevalent. For example, thousands of water-powered mills lined European streams as early as AD 1100 [1,49]. Analysis of three streams in southern England indicates that mill damming significantly altered entire valley bottoms and the morphodynamics of modern streams and floodplains [88].

Vast tracts of wet meadows and possibly other wetland types were buried in the mid-Atlantic region, as illustrated by a prominent dark, organic-rich buried soil commonly found beneath reservoir sediment. The streams in these wet meadows were likely to have been multiple and small, associated with stable, low-vegetated mounds and islands. Pre-settlement streams did not carry all of the surface water in the valleys, but rather were part of an integrated surface and groundwater system with base flow at or near the level of wetland plant roots. Base-level forcing from anthropogenic activities, particularly mill damming, has altered substantially the future trajectory of geomorphic, hydrologic and ecological processes for impacted valley bottoms.

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