The Big Spring Run Restoration Experiment: Policy, Geomorphology, and Aquatic Ecosystems in the Big Spring Run Watershed, Lancaster County, PA

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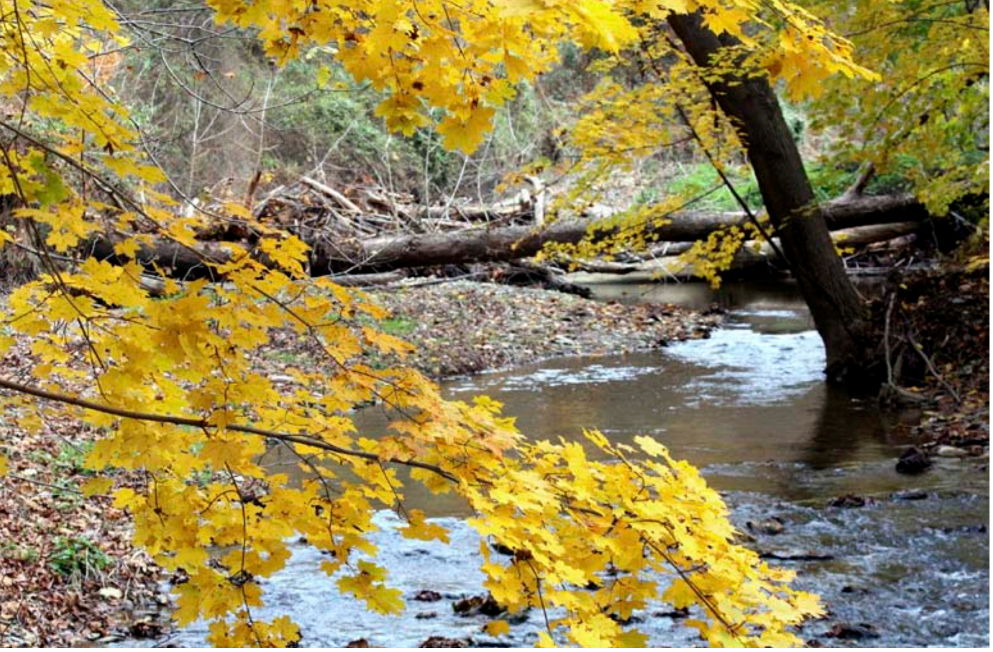

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The need to better understand natural and anthropogenic controls on water quality has imminent global significance. The Chesapeake Bay, for example, has experienced over a half century of poor water quality despite extensive restoration efforts and is estimated to have achieved less than 25 percent of water quality goals established by the US Environmental Protection Agency (USEPA, 2011). In 2009, the President of the United States issued Executive Order 13508 that calls on the US Environmental Protection Agency (EPA) to define a new generation of tools and to refine policies that will reduce sediment and nutrient loads to the Chesapeake Bay. Identifying and quantifying the relative contribution of the many sources of sediment and nutrients to the Chesapeake Bay has substantial scientific value for understanding complex biogeochemical and physical interactions that control sediment and nutrient mobility. Such investigations also will assist resource managers to identify and possibly control sources of sediment and nutrients that pollute streams and waterways. Pennsylvania's Chesapeake Watershed Implementation Plan was developed in order to address EPA's expectations for the Chesapeake Bay Total Maximum Daily Load (TMDL)[1]. *The Natural Floodplain, Stream, and Riparian Wetland Restoration Best Management Practice* (*NFSRWR-BMP*) proposed by the Pennsylvania Department of Environmental Protection (PADEP), and discussed here, is included in PA's strategies for reaching nutrient and sediment reduction goals[2].

The unglaciated mid-Atlantic region is a hotspot of stream restoration in terms of cost and number of projects (Bernhardt et al, 2005; Hassett et al, 2005), but the practice of aquatic ecosystem restoration has outpaced scientific investigation and our understanding of the full benefits (NRC, 2010). As noted by Palmer and Filoso (2009), stream restoration practices to date consist largely of "reshaping a channel and adding wood or rocks", but actual improvements to water quality or biodiversity are uncertain (Bernhardt et al, 2005; Palmer, 2009). Due to insufficient monitoring, it is difficult to assess most of these restorations. In the Chesapeake Bay watershed, for example, less than 6% of recent river restoration projects reported that monitoring occurred (Bernhardt et al, 2005; Hassett et al, 2005).

While scientific investigations that involve pre- and post-restoration monitoring of multiple physical, biological, and chemical parameters are rare (Bernhardt et al. 2005), some studies have evaluated individual stream ecosystem functions, such as denitrification. Previous work indicates that 1st to 3rd order streams have the highest potential for nitrogen removal post-restoration (Ensign and Doyle, 2006; Craig et al, 2008). Furthermore, denitrification is enhanced when floodplains are "reconnected" to surface water flow and increasing groundwater-surface water interactions within the hyporheic zone (Kaushal et al, 2008). Hyporheic exchange is fundamental to restoring ecological services and functions (Craig et al, 2008; Hester and Gooseff, 2010). Recent studies conclude that stream restoration must go beyond merely modifying stream channel form, and include approaches that are designed to improve water quality and ecosystems (Mitsch and Jorgensen, 2004).

Prerequisite to designing sustainable aquatic ecosystem restorations with high potential for improved ecosystem services is a better understanding of how ecosystems evolve and respond to environmental change and human impacts (NRC, 2010). Single-thread meandering channels, once deemed "natural" for the mid-Atlantic Piedmont (c.f., Leopold, 1973) are instead the result of human manipulation of valley bottoms for water-power and are decidedly "un-natural" (Walter and Merritts, 2008a; Merritts et al, 2011). Previous workers recognized widespread historic sedimentation in mid-Atlantic valleys, but interpreted it to be the result of overbank deposition by single-thread channels with an excess supply of upland sediment (e.g., Costa, 1975; Jacobson and Coleman, 1986). Incised channels—now prevalent in the mid-Atlantic region—were thought to indicate a decrease in sediment supply and/or increase in storm water runoff in the 20th century due to increased urbanization, yet in many places modern sediment loads are high regardless of land use (Gellis et al, 2005, 2009; Merritts et al, 2011).

Instead, our research reveals that historic sedimentation resulted from increased upland soil erosion in combination with base-level rise due to the construction of tens of thousands of milldams on 1st-3rd order streams in this region (Walter and Merritts, 2008a). Holocene (pre-settlement) streams were much different than today and the legacies of human impacts (post-settlement) are more complex than previously realized (Wohl and Merritts, 2008; Walter and Merritts, 2008a, 2008b, 2008c; Pizzuto and O'Neal, 2009; Merritts et al, 2011). At Watts Branch in Maryland, once held as a model for natural meandering stream evolution (Leopold, 1973), stream channel incision formed only after early 20th c. base-level fall from milldam breaching, and decades before urbanization and increased storm water runoff (Walter and Merritts, 2008a; Merritts et al, 2011).

Our research reveals that many current models of "natural" floodplains, channels and riparian ecosystems are of limited value in the low-relief, humid-temperate mid-Atlantic region. We have documented that milldams and other structures built across valley bottoms trapped sediment and buried pre-existing anastomosing channel valley bottom floodplain systems (ACFS) and toe-of-slope colluvial deposits (Walter and Merritts 2008a; Merritts et al, 2011). Sediment trapping in reservoirs upstream of dams is not directly correlated to upland land use because reservoirs add a lag time in sediment storage that is a function of trap efficiency, which depends on parameters including discharge, dam height, and reservoir geometry and age. Rate of sediment release depends on time since dam breaching and depth of post-breach incision (Merritts et al, 2011). These hydrologic changes are not merely the result of changes in upland runoff or sediment supply, but also of substantial changes to valley bottom landscapes and ecosystems.

We postulate that 1st to 3rd order Piedmont pre-settlement ACFS, in which shallow vegetated channels were well-connected with floodplains and the groundwater table, had greater hyporheic fluxes and biogeochemical reaction rates than modern deeply incised streams. Whereas modern incised channels infrequently flood the entire valley bottom (depending on thickness of post-settlement sediment and bank height), the pre-settlement streams flowed overbank often and at relatively low-flow stages.

Understanding a stream's evolutionary trajectory and response to historical land use change is relevant to correctly diagnosing the causes of modern impairments such as bank erosion and high suspended sediment loads, as well as to developing restoration approaches that are likely to be sustainable. The majority of once widespread indigenous aquatic ecosystems

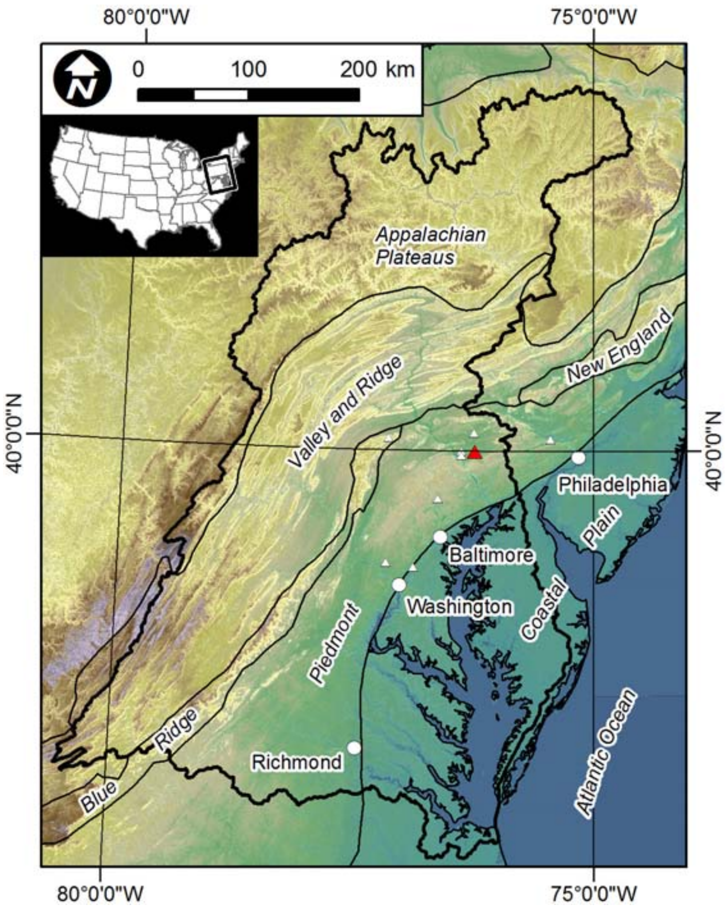

Figure 1. Big Spring Run (red triangle) is a Piedmont stream in the lower Susquehanna River basin, Chesapeake Bay watershed (heavy black line). White triangles: Key field sites for research on historic sediment, incised streams, buried ecosystems, and Pleistocene-Holocene landscape evolution.

located in valley bottoms of the mid-Atlantic piedmont were not drained during settlement in the late 1600s to 1800s, but instead were ponded and then buried by historic sediment as valleys were dammed for milling (i.e., hydropower). Spaced 2-5 km apart, milldams led to a decrease in water surface slopes along valley bottoms by as much as 50%, while upland deforestation for farming and mining led to a simultaneous increase in sediment supplies. Other grade control structures that affected sedimentation included dams built for purposes such as ice ponds, and bridges with embankments that crossed valleys. Eventual breaching of these various structures during the 20th c. has generated incised, high-banked, meandering channels which expose the post-settlement sediment, buried paleo-wetland organic layer, periglacial basal gravels, and underlying valley bedrock (Walter and Merritts, 2008a; Merritts et al, 2011).

Our findings support the proposition of Brantley et al (2011) that restoring Critical Zone (CZ) ecosystem function requires restoring synergistic interactions among physical, biological, and chemical processes. Brantley et al (2011) propose that biodiversity and biogeochemical processes cannot be restored until

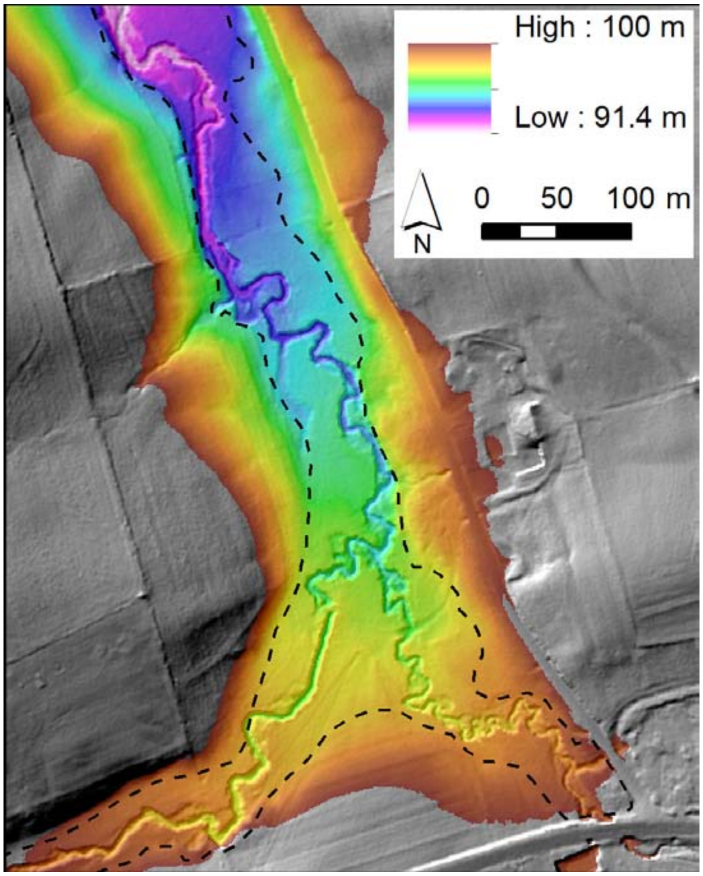

Figure 2. Lidar-derived shaded relief illustrates sub-planar surface of historic sediment fill (bounded by dashed lines) sloping gently downstream. Note incised, sinuous modern channel. USGS stream flow gaging stations are located at upstream ends of two tributaries in BSR headwaters to monitor incoming suspended sediment load and discharge; another gaging station is located just downstream of the restoration area on the main stem (flow toward top, to north). (Lidar data provided by the NSF funded National Center for Airborne Laser Mapping, 2008.)

essential physical attributes (e.g., hydrologic pathways, valley morphology) are re-established. Once ecosystem physical attributes are re-established, there will be a lag time of years before hydrological processes recover and perhaps longer to recover biodiversity and biogeochemical processes. Thus, restoring natural floodplains, streams, and riparian wetlands to their pre-settlement morphology by removing historic sediment should be the foundation for restoring ecosystem function and services (US EPA, 2000).

Big Spring Run (BSR), PA, a low-relief (~30 m) 2nd-order Piedmont stream (drainage area 15 km2) located in the Chesapeake Bay (CB) watershed, is a national test-case for a new and innovative approach to restoring aquatic ecosystems (Fig. 1, 2). The United States Geological Survey (USGS) conducted a nearly 8-year paired-watershed study at BSR from 1993-2001 (Galeone et al, 2006). The study documented stream flow, nutrient and sediment loads from several gaging stations, 17 piezometers, and 2 wells in both "treated" and control basins. The current restoration experiment at BSR is located in the same basin used as the "control" basin in the earlier paired watershed study. The pre-existing scientific research and hydrologic (surface and ground water) monitoring data at BSR was an important factor in PA Department of Environmental Protection's (PADEP) decision to evaluate a new approach to aquatic ecosystem restoration at this site.

At present, BSR is an incised, single-thread meandering channel that has cut ca. 1.5 m into several generations of historic sediment during the 20th century and now flows on either highly weathered bedrock or Pleistocene toe-of-slope gravelly colluvium (Fig. 3a). We are investigating whether restoring an ACFS, a rarely studied type of stream and floodplain ecosystem, can effectively restore CZ functions. Our approach includes the following three steps: (1) Developing significant metrics to assess CZ processes; (2) Developing, implementing, and monitoring a restoration project that diagnoses the cause(s) of CZ impairments; and (3) Working with resource managers and scientists at PA DEP, USGS, and EPA to evaluate the implications of this restoration strategy. The BSR restoration experiment provides an ideal opportunity to test hypotheses about the natural functioning of mid-Atlantic Piedmont streams and wetlands. We know of no other site for which interactions among ground and surface water, sediment transport, sedimentation, geomorphic processes, ecology, and biogeochemistry have been monitored both pre- and post-restoration.

With a multidisciplinary team of 26 scientists and resource managers from 12 agencies and academic institutions, we are collaborating to accomplish essential monitoring of ecological, hydrological, and geomorphic processes at BSR. Currently, we are completing the 3rd yr of pre-restoration monitoring at BSR. In the summer of 2011, about two km of valley bottom will undergo restoration[3] activities. The BSR restoration experiment will test a new paradigm of ecological restoration of aquatic landscapes and resources that have been buried beneath historic sediment, and will provide better understanding of the mechanisms responsible for development and stability of landscape patterns in ACFS. This paradigm is based on an investigation of the conditions that existed prior to ecosystem degradation.

Our previous work documented that a wet meadow ACFS existed at BSR for thousands of years prior to 18th-19th century sedimentation and 20th century stream channel incision into post-settlement sediment (Walter and Merritts, 2008a; Voli et al, 2009; and Merritts et al, 2011). The wet meadow ACFS with organic-rich wetland-floodplain transported water, sediment, and nutrients down-valley through multiple hydrologic pathways at the surface and subsurface, with substantial amounts of hyporheic exchange and frequent inundation of the valley bottom. Hydro-ecological mechanisms and feedbacks among vegetation, flow transport capacity, and sediment supply are responsible for the development and stability of different landscape patterns in shallow vegetated flow (Larsen and Harvey, 2010). Paleogeography

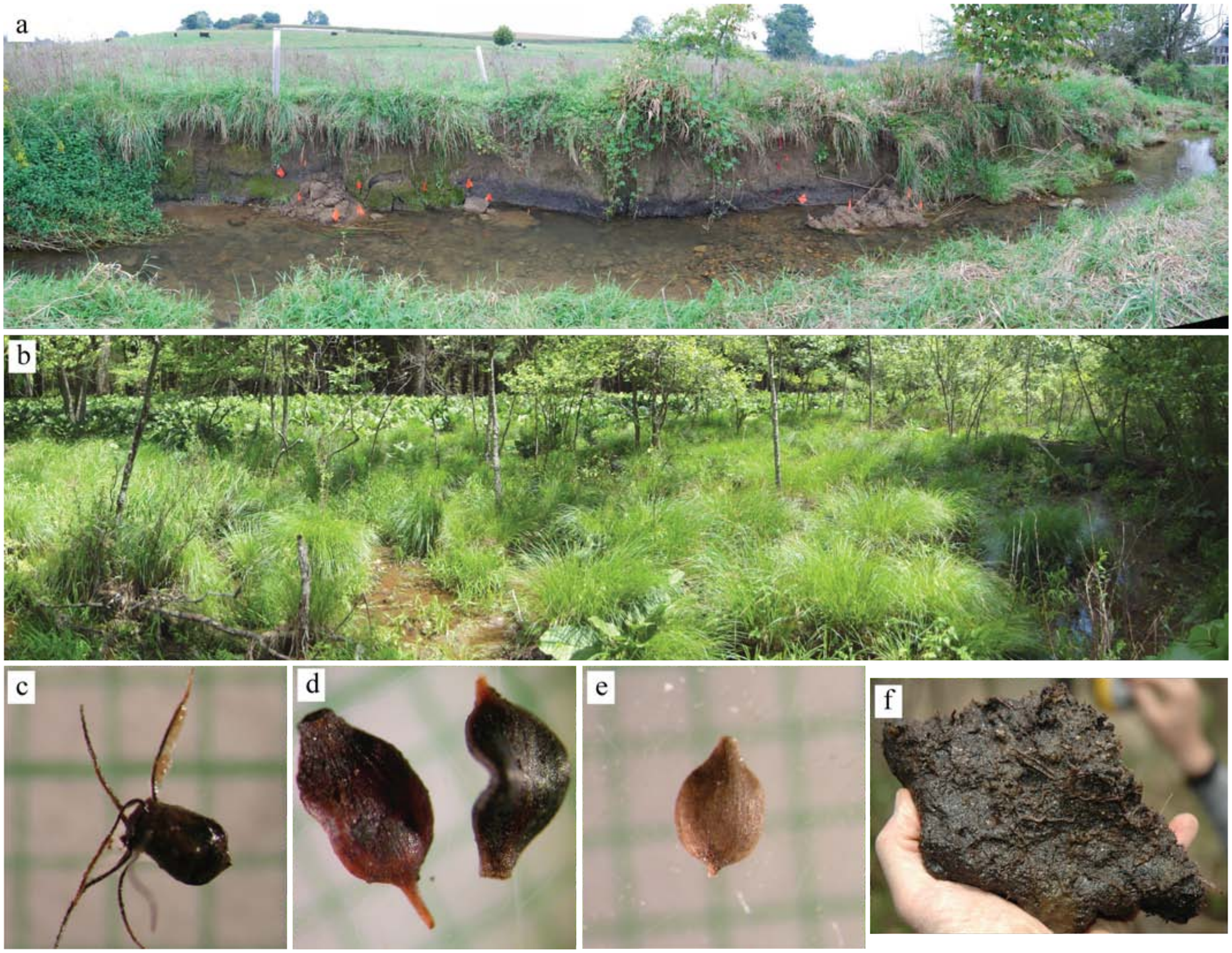

Figure 3. (a) Incised stream bank, BSR. Dark, organic-rich hydric soil buried by historic sediment exposed at base of bank; collapse blocks from recent wetting-drying of high-stage flood. Flow to right. (b) Rare patches of historic valley-bottom wetlands not covered by millpond sediment include tussock sedge meadows with low-energy channels and sloughs (Gunpowder Falls, MD) and species identical to palaeoseeds in buried hydric soils. Microscope photos of seeds from buried hydric soil at BSR: (c) *Eleocharis obtusa* (blunt spikerush), (d) *Carex crinita* (fringed sedge) and (e) *Carex stricta* (tussock sedge), obligate wetland species. Grid markings are mm spacing. (f) Organic-rich hydric paleosol.

and paleoecology for the period of time spanning ~10,000 yrs ago to 1700 AD, as reconstructed from six years of field mapping, backhoe trenching, stratigraphic analysis, paleoseed analysis, and multiple radiocarbon dates at BSR, serve as guides to restore a wet meadow and associated channel system (Walter and Merritts, 2008a; Voli et al, 2009; Merritts et al, 2011).

The wet meadow ACFS, now rare in the mid-Atlantic Piedmont, was widespread before post-European settlement landscape changes that led to valley-wide sedimentation and subsequent incision (Walter and Merritts, 2008a; Merritts et al, 2011). At several places not impacted by mill damming and sedimentation, remnants of such wet meadow ACFS ecosystems--with plant communities similar to those archived by seeds in buried hydric soils--still exist in Maryland and Pennsylvania (c.f., Martin, 1958) despite upland land use that includes agriculture and urbanization (Fig. 3b). A similar wet meadow ACFS was re-established and persists after historic sediment and remnants of a small dam were removed during a restoration by LandStudies, Inc., along Lititz Run, PA, in 2004.

Paleoseed analysis of buried hydric soils at multiple sites (including BSR) indicates that the plant communities of wet meadow ACFS included obligate wetland species (99% probability of occurrence within wetland conditions; c.f., Hilgartner et al, 2010). The suite of species at BSR includes *Carex (C) prasina, C. hystericina, C. stricta, C. stipata, and Eleocharis obtusa* (Fig. 3c-e). These species within a plant community are indicative of a wet meadow herbaceous environment (Voli et al, 2009; Merritts et al, 2011) with waterlogged soil near the surface, but without

standing water most of the year (Mitsch and Gosselink, 2007).

At BSR, carbon, nitrogen, and phosphorous accumulated to form a hydric soil that contains 10-200 wetland paleoseeds per cm3. More than 1000 paleoseeds extracted to date provide a rich record of wetland plant communities and hydrologic conditions (see Fig. 3c-f). Well-preserved seeds, leaves, stalks, insect remains, and other organic matter in the hydric soil indicate that low energy conditions persisted throughout the valley bottom for at least 3300 yrs. We postulate that the large surface area of wetland plant matter, and roughness imparted by mounded vegetation (e.g., from tussock forming sedges) diminished water flow velocity, bed shear stress, and sediment transport.

Coupled interactions between biota and geomorphic processes resulted in stable, resilient landforms and ecosystems that stored sediment, nitrogen (N), carbon (C), and other nutrients. The primary sink for sediment and nutrients at BSR was a cohesive hydric soil, or “muck”, that accumulated on the colluvial rubble substrate for thousands of years during the Holocene interglacial period (Fig. 3f). Carbon in the <2 mm fraction ranges from 4.7-9.4% C (47,000-94,000 mg-C/kg soil), with average C content 7.2% (72,000 mg-C/kg soil). Total N in the <2 mm fraction ranges from 0.32-0.57% N (3200-5700 mg-N/kg soil), with average N content 0.43% (4300 mg-N/kg soil). These findings indicate that restoring the valley morphology of BSR is likely to increase organic carbon production in the system (i.e., restoring wetland habitat) and increase spatial and temporal contact of surface and groundwater with carbon (i.e., enlarging floodplain area and increasing hyporheic exchange by removing historic sediment). These changes could significantly increase anaerobic denitrification processes, potentially having a large effect on biogeochemical cycling of nutrients in surface and groundwater and the ecosystems through which they flow.

Ongoing monitoring and instrumentation at BSR include multiple USGS gaging stations with turbidity sensors and sediment samplers, piezometers, soil temperature/moisture sensors, monumented channel cross sections, bank erosion pins, and sediment deposition pads. A network of 18 piezometers was installed by the USGS at six locations in 2008. USGS stream flow gaging stations are located on both tributaries entering the proposed restoration area and on the main stem just downstream of the proposed restoration area. Samples are collected routinely for both surface and ground water chemistry at the BSR restoration site.

The significance of the BSR monitoring stems from its unique position as a long-term scientific investigation of ecosystem restoration based on understanding geomorphic context and response to land-use change. Three years of continuous pre-restoration data, and almost eight years of previously collected USGS data from the same watershed, will be used as a baseline by a multidisciplinary team of scientists that includes ecologists, hydrologists, geomorphologists, and geochemists, to evaluate the response of a suite of CZ processes to restoration. We will be able to determine, for example, changes in plant communities (ongoing repeat vegetation transects), suspended sediment load, bed load transport, and hyporheic exchange and denitrification in the floodplain, surface water, and groundwater. We know of no other restoration site for which interactions among so many CZ process have been monitored for such a long-duration experiment.

As we develop, implement, and monitor this restoration project, we are establishing meaningful, statistically significant metrics to evaluate healthy and degraded CZ systems in landscapes with substantial anthropogenic alterations and impacts. We anticipate that the results of this work will provide better understanding of the mechanisms responsible for development and stability of landscape patterns in ACFS. This landscape-scale experiment will enable us to assess whether a new restoration approach optimizes ecosystem function and restores ecosystem services. Our long-term monitoring will determine whether reshaping floodplains, streams, and riparian wetlands that have been buried beneath legacy sediment for several centuries will not only restore historical landscape structure, but improve ecosystem function and water quality as well.

Jeffrey Hartranft (B.S., Susquehanna University; M.A., Connecticut College) is a biologist, botanist, and ecologist. He is a Water Program Specialist with the Pennsylvania Department of Environmental Protection in the Bureau of Waterways Engineering, Division of Dam Safety. Since its inception in 2006, he has been the Co-Chair of the Legacy Sediment Workgroup that continues to develop strategies to address legacy sediment issues in Pennsylvania.

Dorothy Merritts (B. S., Indiana University of Pennsylvania; M.S. Stanford University; Ph. D. University of Arizona) is a geomorphologist who has conducted research throughout the U. S., Indonesia, South Korea, East Timor, Australia, and Costa Rica. She is the recipient of the Dewey Award for Outstanding Scholarship at Franklin and Marshall College, and was chair of the National Research Council Committee on Opportunities and Challenges in Earth Surface Processes (2007-2010). In 2008, she and her colleague Robert Walter were the recipients of *Pennsylvania Senate Resolution 283* for their research on post-settlement (‘legacy’) sediment, stream restoration, and water quality improvements to the Chesapeake Bay.

Robert Walter (B.A., Franklin and Marshall College; Ph.D. Case Western Reserve University) is a geologist, geochemist and geochronologist. He has conducted field research in East Africa, North America, and around the Pacific Rim. He is a Fellow of the California Academy of Science, and is a former AAAS Diplomacy Fellow to the U.S. Department of State. Currently, he is Associate Professor of Geosciences in the Department of Earth and Environment at Franklin and Marshall College, where his research has focused on soil-sediment-bedrock-water interactions, and human disturbances of these systems.

Micahel Rahnis (B.A., Franklin & Marshall College; M.A., The University of Texas at Austin) is a sedimentologist and works as GIS research specialist at Franklin & Marshall College, Department of Earth and Environment.

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Endnotes

1 http://www.portal.state.pa.us/portal/server.pt/community/chesapeake_bay_program/10513

2 http://www.portal.state.pa.us/portal/server.pt/community/chesapeake_bay_program/10513/workgroup_proceedings/553510#legacy

3 As used here, 'restoration' refers to actions taken in a degraded natural wetland, and associated streams, that result in reestablishment of ecological processes, functions, and biotic/abiotic linkages and lead to a persistent, resilient system integrated within its landscape (from the Society of Wetland Scientists, www.sws.org).

Acknowledgements

Funding and support for this work were provided by the Pennsylvania Department of Environmental Protection, the Pennsylvania Delegation of the Chesapeake Bay Commission, Franklin and Marshall College, the United States Geological Survey, the US Environmental Protection Agency, and the National Science Foundation (EAR-0923224). Lidar was provided by the National Science Foundation's National Center for Airborne Laser Mapping and the state of Pennsylvania. We are particularly grateful to Joseph Sweeney (Lancaster, PA) and the Masonic Villages (Elizabethtown, PA) for permission to work on their property. Nearly 30 scientists and students are involved in ongoing research at the Big Spring Run site. This work has benefited substantially from support for continuous monitoring of stream flow, suspended sediment loads, and groundwater, and of sediment fluxes by Michael Langland, Allen Gellis, Dan Galeone, and Dennis Lowe of the US Geological Survey.

Definitions

Denitrification--A microbially facilitated process by which nitrates are converted to nitrogen-containing gases that can be lost from the soil or water column to the atmosphere.

Colluvium--Loose sediment that is transported down slope by gravity and deposited or built up at the toe, or base, of a slope. In periglacial areas with permafrost, freeze-thaw processes are significant to colluvial processes.

Anastomosing--A multi-thread network of stream channels that both branch out and reconnect to form a netlike pattern. As used here, it refers to multi-thread channels in a wetland environment.

Hyporheic zone--A region beneath and lateral to a stream, where shallow groundwater and surface water can mix together.

Paleoseed analysis—The extraction and identification of seeds from paleo-sediments, those that were deposited in the past, or "ancient" times. For this paper, the past refers to ~10,000 to 300 years ago, just prior to Colonial settlement in the mid-Atlantic region.