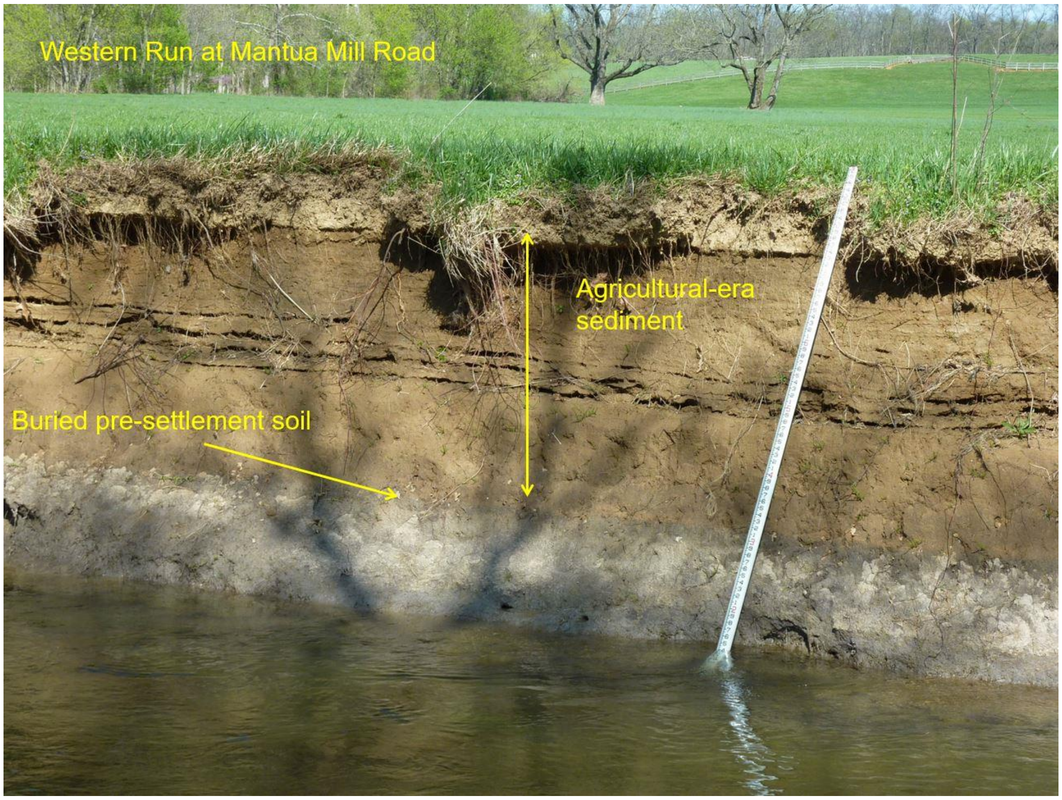
Legacy Sediment, Riparian Corridors, and Total Maximum Daily Loads



STAC Workshop Report
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Cover graphic: Western Run at Mantua Mill Road in northern Baltimore County, photo credit Andrew Miller

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Executive Summary

The question of whether historical "legacy" sediment deposits exposed in stream banks represent a major source of sediment and nutrients affecting water quality in Chesapeake Bay has become an active topic of discussion over the past decade. This workshop report examines the state of the science, describes mitigation options for legacy sediments and other sources of sediment and nutrients, and cites questions raised by managers and policymakers involved in Bay watershed restoration. Several key observations and recommendations are:

1. For the purposes of Bay management, we define legacy sediment as sediment stored in upland and lowland portions of the Bay's tributary watersheds as a byproduct of accelerated erosion caused by landscape disturbance following European settlement, most prominently in the Piedmont and Coastal Plain provinces.

2. Legacy sediment is ubiquitous throughout the region, but the sites that have received the most public attention are valley deposits stored upstream of thousands of historic mill dams. Most of the Bay's drainage network and most legacy sediment subjected to erosion is located along low-order channels.

3. There is general agreement that legacy deposits represent a large reservoir of fine-grained sediment potentially available for remobilization, particularly by bank erosion; but scientific findings differ regarding the relative contributions of bank erosion versus upland sources to sediment and associated nutrient loads reaching tidewater. Such differences likely result from spatial and temporal heterogeneity across the Bay watershed with respect to the relative contribution of different sediment sources to total loads, nutrient concentrations, residence times of stored sediment, and time lags for delivery to tidewater. *Therefore, no one set of assumptions or solutions can be applied uniformly across the Chesapeake Bay watershed.*

4. There is a need for additional research to identify erosional hot spots for fine-grained material, some of which are associated with mill dams that have recently been breached or are at risk of being breached. Because a large fraction of eroded sediment may be stored at intermediate locations such as floodplains, channel bars, or riparian wetlands before reaching tidewater, there is also a need to identify active sediment storage sites that should be protected.

5. Although sediment is considered a pollutant under the existing TMDL, historical degradation of Bay water quality is more directly related to the dramatic increase in nutrient loads associated with intensive application of chemical fertilizers and concentrated animal feeding operations, and with rapid population increase in the Bay watershed in the mid-20th century. Control of nitrogen and phosphorus loads to tidewater is therefore more critical to the Bay restoration effort than control of mineral sediment.

6. Mitigation efforts either for legacy sediment or for other upland sources should focus first and foremost on the content of biologically available nutrients. The highest nutrient concentrations are typically found in modern agricultural soils and in sediment eroded from those soils. More research is

needed to characterize biologically available nutrient content of legacy sediments and other sediment sources contributing to loads at tidewater.

7. A recent approach to mitigation of watershed loads involves removal of valley-bottom legacy sediments to restore local ecosystem services and to prevent downstream transport. Studies in progress show promising trends in water quality, hydrologic condition and vegetation at restoration sites, but there is not yet enough information to quantify long-term engineering reliability or benefits across the Bay watershed.

8. Documented approaches to control surficial sources of sediment and nutrients include riparian forest buffers, BMPs that retain nutrient-rich topsoil on agricultural sites, and stormwater management to control peak flows, filter runoff, and reduce fluxes from developed watersheds. Such approaches may be as, or more, effective than legacy sediment removal under certain conditions, and so should remain part of a mitigation portfolio.

9. Given uncertainty about how rapidly mitigation efforts upstream will lead to observable reduction in sediment and associated nutrient loads downstream, sites with closer functional proximity (e.g., potential for transport, storage, and delivery) to tidewater should be weighted more heavily than sites that are farther from tidewater or that have a lower probability of delivery to tidewater.

10. We recommend a continued primary focus on avoidance, minimization, and mitigation of nonpoint source water quality problems in uplands. Consideration should be given to management of valley legacy sediments where their influence on Bay water quality is determined to be substantial. Protection of sites with potential to retain sediment and nutrients should also be a management goal.

Introduction

The Scientific and Technical Advisory Committee (STAC) of the Chesapeake Bay Program (CBP) sponsored and convened a workshop on Legacy Sediment in Annapolis, MD on April 24-25, 2017. This workshop was developed in response to a request from the Chesapeake Bay Commission (CBC) with the primary goal of reviewing our collective understanding of "legacy" sediment and its relative influence on habitat and water quality, both locally and across the Chesapeake Bay, as well as the relative merits of different management approaches. This is a complex topic with important implications for Chesapeake Bay and speakers were invited to ensure a broad and comprehensive assessment of the relevant issues. As articulated by CBC Executive Director Ann Swanson, “A STAC workshop, with presentations from various points of view and a free and rigorous scientific debate, would greatly assist policymakers in understanding how “legacy” sediments fit within a suite of management activities to reduce nutrient and sediment loads to the Chesapeake Bay.”

The workshop was organized into three themes: State of the science, mitigation strategies, and management issues. Questions related to each of these themes were addressed during five sessions (see Appendix A for a copy of the agenda). For each session, a panel of several invited speakers were asked to present key observations related to the session theme. Panelists made short presentations with a small number of slides to illustrate major points, and in some cases provided supporting documentation to be made available on the STAC workshop web page. This allowed enough time for informed discussion with the assembled group during extended question and answer sessions. The steering committee also empaneled five teams of "synthesizers" to integrate the information presented in each session along with their own expertise, so as to summarize the state of the science and to outline key information/research needs. In the afternoon of the second day of the workshop, the synthesizer teams for each session provided their responses to the presentations and to the ensuing discussion on each theme, and then discussion was opened up to the group as a whole.

This report encapsulates the key observations made in each of the five workshop sessions and in the summaries by each synthesizer team. Important questions and observations from the audience were also captured, including those raised during the question and answer sessions in the five thematic sessions and in follow-up discussion of the synthesizer presentations. Notes on these discussions are provided in Appendix B.

Following the workshop, the members of the steering committee reviewed what was learned with the objective of providing useful feedback for managers and decision-makers that may help to inform policy and resource allocation for mitigation strategies. This review is the basis for the Findings and Recommendations section of the present report. We tasked ourselves initially with writing a report that identifies areas of consensus, areas where consensus does not yet exist, and areas where more information is needed. In the deliberations of the steering committee, we found that although there were indeed some areas where consensus does not yet exist, a major reason had to do with the inherent spatial heterogeneity of conditions across the Chesapeake Bay watershed; so that different answers may be appropriate in different locations depending on geomorphic setting and local history. Furthermore, it was also concluded that in practice the synthesizer groups did not all follow the same approach in delivering their summaries of what they heard in each of the five panels. For this reason, the summaries as presented in the main body of the report are simply provided as numbered lists of bullet points; where there are differences these are indicated but the contrast between areas of consensus and lack of consensus is not used as an organizing principle.

Introductory remarks were made prior to the first session by Andrew Miller, who served as chair of the steering committee. This brief presentation provided some historical background and described the agenda for the workshop. Observations from that presentation include the following:

- Scientists have been describing the effects of forest clearing, agriculture, mining, and urban development on erosion and deposition and associated landscape processes for at least 100 years.
- These observations have been made both in the Chesapeake Bay watershed and in other locations throughout the southeastern, northeastern, and midwestern U.S. as well as in the western U.S.
- It is clear that from the colonial period onward there were dramatic increases in the amounts of sediment eroded off the landscape and delivered to downstream receiving waters, including Chesapeake Bay.
- It is equally clear that a large fraction of this sediment – in some cases, the great majority – has not reached a "final" destination but is stored at intermediate locations in the landscape. Much of this "legacy" sediment can be identified and traced to the periods of intensive land use that triggered the wave of accelerated erosion.
- Within the Susquehanna River watershed, a wave of sediment contributions from hydraulic mining of anthracite coal began in 1840, with large volumes of mining-related sediment accumulating as channel island deposits and vertical aggradation deposits on floodplains along the lower Susquehanna over the ensuing 130 years. Rates of island growth accelerated after closure of Safe Harbor Dam in 1929 (Lintner 1983).
- Other studies of river and floodplain aggradation from "culturally accelerated soil erosion" at sites including the Gulf Coast Plain of Mississippi, the southern Piedmont, the upper Mississippi and Ohio Valleys and local examples from Maryland to California were described by Happ, Rittenhouse and Dobson (1940). The characteristic cycle of soil erosion and sediment yield associated with changing land use in the Maryland Piedmont was described in an often-cited publication by Wolman (1967), and the physical character of sediment deposits aggraded on floodplains in the Maryland Piedmont was described by subsequent publications (Costa 1975; Jacobson and Coleman 1986). Work by other authors including Knox in the upper midwest (1972, 1977, 1987, 1996) and Trimble in the southern Piedmont (1974, 1977) and in the upper midwest (1983, 2009) documented long-term storage of sediment derived from upland erosion as colluvium on hillslopes or as alluvium on valley floors.
- Research by Trimble (2009) indicates that even with major reductions in erosion as a result of improved land-use practices between 1938 and 1993, there was virtually no change in sediment yield to the Mississippi River from the Coon Creek watershed in Wisconsin and there was still net storage of sediment in the tributary and main valleys.
- Work published by Walter and Merritts (2008) and in subsequent papers (Merritts et al. 2011, 2013) highlighted the importance of tens of thousands of mill dams as storage sites for sediment trapped upstream in mill ponds between the colonial period and the 20th century. In Pennsylvania, perhaps half of these dams are still intact and subject to breaching. Although other states do not have historical inventories comparable to what is available in Pennsylvania, most of the historic mill dams that we have seen in other Bay watershed states appear to have been breached since sometime in the early 20th century. As is the case with other contemporary dam removals or

breaching episodes, rapid upstream incision contributes large sediment loads to the channel downstream in the initial period after breaching. Bank erosion of legacy sediment deposits, sometimes characterized as terraces, contributes sediment for some time thereafter. Ongoing research in the mid-Atlantic region is aimed at determining the response times of channel incision and bank erosion to dam breaching, and hence the lag times in erosion of legacy sediment from former millponds.

- There is now widespread interest in the role of legacy sediment deposits as sources of sediment and nutrients, both locally and as contributors to sediment and nutrient loads that are subject to total maximum daily load (TMDL) requirements under the terms of the Chesapeake Bay Watershed Agreement. Particularly in Pennsylvania, but to some extent in other jurisdictions, some mitigation plans call for removal of legacy sediment deposits associated with mill dams by excavation down to the pre-settlement horizon with the goal of establishing wetland meadows in direct contact with groundwater at the original base level (i.e., the water level prior to damming). Legacy sediment removal is one among a suite of management options that local and state agencies consider both for local remediation of streams with erosion problems and for meeting TMDL requirements. There are ongoing studies in several locations, most notably at Big Spring Run in Lancaster County, PA, to assess the costs and benefits of this approach.

Theme A: State of the Science - Characterization of legacy sediment and its relative importance to the Bay

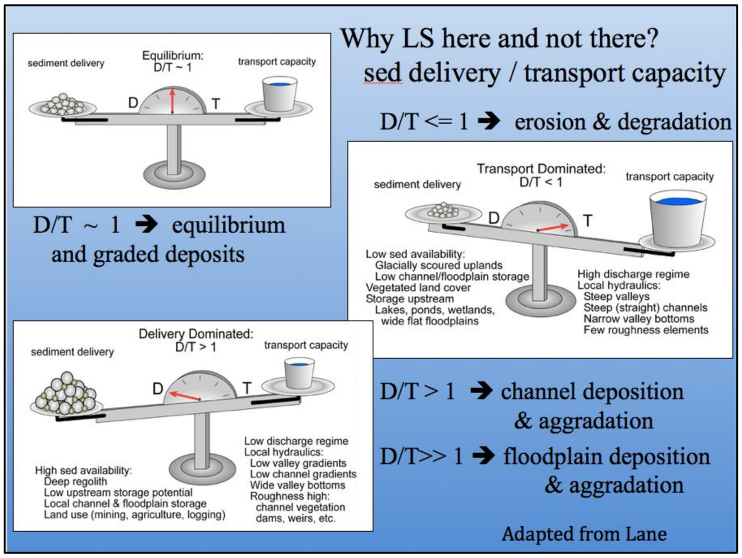
Panel A1 – *Allan James (University of South Carolina), Sean Smith (University of Maine), Dorothy Merritts (Franklin and Marshall), Greg Noe (USGS)*

A1 Synthesizers – *Michael Langland (USGS), Andy Miller (UMBC), Bob Walter (Franklin and Marshall)*

Questions:

- How should legacy sediment be defined in the context of the Chesapeake Bay management effort?
- What is the importance of legacy sediments compared to other sediment sources affecting Bay conditions?
- To what extent do legacy sediments provide an important source of nutrient contributions by comparison with other sources?

The presentation by Allan James provided an overview of the history of how legacy sediment has been described and characterized in other regions not limited to the Chesapeake Bay watershed. James pointed out that the term can be applied to many kinds of deposits across many different geographic regions and can be construed to include any sediment mobilized and stored in identifiable deposits as a result of human activity. Authors working in many parts of the U.S. have described deposits of anthropogenic origin resulting from landscape disturbance and deposition of eroded sediment, and these studies go back at least a century to the work of G.K. Gilbert (1917) who studied hydraulic mining debris in the Sierra Nevada. Other early research was conducted by Happ et al. (1940), Happ (1945), and Trimble (1974, revised 2008), and other authors including Knox in the midwest (1972, 1977, 2006) and Costa (1975) and Jacobson and Coleman (1986) in the mid-Atlantic region.



Why LS here and not there?
sed delivery / transport capacity

D/T <= 1 ➔ erosion & degradation

D/T ~ 1 ➔ equilibrium and graded deposits

D/T > 1 ➔ channel deposition & aggradation

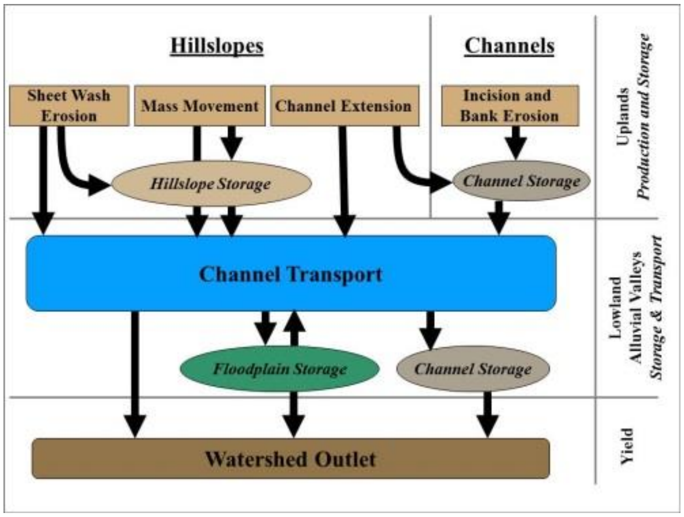
D/T>> 1 ➔ floodplain deposition & aggradation

Adapted from Lane

James suggests that the well-known Lane diagram, describing the balance between sediment supply and transport capacity, is a useful tool to assess whether channels and floodplains will aggrade or degrade.

The term "legacy sediment" has attained widespread usage over the last decade and particularly in association with tens of thousands of sites of mill dam impoundments in the mid-Atlantic Piedmont as described by Walter and Merritts (2008). A more detailed definition encompassing both mill dam sediments and other kinds of historic deposits was provided by Hartranft, Merritts and Walter in a 2006 report to the Pennsylvania Legacy Sediment Workgroup. James' presentation included a stratigraphic profile from Lyons et al. (2015) with mill pond legacy sediment underlain by pre-dam legacy sediment.

James recommended a more expansive definition of legacy sediment not limited to the common usage current in the mid-Atlantic region, and also suggested a physical/mechanical criterion based on the well-known Lane diagram (the ratio of sediment delivery to transport capacity; Lane 1995, James 2013) for identifying conditions where legacy sediment deposits might form by aggradation, might remain in equilibrium, or might experience erosion and degradation.



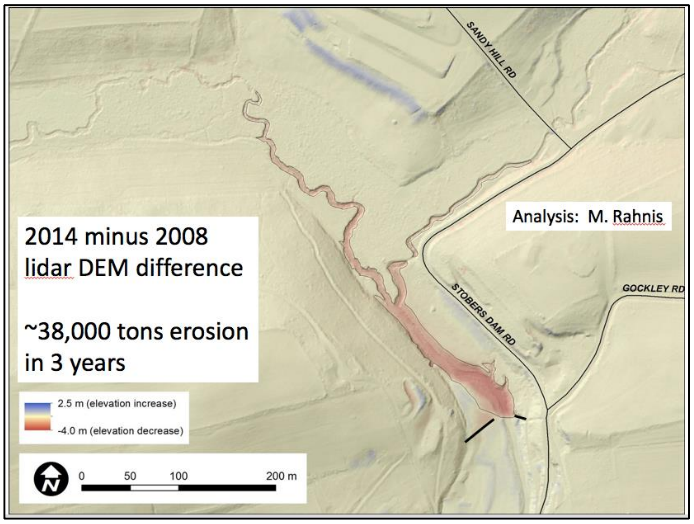
Watershed sediment budgets traditionally are partitioned according to source areas, zones of storage and transport, and export at the mouth of the watershed.

The relative importance of contemporary upland sediment sources by comparison with legacy sediments stored in valley bottoms was a primary topic of discussion in the presentation by Sean Smith. Smith provided a conceptual diagram illustrating sources and storage compartments in the watershed sediment budget (left). Smith's work focused on Maryland Piedmont watersheds in the Baltimore-Washington metropolitan area, providing a closed sediment budget for a high-order drainage basin.

Smith pointed out that a large percentage of the cumulative length of channels in most watershed drainage networks is made up of headwater streams. A comparison of zero- and first-order upland watersheds with larger watersheds up to several hundred km^2 indicates that erosion in headwater areas is pervasive even in forested areas and that upland sediment yield is much higher than the yield from higher-order streams and rivers over the last several decades. The highest yields he has observed are associated with upland locations with gullied channels, and with hillslopes and first-order channels in urbanized settings. According to Smith, upland sediment yield in the Maryland Piedmont is very high relative to estimated regional background levels, and it contributes to ongoing net storage on floodplains and lowland "alluvial" valley bottoms in higher-order drainages over the past half century, including many that are underlain by historical legacy sediment. He concluded that if lowland valley-bottom rates of sedimentation exceed erosion as indicated by recent studies, then the proportion of watershed sediment yield derived from lowland valley (second-order +) stream banks is necessarily small. These observations in turn may have implications for the choice of where mitigation efforts may have the greatest potential for sediment source reduction.

Culprits responsible for the high upland sediment yield in the contemporary Piedmont surrounding Washington D.C. and Baltimore include the following:

- high surface runoff rates in both urban and rural settings due to impervious surface and historic erosion of upper soil horizons,
- rapid erosion of first-order channels into upland legacy "sheet-wash" sediment deposits previously described in a watershed-scale sediment budget for the Maryland Piedmont,
- intense sediment-generating disturbances in localized areas that are individually temporary but cumulatively pervasive in contemporary urban landscapes, and
- the efficient delivery of sediment in both urban and rural areas due to direct and indirect upland drainage modifications.

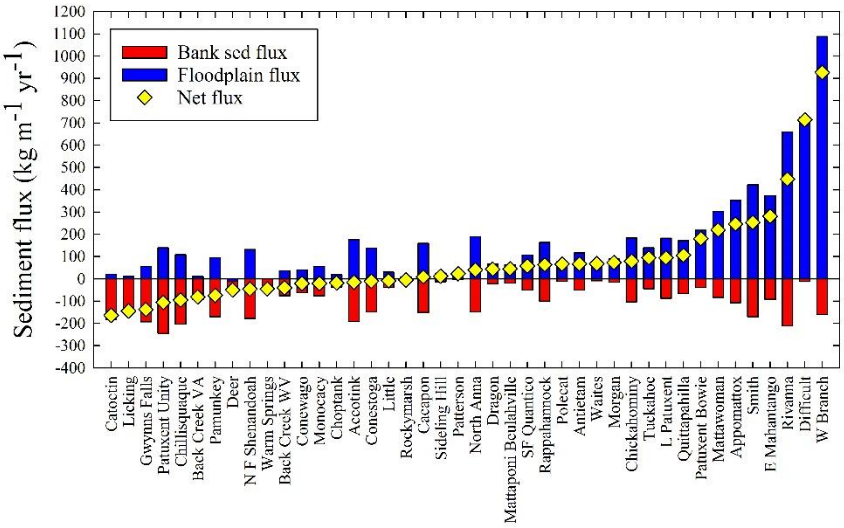


Headward incision of Stobers Branch , Indian Run, PA, during the period following breach of a historic mill dam. Changes are based on comparison of high-resolution LiDAR topographic data.

The presentation by Dorothy Merritts focused on the relative importance of mill dam deposits as active and potential contributors to watershed sediment budgets, due in part to the large number of mill dams in the landscape, including a very large number that are still intact in Pennsylvania. She pointed out that the deposits immediately upstream of the dam site can be as high as 15-25 feet and that when a breach occurs there is a locally steep gradient that can lead to rapid incision and headcut migration which may propagate upstream along the main valley. These steep gradients at the site of a headcut may allow rapid erosion. Headcut incision can migrate into tributary drainage networks upstream of the original mill dam deposit, and the propagating wave of incision could release large volumes of sediment into the downstream drainage network that might continue to contribute sediment over long time intervals even as the initial rate of evacuation declines. The availability of multitemporal LiDAR data now makes it possible to calculate volume and mass of remobilization of sediment by differencing of digital elevation models (see figure from the Water Science Institute, left). Many of the unbreached mill dams in Pennsylvania are potential hotspots of future erosion if the dams were to be removed or fail.

Merritts also pointed out that mobilization of bank material is not limited only to the impacts of flood flows, as freeze-thaw and mass-wasting processes in winter can account for substantial amounts of erosion providing sediment directly to the channel (see also Wolman 1959). She stated further that high erosion rates along channel reaches affected by rapid incision might occur independently of contemporary land use and could include forested sites. A mathematical model assuming random timing of dam breaching with increasing cumulative length of eroding channels was used to simulate increasing rates of sediment production that could continue to contribute sediment to Chesapeake Bay over a period of centuries. Merritts questioned whether there is sufficient storage capacity in modern valleys to accommodate all of the material that might be released by the evacuation of sediment from these breached mill dam sites.

The presentation by Greg Noe focused on work being done by Noe and USGS colleagues as part of the Chesapeake Floodplain Network, which has 43 sites throughout the Bay watershed across a range of drainage areas and physiographic provinces (below)[1]. At these locations data are being collected to quantify mobilization of sediment from streambanks and sediment trapping associated with floodplains in order to derive net mass balance data for each site. Bank sediment samples and floodplain surface sediment samples are collected along two cross-sections at each site and physical and chemical characteristics are determined including bulk density, mean and median particle size, percent fine sediment, percent mineral fraction, total organic carbon, total N and P, and a suite of



Comparison of field sites from the Chesapeake Floodplain Network showing the balance between sediment flux associated with floodplain deposition and bank erosion.

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[1] This information is preliminary or provisional and is subject to revision. It is being provided to meet the need for timely best science. The information has not received final approval by the U.S. Geological Survey (USGS) and is provided on the condition that neither the USGS nor the U.S. Government shall be held liable for any damages resulting from the authorized or unauthorized use of the information.

other major cations. Although samples are not explicitly identified as legacy sediment or presettlement sediment, lower and upper-bank samples are collected separately at each site so that it is possible to assess potential nutrient loads that may be mobilized by bank erosion as well as nutrient storage in floodplain deposition. Work being carried out also includes studies to assess bioavailability and turnover rates in grams of N and P produced per year per unit of mass in storage.

For 41 of 43 sites, data analysis indicates that there is more sediment being stored by floodplain trapping than the amount being lost from bank erosion. At 43 out of 43 study sites researchers have observed evidence of overbank deposition within the last 2 years.

The measured total concentrations of N and P in surficial floodplain soils are higher than in lower banks and the upper 1/3 of the bank is higher in N than the lower 1/3. Phosphorus concentrations typically range between about 0.3 and 0.7 mg/g and mean turnover times for N and P are 20 years and 48 years respectively, leading the researchers to conclude that much of the stored nutrient has relatively low bioavailability, especially in the Piedmont.

An additional goal of the project is to develop tools for processing geospatial data to provide data on bank height and migration rate for stream channels throughout the Chesapeake Bay watershed excluding headwater sites upstream of the traditional blue-line drainage network. These will be used together with upland erosion estimates based on the Revised Universal Soil Loss Equation (RUSLE) to assess both upland source loads and net flux rates for floodplains that can be integrated and used as inputs to the Chesapeake Bay Watershed Model. These tools are being developed for use with the Phase 6 model (approved for use by the EPA Chesapeake Bay Program Principals Staff Committee in December 2017[2]).

The synthesizer team and audience members who asked questions following this first panel emphasized the following key points.

1. For the purposes of the Chesapeake Bay management effort, we define legacy sediment as sediment stored in the landscape as a byproduct of accelerated erosion caused by landscape disturbance following European settlement. Other interpretations are possible but this focuses attention on the issue of greatest current concern.
2. Legacy sediment remobilized from floodplain storage by bank erosion can be more easily identified, and its volume quantified, than sediment derived from widely dispersed upstream surficial sources. Because the bank erosion numbers are sometimes quite large, they are equivalent to a relatively large fraction of watershed sediment yield. However, this does not mean that upland sediment sources are not equal or greater in magnitude. Smith concludes that headwater sediment yields are significantly larger than sediment yields at the watershed mouth. Smith’s work and Noe’s work suggest that storage is a large component of the sediment budget, that there is continuing floodplain storage at downstream watershed locations, and that floodplains may still be a net sink rather than a net source in many watersheds.

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[2] A summary of the Phase 6 model can be accessed at the following link. The model is discussed in further detail in a presentation by G. Shenk in Theme C of this report. https://www.chesapeakebay.net/documents/Phase_6_Modeling_Tools_1-page_factsheet_12-18-17.pdf

3. The role of improved technology for collection of topographic data was highlighted as providing the opportunity to better quantify changes in storage over time by bank erosion or gully incision. Surface wash and floodplain aggradation are more difficult to quantify than bank erosion using remote sensing techniques, and thus field measurements will still be needed to provide reliable estimates of net storage or net export.
4. Where significant numbers of mill dams are still extant and could breach or be removed (as is the case in Pennsylvania), potential hot spots that could trigger a wave of headward incision, releasing large amounts of sediment after a dam breach, should be identified and assessed.
5. Data on nutrient concentrations in floodplain soils and in both legacy and presettlement floodplain sediments should be requested from the various researchers and/or agencies collecting this information and deposited in a common database with metadata about analytical methods and similar units in order to ensure comparability across different sites in the watershed. To the extent that quantitative information about bioavailability and turnover rates is available, this should be collected as well. This will help in assessing the relative importance of nutrient contributions to the Bay from eroded floodplain sediments.

Panel A2 – *Allen Gellis (USGS), Karl Wegmann (North Carolina State University), Cliff Hupp (USGS, retired), Jim Pizzuto (University of Delaware)*

A2 Synthesizers – *Dorothy Merritts (Franklin and Marshall), John Brakebill (USGS), Katie Skalak (USGS)*

Questions:

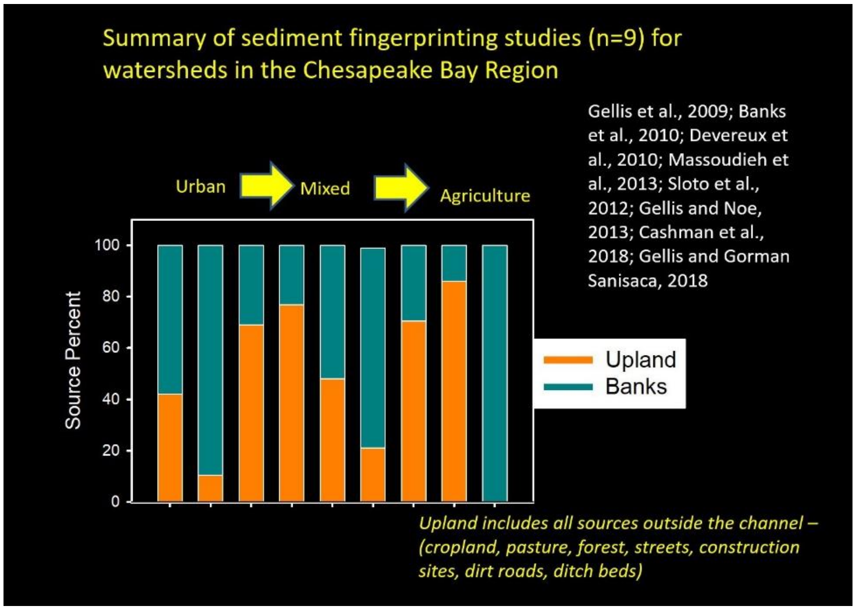
- How do the distribution, characteristics and relative magnitude of legacy sediment vary with watershed scale or geographic location?
- To what extent are lag times for sediment delivery and intermediate floodplain storage processes relevant to our assessment of the problem?

The presentation by Allen Gellis argued that in order to reduce sediment loads to streams in the TMDL framework, we should adopt a ‘common sense’ approach:

- Target sources of sediment, particularly those locations with known high suspended sediment loads;
- Mitigate erosion at these sources; and
- Monitor the results.

Many streams in the Chesapeake Bay region have high suspended sediment loads, and geochemical sediment fingerprinting is a valuable assessment tool to determine the source(s) of that sediment. The basic approach with sediment fingerprinting is to identify and sample all possible sources and to determine their geochemical fingerprint. These fingerprints can be compared to those of sample targets, such as suspended or bed sediment in a stream, or sediment deposited in a floodplain. A manual published by EPA (Gellis et al. 2016) describes the approach. A mixing model is employed (Gorman-Sanisaca et al. 2017a, b) to apportion the sources of delivered sediment.

Fallout radionuclides with different half-lives (^{210}Pb half-life 22 y, and ^{7}Be half-life 53 days) can be used to "date" the surface-derived portion of fine grained sediment (<0.063 mm). For this approach, "dating" the sediment refers to determining the most recent time it was deposited. Where Gellis et al. (2017a) used this approach in a mid-western basin in Iowa, ages ranged from years to decades, with a portion of sediment younger than 1 year. Similarly, in Smith Creek, Virginia, preliminary results show that some fine-grained sediment moves rapidly through these systems.


Summary of sediment fingerprinting studies (n=9) for watersheds in the Chesapeake Bay Region

Gellis et al., 2009; Banks et al., 2010; Devereux et al., 2010; Massoudieh et al., 2013; Sloto et al., 2012; Gellis and Noe, 2013; Cashman et al., 2018; Gellis and Gorman Sanisaca, 2018

Upland includes all sources outside the channel – (cropland, pasture, forest, streets, construction sites, dirt roads, ditch beds)

Comparison of percent of sediment reaching the watershed outlet derived from different sources for nine watersheds in the Chesapeake Bay Region.

Results of sediment fingerprinting studies for nine watersheds that span urban to mixed to agricultural land uses in the Chesapeake Bay region indicate that the ratio of upland:bank sources varied from 0:100% to about 90:10%. These results show that in agricultural watersheds, topsoil from uplands is not the only source of sediment. Stream banks are also important and in some cases dominate. In urban areas with high impervious cover, both banks and upland slopes can be important sources of sediment in streams.

Phosphorus commonly is transported in forms adsorbed to fine sediment particles; a study from an agricultural watershed in Wisconsin indicated that significant fractions of particulate phosphorus load were derived from bank erosion, agricultural land and forested land, with an average 30% coming from eroding banks and 70% from upland agriculture (Fitzpatrick, USGS, unpublished).

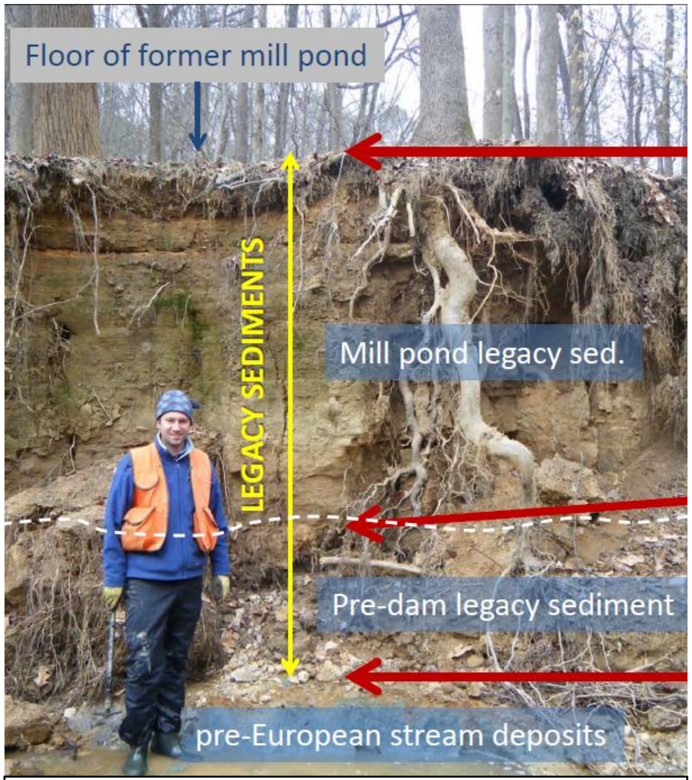
Sediment fingerprinting apportions sources of sediment (e.g., bank erosion vs. upland erosion), but a sediment budget is needed in order to locate and quantify the fluxes of specific sources throughout a watershed. Monitoring over lengthy time periods is essential, however, because of high variability in rates of each important process with time. Freeze-thaw processes and storms in particular can cause large amounts of erosion and deposition, and carry much of the annual sediment load in a watershed. For these reasons, Gellis also recommends targeting streams with high suspended sediment loads and then monitoring and mitigating them at management scales.

Gellis et al (2017b) developed a sediment budget for the upper portion of Difficult Run in northern Virginia (drainage area 14.2 km^2) and determined that large contributions of suspended sediment are from streambanks (up to 82%). Gellis suggested that before modelers create the next version of their models, they reach out to geomorphologists and engineers to apply the 'state of the knowledge of bank erosion' to their models.

Sediment in channels can be an important storage component of a sediment budget, albeit one with a shorter residence time than other storage components. In the dominantly agricultural Smith Creek basin in Virginia, for example, Gellis' work shows that 2.5 times the average annual sediment load is in channel storage. Sediment deposited on the bed buries aquatic habitat, and is the reason that many streams are listed by EPA as impaired by sediment.

The presentation by Karl Wegmann provided background on legacy sediment in the Piedmont of North Carolina. Post-European settlement forest clearing and agricultural practices led to rapid erosion of upland soils at rates almost 100 times greater than the long-term background rate of soil production and erosion in the southern Appalachian region (Trimble 1977, Reusser et al. 2015).

Historically, southern Appalachian Piedmont streams exported only about 6% of this eroded upland material (Trimble, 1977, Phillips 1992, 1993, Reusser et al. 2015). The other ~94% of eroded sediments remained as legacy sediment stored at the base of hillslopes and along valley bottoms. Wegmann's recent work and radiocarbon dating show that many reaches of North Carolina streams have high banks consisting of fine-grained, highly erodible legacy sediment that date to the historic period.



Stratigraphic profile of sediment deposits representing different time periods. Photograph taken along Reedy Creek, William B. Umstead State Park, Raleigh, NC.

Wegmann and collaborators document that mill dams contributed to trapping large volumes of these fine-grained sediments, although at some sites they observe historic sediment where they have not found records of actual mill dams. A thin sandy unit—also historic in age—sometimes underlies millpond sediment (Wegmann et al. 2012, 2013). Wegmann interprets this sandy unit as a "first-wave" of erosion and sediment that was deposited before the damming of valley bottoms led to accumulation of many feet of silty sediment upstream of dams.

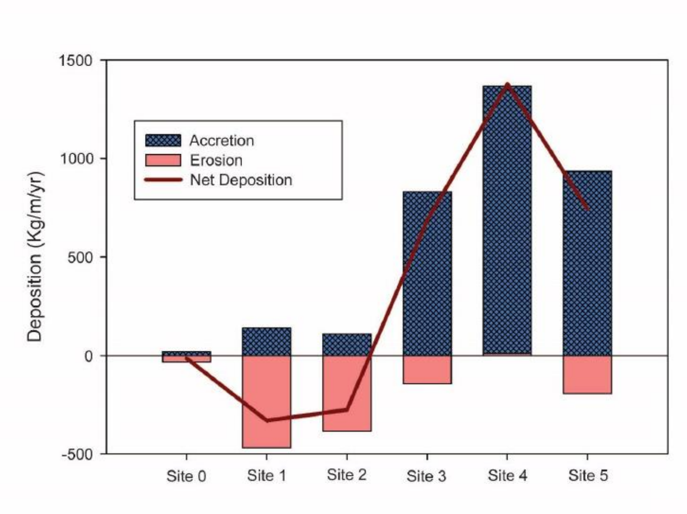
Beneath the historic sediment he finds a dark black, organic rich soil that he interprets to be the result of organic matter accumulating in a wetland environment, probably a wet meadow, and possibly associated with beaver activity. Wegmann noted that these wet meadows would have had significant longitudinal channel complexity, low peak flows, and extensive hyporheic exchange with groundwater connected to surface water at channel to floodplain levels.

Wegmann cited research on sediment storage at Richland Creek, a third-order Piedmont tributary to the Neuse River, North Carolina, to demonstrate the volume of historic sediment in storage in its valley bottom (Wegmann et al. 2012, 2013). Using LIDAR he estimated that ~800,000-1.6 million cubic meters of historic (i.e., legacy) sediment was stored in the valley bottom, but only 11 to 23% has been removed by stream erosion with the remainder in valley storage. At current sediment export rates, the remobilization of legacy sediment will remain a water quality problem for centuries to millennia (e.g. Jackson et al. 2005). The estimated volume of stored legacy sediment within this single tributary is equivalent to approximately 130,000 dump truck loads. Wegmann suggested that given the cost and impracticality of removal at this scale, an alternative restoration strategy might involve encouragement of beaver impoundments to raise base levels, restore low-order valley-bottom wetland meadow complexes to increase channel complexity, raise water tables, reduce peak flows, and reconnect shallow groundwater to the floodplain. His presentation illustrated several examples of engineered structures created as analogues to beaver dams, in some cases subsequently colonized and maintained by beavers.

Wegmann and colleagues used a geochemical-fingerprinting approach to estimate the source of suspended sediments collected from tributaries entering Falls Lake, a 50-km^2 drinking water reservoir on the Neuse River, North Carolina, USA (Voli et al. 2013). Results indicate that stream bank erosion is the largest contributor to the suspended sediment load in New Light Creek (62%), Ellerbe Creek (58%), and Little Lick Creek (33%), and the second largest contributor in Lick Creek (27%) after construction sites (43%).

The presentation by Cliff Hupp summarized results from investigations of sedimentation along several streams that include non-tidal and tidal reaches. The first of these was a summary of a study of Difficult Run, VA, a fifth-order watershed (151 km^2) with extensive land clearing for agriculture beginning in the Colonial period, followed by urbanization and reforestation during the 20th century (also discussed by Gellis, above). With about 20% impervious cover, this watershed has been the focus of investigation by USGS and other scientists because it is considered to be representative of urbanizing Piedmont parts of the Chesapeake Bay watershed (Schenk et al. 2012, Hupp et al. 2013, Gellis et al. 2017).

Large amounts of historic sediment occur along the valley bottom throughout the Difficult Run watershed, with bank heights up to several meters including both legacy sediment and modern overbank deposits. At least six mill dams dating to as early as the mid-1700s are known to have been present on the main stream, and other mill dams were located on tributaries to Difficult Run. All mill dams on the mainstem were breached by the early 1900s. According to Hupp, substantial historic deposition occurred at sites with and without known mill ponds. Hupp concluded that mill ponds are not requisite for substantial historic deposition on floodplains and that they remain active fluvial features, not terraces.



Comparison of the balance between measured bank erosion and floodplain deposition rates at six sites along Difficult Run, Fairfax County, VA.

Hupp et al. (2013) monitored bank erosion and floodplain deposition using bank pins and clay pads at 6 reaches (100-200 m in length) along the mainstem of Difficult Run (total mainstem length 25.6 km) from 2008 to 2011. They found that bank erosion exceeded floodplain deposition in the upper 3 reaches with drainage areas of 3, 14, and 28 km^2. In contrast, annual mass of floodplain deposition per unit reach length exceeded bank erosion at the lower three reaches, with upstream drainage areas of 74, 117, and 141 km^2. Hupp concludes that there is net storage on the lower floodplain, even where underlain by legacy sediment. He notes the benefits of overbank flow and deposition to ecosystem functions and underscores their importance for preserving floodplain connectivity.

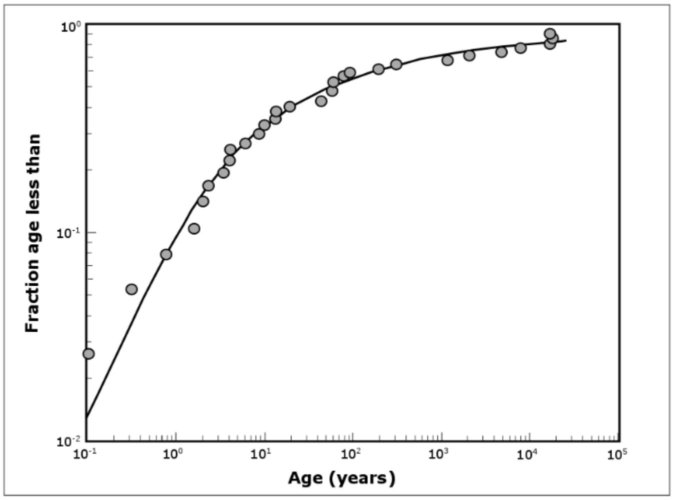
Results from a study along the Lower Roanoke River, NC, were presented to compare patterns of erosion and sedimentation along tidal and non-tidal reaches (Hupp et al. 2015). Here, the upper and middle nontidal reaches are characterized by incised channels and relatively steep banks, which are the source of most suspended sediment. Lower tidal reaches have low to almost no banks and trap substantial amounts of suspended sediment.

The Lower Roanoke valley bottom supports the largest intact forested wetland in the mid-Atlantic. This bottomland experienced considerable post-colonial aggradation, up to 6 meters since 1725. Stream flow upstream has been regulated by a series of Piedmont dams for about 60 years, and these also have trapped historic sediment that might have made it farther downstream. Longitudinally varying sedimentation rates through time were obtained from analyses of pollen, dendrochronology, and clay pads.

Hupp posed the question of what happens when the sediment load from a watershed hits the tidal zone: Might it influence wetland resilience to sea level rise? He noted that the magnitudes of sediment sources and rates of accumulation change along a tidal river gradient, creating a sediment shadow effect. High historic accretion (floodplain deposition) from the watershed occurs in upstream non-tidal reaches. Low and variable accretion occurs at the head of tide. Lowest accretion rates occur in the tidal freshwater zone. Highest accretion occurs in the oligohaline zone (presumably from marine sources). The lower Roanoke is not an embayed system like the James, Potomac, and Susquehanna Rivers, which have less low gradient wetland area to trap sediment.

The presentation by Jim Pizzuto categorized take home points based on his and collaborators' work as related to scientific questions and management needs. His scientific points were as follows:

Alluvial rivers store sediment, and tend to release it "later", delaying downstream delivery. Alluvial storage occurred in the mid-Atlantic region before European settlement, and continues today. Legacy sediments are potentially not as important as one might think, based on modeling of the data sets he and his collaborators are collecting.



Cumulative age distribution for floodplain sediments in South River, VA using a weighted distribution from sediment budget data, including in-channel deposits.

Storage timescales are long relative to timescales of watershed management (1-1,000,000 years based on a compilation of worldwide data and modeling). Sediment storage in river corridors is currently an important process. A range of 1-44% of suspended sediment in transport in streams is stored per km of downstream distance. Particles typically do not move far without being stored at least once (Pizzuto 2014). Storage timescales from a study in preparation by Skalak et al. indicates that sediment can be stored from one to 20,000 years, with a median duration of storage of about 100 years.

If transport distances are large, sediment is likely to be stored at least once before reaching the basin outlet. Delivery timescales therefore are determined by storage rather than by transport during events. Sediment delivery timescales, similarly to alluvial storage timescales, greatly exceed watershed management timescales.

Sediment science in the Chesapeake Bay watershed requires continued research to guide management decisions. A limited focus on eroding banks, for example, might be misleading. Critical questions still remain regarding locations and magnitudes of upland sources. We have a great need for watershed-wide sediment budgets. Where is sediment stored? Where is sediment NOT stored? How much is stored? What is the frequency distribution of storage timescales?

Pizzuto et al. (2017) conducted a numerical experiment based on a sediment routing model that features rapid in-channel event transport, the probability of storage, and the duration of time that particles "wait" once deposited. The model watershed is similar in size to that of the Susquehanna River basin. Modeling results suggest three take home points for management needs:

1. The location of best management practices (BMPs) matters. BMPs far upstream from basin outlets might have little impact over timescales of relevance to management concerns. Should BMPs address upland sources or downstream storage zones? We need additional data to answer this question.

2. Improvements imposed by BMPs on sediment delivery will be transient over management timescales. The full steady-state benefit of BMPs may take centuries or longer.

3. Existing watershed models do not adequately account for storage timescales and processes. Current model predictions are not very useful for managing sediment.

The synthesizer team and audience for panel A2 emphasized the following points.

1. The Piedmont is an important source of suspended sediment in the Chesapeake Bay watershed. Great spatial variability exists for erosion, deposition, storage and lag times for downstream delivery. Over time the landscape has evolved from one with generally low erosion rates, to one with rapid erosion and large volumes of deposition, to one where remobilization of stored sediment is a potentially important part of the sediment budget.
2. Awareness of the primary component parts of watershed drainage basins is important to interpretation of sediment budget information and management responses. First-order watersheds are estimated to comprise over 60% of the total area of fourth-order watersheds and ~50% or more of the associated total stream channel network length in the Piedmont. Collectively, first- through third-order drainage basins are estimated to comprise the majority (possibly ~80%) of the Chesapeake Bay watershed.
3. Legacy sediment is a useful construct and valley legacy sediment deposits have similar characteristics at sites in Pennsylvania, Maryland, Virginia and North Carolina. However, it is not clear whether we need to treat this material separately from other fine sediment in storage if our overall goal is to manage sediment export.
4. Understanding the historic condition is important for providing potential “restoration” benchmarks as well as trajectories. Valley configurations were different before deposition of legacy sediment. In some landscapes we have lost the ecosystem benefits of thousands and thousands of acres of non-tidal wetlands because of historic sedimentation. The role of beaver dams in pre-colonial valleys may have been important but is not known; there may be potential for beaver-dam analogues as part of restoration efforts in the modern landscape.
5. We need sediment budgets to assess relative magnitudes of sediment sources, information on spatial distribution of stored sediment, rates of erosion and deposition on the landscape, and ages of sediment contributing to water-quality impairment. We also need sediment residence time information to inform our approach to management actions. All four panelists noted that lag times for valley-bottom storage and downstream delivery are highly variable.
6. We also need better models that can simulate all components of the sediment budget, including the impacts of large storms.
7. New tools and techniques, including high-resolution digital elevation data and drone technology as well as geochemical or radionuclide fingerprinting, may enable us to quantify sources and sinks as well as rates of erosion and deposition; what is needed is time and resources to do the monitoring, analysis, and quantification.

Theme B: Mitigation Approaches and Assessment of Their Effectiveness

Panel B1 – *Art Parola (Stream Institute, University of Louisville), Solange Filoso (University of Maryland Center for Environmental Science), Drew Altland (RK&K), Tess Thompson (Virginia Tech)*

Synthesizers – *Scott Lowe (McCormick Taylor), Mike Trumbauer (Biohabitats, Inc.), Sean Smith (University of Maine), Jeff Hartranft (PA Department of Environmental Protection)*

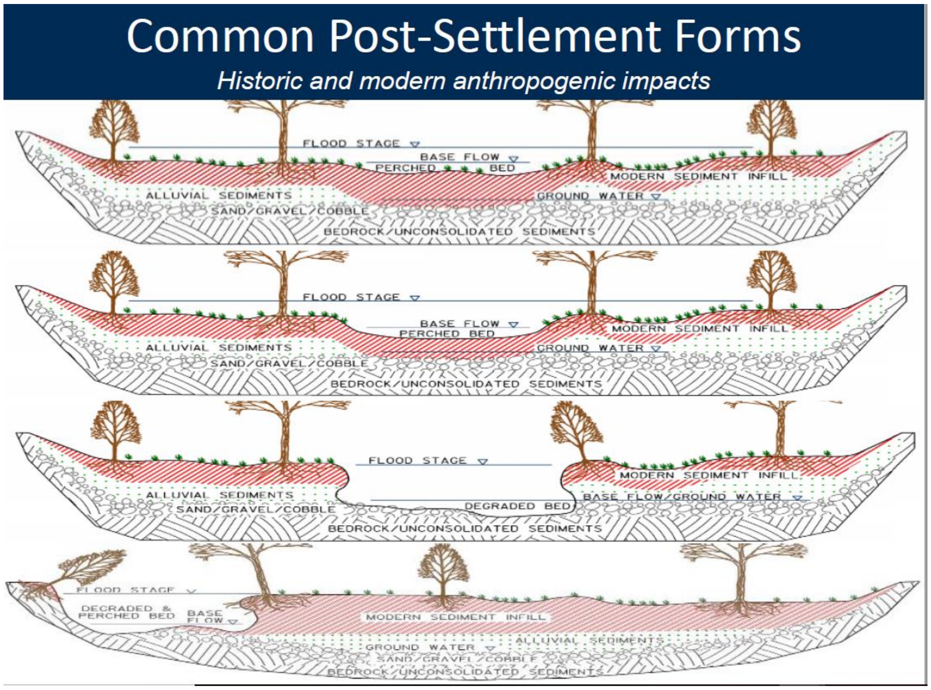
Question:

- What do we know about the engineering reliability and water-quality effectiveness of practices designed to mitigate the potential downstream impacts of legacy sediment at the watershed scale?

The presentation by Art Parola targeted impairments evaluated based on a reference set of conditions believed to be present in lowland valleys prior to inundation by legacy sediment generated from historical watershed disturbances. The conceptual model he used for design purposes is one in which the historical setting is a bedrock valley bottom overlain by a colluvial cobble/gravel bed and floodplain soils described as peaty, organic, and porous. He described flow that is either ponded or in multiple channels with low banks, where the valley bottom is inundated by minor flow events, valley-bottom soils are saturated, and there is direct hydraulic connection between the valley aquifer and the channel. In this model, roots grow into the substrate close to the water table, placing carbon into the substrate which can be retained as peat, and creating a condition that may promote hyporheic exchange and denitrification. In the modern setting contemporary valleys underlain by legacy sediment have single-thread channels that have incised through the legacy sediment. The modified condition was described as altering hydrology and hydraulics within the affected valley segment, changing the relation between vegetation and the water table, and increasing the flux of sediment, nutrients and water compared to the historic condition.

Options for mitigation could include raising the bed level and perching the entire system on top of the silt-rich legacy deposits, or excavating the underlying legacy sediment in order to restore connectivity with the aquifer, if physically and economically feasible. Parola suggested that a stream-wetland complex with groundwater at the level of plant roots would have a higher degree of reliability than the system currently in place at sites where a channel is deeply incised between high banks of silt-rich legacy sediment. He advocated for excavation of the legacy sediment deposits making up most of those banks, and introduced the goal of disrupting transport in stream systems (both sediment and carbon) as a contrast to the "Rosgen" natural channel design approach that leads to efficient transport of coarse and fine sediment rather than retention. He proposed the use of hydraulic modeling to assess shear stresses for alternative designs so as to prevent mobilization of bed material and erosion of banks in moderate flood events, and suggested that the redesigned system could be hospitable for beaver recolonization.

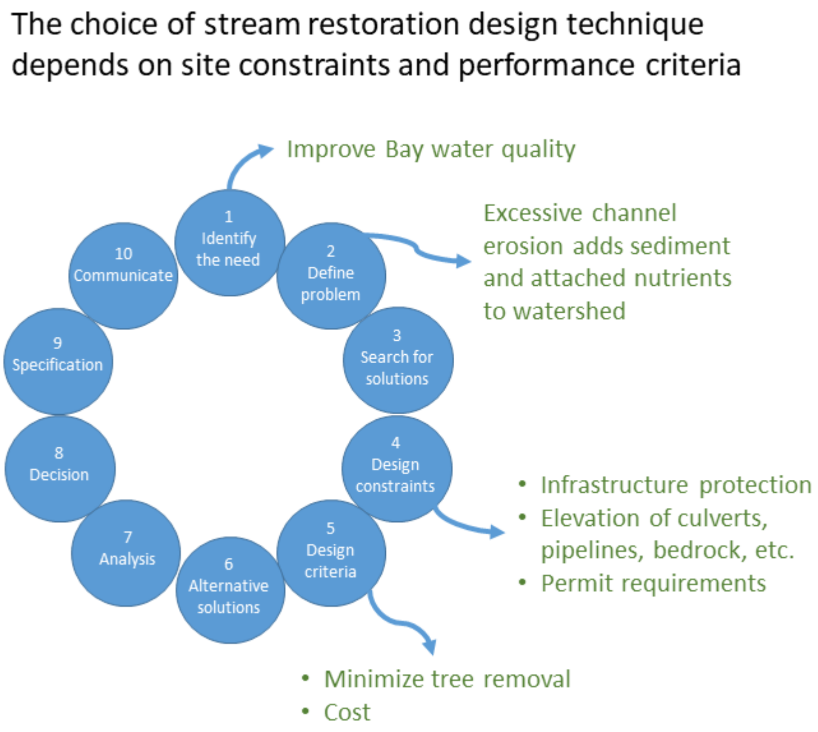
The presentation by Drew Altland provided some additional technical detail on the conceptual model presented by Parola, positing a reference form with small, stable flow paths, retention of sediment, nutrients and carbon, stable epifaunal substrate, regulation of water temperature by groundwater influence, and root zone connection to groundwater. Altland described a series of scenarios associated with historical aggradation followed by entrenchment of legacy sediment, as illustrated at right.



Alternative conceptual models describing the historic and modern relationship between the channel and the valley floor in valleys aggraded by legacy sediment during the historic period and subsequently incised by streams cutting back down to base level following a dam breach.

Potential intervention strategies include removal of modern sediment to reconnect the floodplain, incised channel stabilization to retain legacy sediment in storage, or raising the streambed to connect the channel with the adjacent surface. Altland proposed that the first approach is most consistent with maintenance of ecosystem services that were prevalent under reference conditions. He highlighted three major considerations: (i) removal of high stream banks reduces erosion potential with relatively high certainty; (ii) hydraulic predictions with 2-D modeling can be used in the design process to enhance hydraulic performance outcomes, with the goal of creating designs that lead to reduced channel shear stress and a stable channel bed formed from native cobble and gravel; (iii) the identification of specific impairments is essential to the design planning process. The intervention approach involving removal of modern sediment is designed with the goal of restoring lost functions associated with the reference condition; the Big Spring Run project in Pennsylvania, carried out in collaboration with Walter and Merritts, is the best-known and most thoroughly studied example of this approach.

Tess Thompson's presentation highlighted the connection between stream geomorphology and Clean Water Act goals. She framed the restoration design process as an iterative process intended to maintain a channel form that resists excessive erosion and increased flux of sediment and nutrients from stream banks, while protecting infrastructure and adhering to permit requirements, minimizing removal of trees, and remaining within cost constraints. Although her presentation referenced more general restoration principles, she addressed the legacy sediment mitigation issue as a mass-balance problem with alternative treatments that might either leave legacy sediment in place or remove it.


The choice of stream restoration design technique depends on site constraints and performance criteria

Improve Bay water quality

Excessive channel erosion adds sediment and attached nutrients to watershed

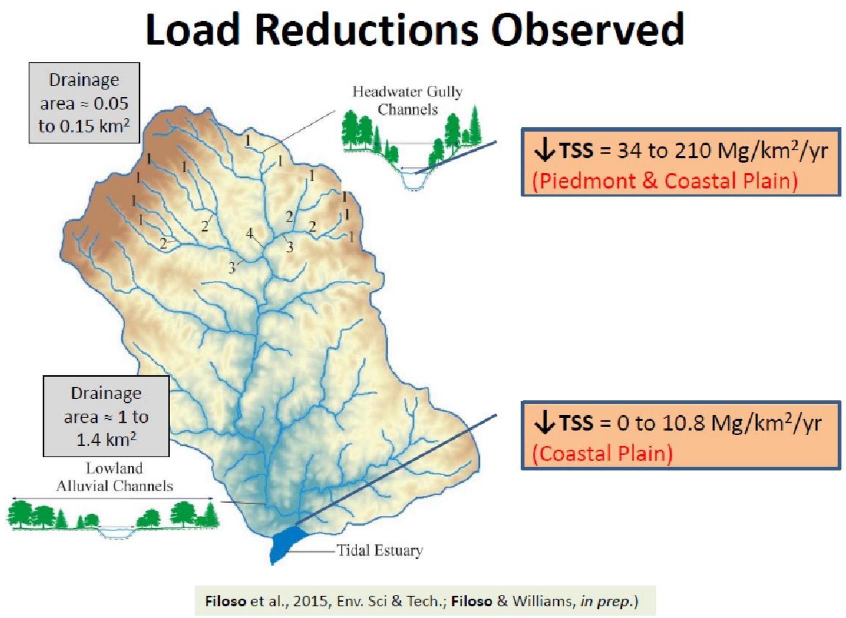
- Infrastructure protection
- Elevation of culverts, pipelines, bedrock, etc.
- Permit requirements

- Minimize tree removal
- Cost

According to Thompson, complete understanding of system behavior requires developing a comprehensive sediment budget, which is difficult and can be costly, and therefore is not always practical for project designs. She emphasized that "healthy" streams are dynamic and we need to restore channel processes rather than an ideal channel form; and that there is no "going back" (e.g., to a pre-settlement reference condition) because of changing land use, hydrology, road crossings and other forms of infrastructure. According to Thompson, we need to allow for some "appropriate" channel migration and we need to reduce bank height either by raising the bed or lowering the floodplain in order to reconnect the channel with the floodplain and to create hydrodynamic conditions associated with greater retention and reduced mobilization of sediment and nutrients. We also need to recognize that the channel will change over time as trees grow; we know for example that stable channel widths are greater in forested streams than in streams with grass-covered banks, so that some channel widening might occur as a natural consequence of forest growth even in a healthy stream.

In her presentation, Solange Filoso described a comparative analysis of water-quality effectiveness of stream restoration projects in headwater vs. lowland channels. She discussed monitoring projects at restoration sites in Anne Arundel County and in the Washington, D.C. suburbs, including zero- and first-order urban and suburban channels in the Piedmont and Coastal Plain (drainage area 0.05-0.15 km^2) and higher-order suburban channels in the Coastal Plain (drainage area 1-1.4 km^2). Yield of suspended solids from the headwater sites was much higher than from lowland sites in the Coastal Plain. Reductions in sediment yield observed downstream of restoration projects were much larger at the headwater sites than at the lowland sites and prevented more sediment from being exported downstream. The upstream sites utilized bank stabilization followed by Regenerative Stormwater Conveyance (RSC) approaches, which are designed to reconnect the channel with the riparian zone. Load reduction approaches in the lowland channels combined sediment retention and streambank erosion prevention approaches. Accumulated alluvial sediment deposits, some of which may be "legacy" or colonial age, are removed or capped in lowland valleys as part of the reconfiguration approach to create Atlantic white cedar swamp habitat.

Presentation information provided by Filoso and Thompson points out that planning targets, design constraints, and watershed position will determine the efficacy of individual projects at reducing problematic water quality loads. Reduction in erosion is identified as the most consistently predictable outcome of stream channel restoration projects. Hydraulic outcomes associated with transport, erosion, and stability are less certain because of the dependence on specific design features and conditions. Monitoring of existing projects will help Chesapeake Bay Program affiliates formulate answers to outstanding questions related to project performance.



Filoso et al., 2015, Env. Sci & Tech.; **Filoso** & Williams, *in prep.*)

Comparison of relative effectiveness of headwater gully restoration vs. restoration at lowland alluvial streams in reducing sediment loads.

The synthesizer team for panel B1 emphasized the following points. The first three points represent consensus views and the remaining points were made by individual members.

1. Removal of stream banks with high erosion potential reduces erosion with relatively high certainty compared to other forms of water quality improvement that have been considered (e.g., denitrification, carbon sequestration).
2. Prediction of the hydraulic effects from valley reconfiguration projects may be enhanced by 2-D hydraulic and other new generations of computer models. Limitations to hydraulic predictions from 2-D models relate to unforeseen morphological changes from sediment inputs and vegetation changes, roughness estimation, limited representation of vertical velocity profiles relevant to sediment transport, errors in sediment transport models, and a scarcity of calibration data.
3. Identification of impairments is necessary for valley restoration planning and design in order to focus investments on design elements that will reliably function over extended time scales.
4. Effective engineering design for restoration practices may be developed using analogue or reference ecosystem characteristics, including their ecological variability and resilience (NRC 1992, Merritts, et al. 2000, SER 2004, Falk et al. 2006). Valley morphology forms and structure that existed prior to legacy sediment erosion and storage represent relevant ecosystem characteristics for consideration in restoration engineering designs.
5. Hydric paleosols buried by legacy sediment are characteristic of naturally occurring aquatic ecosystems, including extensive wetlands in valley bottoms of the mid-Atlantic Region (Jacobson and Coleman 1986, Brush 2008, Walter and Merritts 2008, Merritts et al. 2011, Voli et al. 2011).

Wetlands are detritus driven systems (Mitsch and Gosselink 2000), and increased carbon and water storage is a restoration engineering design objective that results in both allogenic and autogenic carbon driven aquatic ecosystem processes. Restoration engineering designs that reconnect the channel with the floodplain and re-establish natural wetland plant communities are intended to provide aquatic ecosystem stability and biogeochemical processes through feedback pathways that increase carbon retention, flood storage and base flow residence time.

6. We have come a long way over the last 10 years in improving the reliability of some restoration approaches. As a consequence we were able to stabilize some legacy sediments in place. Variation in reliability is partly a function of location in the watershed. We need to understand how these interventions will work as we move further downstream in the watershed and over what time scales. We need to be looking at functional uplift of stream channels, especially comparing ecosystem benefits for the whole valley vs riparian forest that might be removed to make way for it. It's not clear if we know enough about this to work in some of the more urban areas where these forests are among the last contiguous wildlife corridors on the landscape to sustain certain ecosystem functions.
7. In restoration design you want to create something that is sustainable, is stable, and provides the most functional benefit to the system as possible. The presenters identified the ecosystem functions that they were trying to restore and associated those with the wetland types that might be more reliable in achieving those results. Solange Filoso's comments about sequencing were important: we need to plan restoration projects with the coupling between upstream and downstream in mind and recognizing the relative benefits at different watershed scales. With regard to assessment, some of the hydraulic criteria (e.g., shear stresses) are valuable, but it would help to connect this with better understanding of some of the processes associated with storage to understand how they affect the functionality of systems.
8. The presentations by Art Parola and Drew Altland assume a consistent "reference" form (i.e., presettlement condition) for stream channels and valleys; there is also an assumption that if the form is put in place, the processes will occur. This latter assumption is similar to assumptions that have made over the last 20 years of restoration practice. This is a useful conceptual model but we do not currently have consensus among scientists about whether this reference form was really the default condition across all of the watersheds in the region, nor do we know whether the associated processes can be attained effectively across a wide variety of valley settings in the contemporary environment.
9. Monitoring results from the Coastal Plain and Piedmont suggest that headwater channels achieved more improvement than lowland channels and suggest that you get lowland benefits from upland treatment. However you do remove more legacy sediment from lowland valleys. Collecting the data in Big Spring Run and collecting comparative data at different watershed sites the way Solange Filoso has done will help to determine the answer. At the end there is still a decision that a manager needs to make about where to target efforts.
10. An important unmet need is information on long term performance of projects targeting removal of legacy sediment and water quality improvements. This gap is due to limited availability of reports from evaluations focused on the engineering performance of projects in a range of weather conditions and time scales. Important considerations include reliability of structural stabilization, design objectives related to morphometry and vegetation, and the erosion and deposition of sediment in graded valleys. There is also limited extent of monitoring information

to determine water quality benefits in varied settings in a range of conditions (e.g., seasons, weather patterns such as drought) over extended time (i.e., decadal) periods. It will be important to collect additional information along these lines moving forward.

Panel B2 – *Don Weller (Smithsonian Environmental Research Center), Bern Sweeney (Stroud Water Research Center), Peter Kleinman (USDA-ARS), Kathy Boomer (The Nature Conservancy)*

B2 synthesizers – *Karen Prestegaard (University of Maryland), Matt Baker (UMBC), Tom Schueler (Center for Stormwater Protection)*

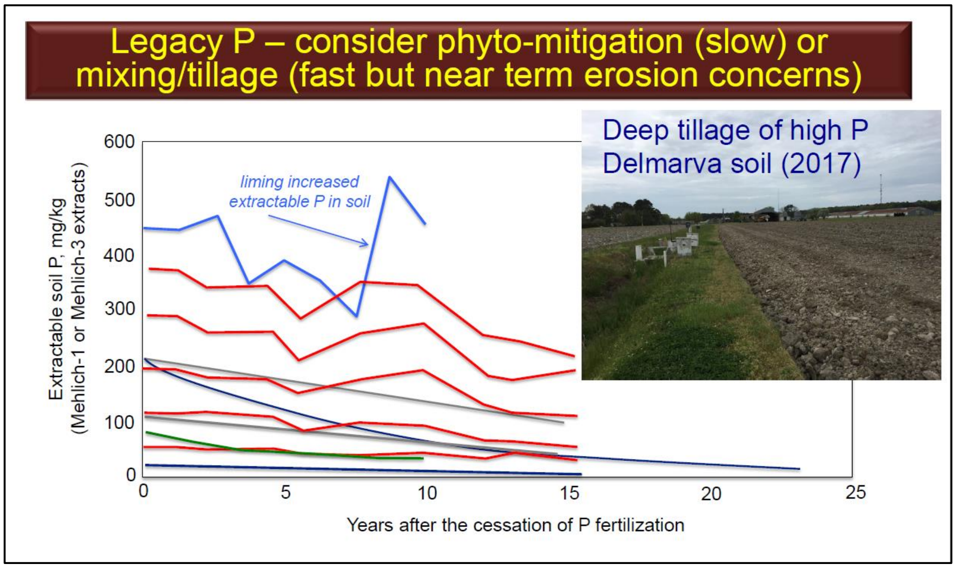
Question:

- What do we know about the relative effectiveness at the watershed scale of practices designed to retain or prevent mobilization of sediment and associated nutrients from sources other than legacy sediment?

A major concern of the Chesapeake Bay Program is the reduction of N and P loads reaching the Bay. The history of N and P loads has a very different trajectory than sediment in the Bay watershed. Suspended sediment loads increased due to land clearance as has been documented by Grace Brush and other researchers that have examined historic sediment loads. This historic sediment, which was also deposited both overbank and in mill ponds to create legacy stored sediment, was not high in N and P if it was deposited prior to the extensive use of fertilizers. Some mill pond sediment and overbank sediment deposited since the 1950's does have higher concentrations of N and P, but the extent of the N and P in legacy deposits has not been extensively investigated. Some of the work described by Greg Noe and by Dorothy Merritts in panel A1 may be helpful in this regard.

The panelists discussed the current state of knowledge of both the sources of N and P on the watershed scale and the effectiveness of practices to retain or to prevent the movement of nutrients and sediment. One of the main points is that N and P concentrations in soils and groundwater are high in agricultural fields now. Nutrient enrichment of soils and groundwater has been increasing exponentially in the U.S. since the 1950's. Although we do not know much about the controls of N and P on the watershed scale, both Peter Kleinman and Bern Sweeney presented research on the effectiveness of integrated measurement and targeted nutrient controls at the field or headwater watershed scale.

Peter Kleinman presented research that described the heterogeneity of P levels in agricultural soils. High P flux from small agricultural watersheds requires both soils that are high in P and a delivery mechanism (usually overland flow). Therefore, high P soils located in areas that generate overland flow runoff can be sources of P delivery to streams. Identification of these potential P sources requires both effective prediction of P content prediction and effective prediction of overland flow runoff and sediment transport.



Legacy P – consider phyto-mitigation (slow) or mixing/tillage (fast but near term erosion concerns)

Deep tillage of high P Delmarva soil (2017)

Drawing down reserves of phosphorus from soils, also called "legacy phosphorus", can be achieved by harvesting crops without additional fertilizer application. This process can take years, even decades if large reserves of soil P are present. The graph above summarizes studies that have investigated this process. The red lines are drawn from different soils in the same field study. The smooth curves are drawn from literature sources. The use of tillage to draw susoil to the surface dilutes legacy P and adds more sorption capacity.

Both P content and overland flow are difficult to predict and require detailed information on soil characteristics and topography. Extensive research is being conducted in these areas (P content and overland flow runoff prediction). Targeted strategies for stabilization of P-enriched sediment, including phyto-mitigation (slow) or mixing/tillage (fast, but with near-term erosion concerns), could mitigate this P delivery.

P-enriched soils can also be mobilized during conversion of agricultural watersheds to urban watersheds. Headward erosion of streams by urban runoff can and has mobilized sediment, some of which may be high in P. As discussed in a previous section, sediment mobilized by headward erosion in urban areas can also be stored within higher order systems.

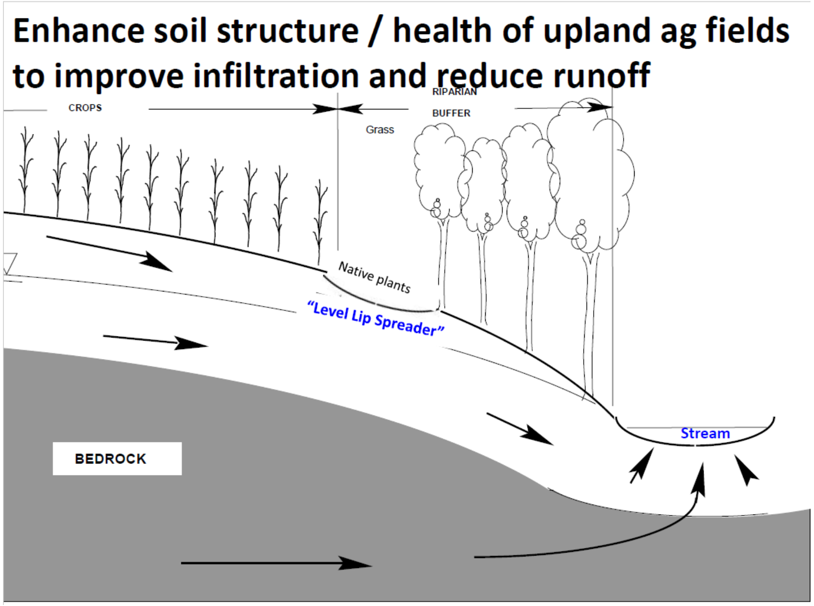
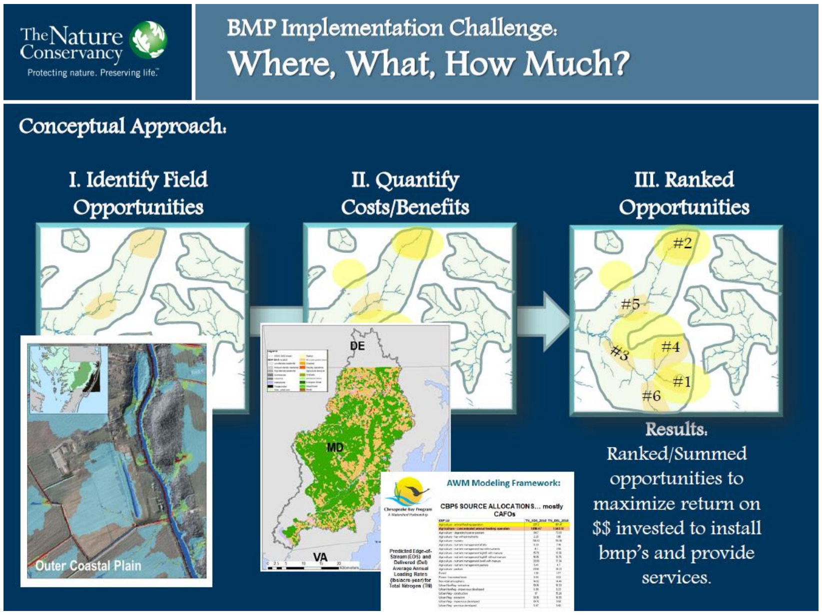


Illustration of flowpaths in an agricultural landscape with riparian forest buffer and engineered swale vegetated with native plants to intercept nutrient-rich runoff.

Bern Sweeney presented work on riparian buffer strips and other techniques (e.g., "level lip spreader" and continuous cover cropping) for reducing nitrogen delivery to streams. These techniques appear to be effective at the field scale in small watersheds - although there was some discussion and debate as to whether other studies indicated similar effectiveness of buffer strips for higher order streams. To be effective, these data synthesis studies will likely require detailed information about stream morphology, soil permeability, and buffer strip characteristics (vegetation type, width, etc.) to tease out the important variables at different watershed scales. Riparian buffer strips can reduce nitrogen concentrations in groundwater through uptake, denitrification, and through development of dilution barriers due to higher infiltration rates in riparian zones compared to adjacent agricultural fields. Many riparian zones have multiple effective processes for reduction of nitrogen delivery, but these have been teased apart in relatively few studies and we do not yet have a robust understanding of these processes that can be applied to widespread prediction of effectiveness.

The effectiveness of nutrient management practices at larger watershed scales is less well understood due to the complexities of the N and P cycles and the complexities of sediment transport and storage. Kathy Boomer's presentation highlighted the importance of identifying appropriate BMP opportunities as a function of location (including physiographic province, location in drainage network, dominant processes for nutrient retention or mobilization) and climate conditions. For example, climate conditions influence perennial stream length and portion of stream network functioning primarily as conduits of storm flow. Differences occur between physiographic provinces and in relation to local slope gradients and landscape features (e.g. steeper and better-drained, riparian, floodplain, incised) that affect surface and subsurface flow paths, connectivity between groundwater and surface water, greater or lesser permeability, hydroperiod and spatial pattern of perennially wet vs drier portions of the landscape, all of which affect potential for landscape elements to serve as natural filters and to promote retention of nutrients and sediments.

Boomer illustrated how the use of geospatial analysis tools coupled with high-resolution databases on landscape characteristics and on costs and benefits of different BMP options can enhance the effectiveness of BMP siting. High resolution remote sensing is one tool that can help to identify increased hydrologic connectivity and small-scale management practices degrading or enhancing regional water resources. Her approach (see figure, above) includes several discrete steps: identifying field opportunities, quantifying costs and benefits, and ranking of opportunities to maximize return on investment and provide environmental services. Ranking of opportunities allows optimal return on investments in terms of net benefits, including prediction of cumulative progress toward TMDL goals such as nitrogen retention.


BMP Implementation Challenge:
Where, What, How Much?

Conceptual Approach:

I. Identify Field Opportunities

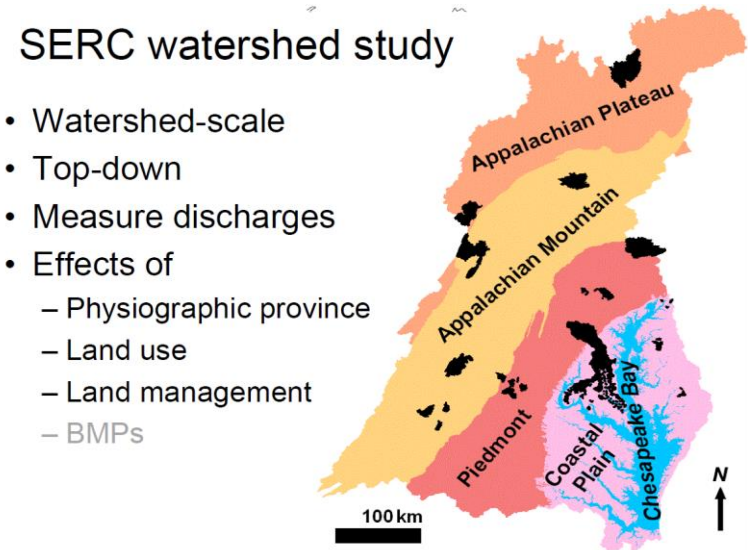
II. Quantify Costs/Benefits

III. Ranked Opportunities

Results:
Ranked/Summed opportunities to maximize return on $$ invested to install bmp's and provide services.

Sequence of steps utilizing high-resolution mapping to prioritize and rank sites for potential BMP installation based on comparison of costs and benefits.

[Don Weller's presentation](#) highlighted the complexities of predicting watershed sediment and nutrient discharge owing to spatial heterogeneity and temporal variability, including large events as major drivers. He noted that it is difficult to evaluate cumulative impacts: not enough is known about relative importance of different sources and transport processes. He also stratified his sample of watersheds by physiographic province, land use, and land management. Nitrogen concentration was strongly related to cropland percentage and to base flow index; this was not a strong relationship for sediment and phosphorus, with phosphorus the most difficult to predict. Chesapeake Bay SPARROW models predicted nitrogen flux and yield well, phosphorus a bit less well, and sediment with the lowest reliability. Hillslope erosion was a poor predictor of phosphorus load and other processes were identified as needing


SERC watershed study

- Watershed-scale
- Top-down
- Measure discharges
- Effects of
  - Physiographic province
  - Land use
  - Land management
  - BMPs

Mapped distribution of Smithsonian Environmental Research Center (SERC) study watersheds within the Chesapeake Bay watershed.

further study, including gully erosion, seepage erosion, stream bank erosion, in-stream erosion and deposition, and floodplain deposition. Targeting source-stream connections in planning buffers was one strong recommendation.

With detailed information, the sources of high P sediment can be identified, but the fate of sediment high in P eroded from agricultural fields is not well understood. Studies of sediment delivery ratios suggest that significant amounts of sediment eroded from small watersheds will be deposited within stream-floodplain systems. This nutrient-enriched sediment could be widely-distributed in floodplains and wetlands, which is suggested by the research of Noe and others. Under reducing conditions, some of this sediment-attached P can become mobilized as aqueous phases and delivered to streams by overland flow or groundwater flow. P mobilized under reducing conditions can be attached to low-P sediment during mixing of water sources at high flows. Nitrogen reduction at larger watershed scales often moves from riparian buffers as a management technique to the use of riparian and other wetlands to enhance denitrification.

The synthesizer team for B2, and audience members, emphasized the following key points.

Effectiveness of nutrient retention practices – the watershed perspective:

1. N and P concentrations are high in agricultural soils, therefore regardless of what we do about legacy sediments it is necessary to keep these materials on or close to the sources.
2. Existing techniques can help keep N and P near their sources (techniques include cover crops, swales, riparian zones), but some continues to leak downstream.
3. P and sediment are mobilized by surface runoff processes in headwater watersheds. Sites of high runoff may or may not correlate with high concentrations of P in soils.
4. Stored soils and P may become sources of P, particularly under reducing conditions.
5. Nitrate in groundwater that traverses high carbon and reducing conditions may be denitrified.
6. Stored legacy sediments may have low N and P if they were deposited prior to the 1950's.

Prediction and targeting of nutrient concentrations

1. We know about erosion and deposition processes of sediment from upland fields and within river corridors. We still know relatively little about how these processes translate into sediment discharges from watersheds.
2. Watersheds are complex with high spatio-temporal heterogeneity. Simulation models may assume scaling of processes but we need statistical models to test discharge to the Bay.
3. Efforts to predict sediment discharges as concentrations from field scale models are very poor. Estimates of loads over longer time scales are pretty variable too. Performance suggests most models do not capture dominant source, transport or delivery processes.
4. Predictive models of N are much better than for P and models including buffers have quantified their impact across broad watersheds, but it has been difficult to show effectiveness of installed BMPs at watershed scale.
5. Targeting sources of N and P and their access to streams is likely required across watersheds.

6. There are new sources of N and P in urban areas (e.g. sewer leaks, waste water, fertilizer, atmospheric deposition, and septic systems).Urban construction and post-construction urban runoff mobilizes sediment resulting in the formation of modern sediment deposits, some of which have high N and P.

Theme C: Management, Policy, and Decision-making

Panelists – *Kevin Smith (Maryland Department of Natural Resources), Stu Schwartz (UMBC Center for Urban Environmental Research and Education), Erik Michelsen (Anne Arundel County Dept. of Public Works), Gary Shenk (USGS/CBPO), Ryan Cole (MD State Highway Administration), Denise Clearwater (Maryland Department of the Environment)*

Synthesizers – *Ann Swanson (Chesapeake Bay Commission), Lisa Wainger (University of Maryland Center for Environmental Science), Dave Goerman (PA Department of Environmental Protection*

Questions:

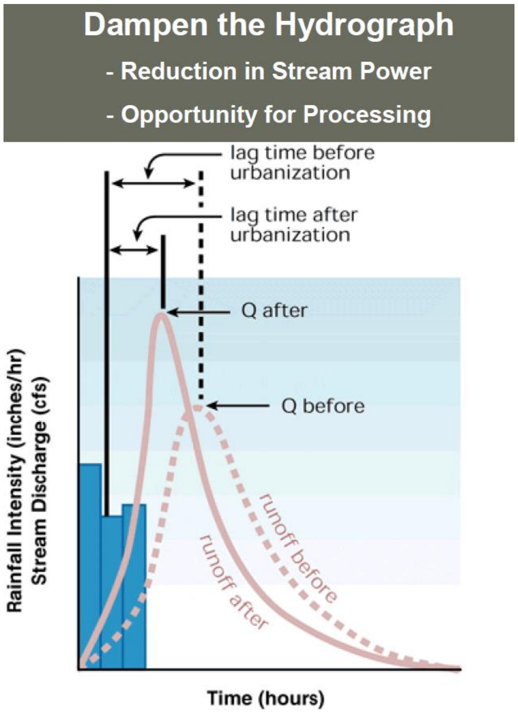
- How do we decide on the appropriate combination of controls from Theme B (both in design and number) to reduce impacts on Chesapeake Bay?
- What are costs and constraints that influence ability to implement practices?
- What additional information do managers need to inform their choices?

Kevin Smith's presentation cited the "top 5" scientific papers that he saw as providing important guidance for understanding what we need to know in order to make sound decisions.

1. The first of these was Brush (2008). This paper provides information on the characteristics of the presettlement ecosystem, which was described as a beaver-dominated landscape with low sedimentation rates and dominance of wetland species among non-arboreal plants (at least in lowland environments.) Although we often discuss the goals of restoration and the question of whether it is realistic to think about "going back" to pre-settlement conditions, it might be worthwhile to see whether we can mimic some of these functions to attain good water quality and high-quality habitat.
2. The next paper cited was Craig et al. (2008). Key takeaway points were the need to increase carbon availability in the flow path, slow down water velocity in order to increase contact time with substrates, increase topographic complexity and maximize the ratio of surface area to volume, increase connection between the stream and adjacent floodplains, and enhance hyporheic exchange.
3. In the third paper (Merritts et al. 2011), observations identified as significant are among those discussed during much of this workshop and include the ubiquitous presence of mill dams throughout the mid-Atlantic region and the Chesapeake Bay watershed, the history of accelerated sedimentation rates coincident with post-settlement land use changes, and the

finding that dam breaches commonly lead to channel incision, bank erosion and increased suspended sediment loads.

4. The fourth paper, Smith and Wilcock (2015), points out that contemporary upland sediment is a significant contribution to overall sediment supply; supports the importance of storage along the entire length of the flow path; and makes the case that it is difficult to demonstrate that any one type of investment will achieve the desired result.
5. The importance of the sediment fingerprinting approach in quantifying sources of sediment load carried during storm flows was highlighted in the fifth paper by Sloto, Gellis and Galeone (2012); agriculture was the source of 53% of sediment for 10 storms sampled whereas stream banks contributed 30% of the sediment.



Smith’s fundamental question was, “Where is this sediment coming from and how do we target our efforts?” His answer is that “it depends - but there are answers”. Solutions proposed include improvements in stormwater management, more attention to zero- and first-order streams, planting of cover crops and other agricultural Best Management Practices, stream restoration favoring depositional channels, and dampening of the storm hydrograph and of peak flow to reduce stream power and increase opportunities for processing of nutrients.

A major reason for sediment loss in developed areas is the increased magnitude of runoff peaks, runoff volume, and sediment transport capacity resulting from increased impervious area and efficient storm-drain networks. Effective management of stormwater runoff is an important approach for reduction of sediment and nutrient loads. (Left)

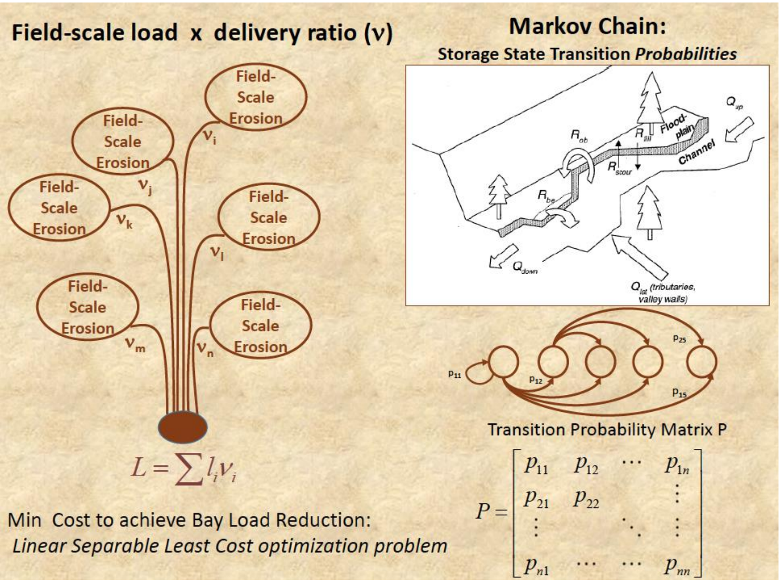
The presentation by Stu Schwartz focused on what advice we need to provide to managers in order to minimize Bay impacts. Much of what we have heard during the workshop was biased to some extent by individual perspectives, but almost all presentations speak to the question of where the sediment is coming from and what we can do about it. Schwartz proposed reframing the question as, “Where is the sediment coming from and what can we do about it *in order to meet the Bay’s sediment TMDL?*” His presentation pointed out that legacy sediment is ubiquitous and not limited to mill dams; storage and mobilization dominates sediment delivery; storage and remobilization time scales are much longer than management time scales; and sediment transport “shreds” environmental signals (e.g., Jerolmack and Paola 2010).

A key question is, what is the source distribution of mean annual load? This cannot be derived simply by multiplying net watershed erosion by a sediment delivery ratio. One approach is to try to understand the distribution of source areas that are contributing to that load. However when we try to understand sources based on looking at the processes that erode the sediment at specific locations, we find that field-scale tools don’t quite work because they don’t account explicitly for the role of storage even if we seek to get around this problem with fixed sediment-delivery ratios. This doesn’t help us target which sources are most important for successful management to meet the TMDL at the watershed mouth.

Examples cited include the use of mercury as a tracer for contaminated sediment along the Shenandoah River near Waynesboro, VA. We might assess the mercury-contaminated sediment as a stable stationary source on the relatively short management time scale, but when considered on a longer time scale we can see that this material is still moving through the system. Mobilization of this material from storage may require exceedance of transport thresholds, and once thresholds are exceeded and large amounts of material are put in motion from a variety of locations it becomes very difficult to track the resulting sediment load back upstream at the scale of a large watershed – hence the “shredding” of the environmental signal (Jerolmack and Paola 2010) that could otherwise tell us what are the most important sources.

Another example was cited from the Monocacy River at the Jug Bridge gaging site near Frederick, MD. Annual sediment loads of the order of 300 tons/mi^2 are the outcome of a storage cascade processing sediment production of 1700 tons/mi^2 in the Monocacy corridor. We see transitions over time in the balance between sediment production (supply) and sediment transport (capacity) and we can’t necessarily predict the flux out of the watershed in any given year based on the sediment production rate.

One suggestion is the application of Markov Chain models. A Markov Chain formalizes the idea that when sediment is mobilized, it is distributed in a probabilistic fashion as it moves downstream. We can use estimated probabilities of storage transitions from one “compartment” to another. These in turn can be incorporated in a transition probability matrix with an optimization scheme to find the minimum-cost approach for reduction in sediment load to Chesapeake Bay.



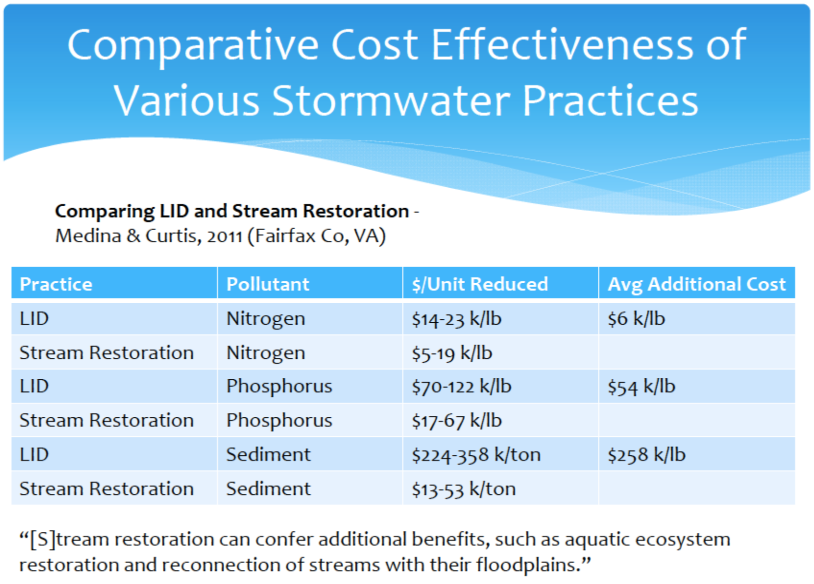
Optimization approach to targeting of watershed sites for mitigation to achieve Bay load reduction targets at minimum cost.

Even if we can achieve an optimal solution for upstream sources, however, there is another major source of uncertainty in the “hungry water” problem. An example involves the large-scale storage of sediment along the lower Susquehanna River floodplain and in the main channel of the river as a result of historical anthracite mining upstream (average of 3 ft floodplain aggradation with average channel width reduced by 40 ft; Lintner 1983) and the addition of 787 acres of land to the state of Maryland (Gottschalk 1945) and storage of about 120 million tons of stored sediment to Susquehanna Flats during the period of intensive erosive land use prior to the construction of Conowingo Dam. This mass of material reduced mean depth at low tide by over 2.5 ft. over an area of 30 mi^2 and represents a larger volume than total storage behind Conowingo Dam. All of this sediment is still available to be mobilized to the Chesapeake Bay. Suppose we could dredge Conowingo Dam and create sediment-free flow, or alternatively that we could cut off much of the supply from upstream; would this reduce sediment loads, or would the resulting "hungry water" simply scour existing available legacy sediment in these exposed locations to replace the sediment no longer being transported from upstream? We don't know enough about these probabilities at the present time to fit them into a Markov Chain model. The challenge is that the decisions we make today will echo through time on decade to century scales just as we are today trying to respond to the legacy of past decisions. Regardless of what we do, we have to anticipate slow watershed-scale response times, long system memory, and potential surprises due to the availability of a large reservoir of stored sediment that might augment supply if upstream sources are reduced.

The presentation by Erik Michelsen explored perspectives on stream and wetland restoration in a large county located entirely within the Coastal Plain through the lens of Municipal Separate Storm Sewer System (MS4) permit compliance and the Chesapeake Bay TMDL requirement. MS4 permits are issued for a five year cycle and a new permit is issued at the end of each cycle for the next 5 years. In each cycle there is a requirement that BMPs treat an additional 20% of untreated impervious area within the jurisdiction. This has a cumulative cost of $250 million over 5 years. Reductions in N, P and sediment to meet the Chesapeake Bay TMDL require stormwater restoration costs of about $900 million. Over a longer period of time the cost to the county is measured in many billions of dollars. Wastewater treatment plants are being upgraded to the limits of technology and there are also about 42,000 septic systems that need to be dealt with. Almost all county waterways discharge to tidal systems that are direct tributaries to Chesapeake Bay. In light of all the money that county taxpayers are committed to, questions about potentially long time scales before results might be seen are concerning, especially given the impression of managers that the science had been settled many years ago.

We know there is a long-term history of change. The 1968 Governor's Conference report cites information on colonial-era siltation of tidewater ports (derived originally from Gottschalk 1945). Yet Little (1917) reported that some of the larger rivers in Anne Arundel County had no marshes of large extent, unlike what is seen in the area now; and Browne (1985) reported that local farmers were able to ship tobacco to port from the North River even long after the colonial period. Some accounts do suggest that marshes have filled in since the mid-1850's. Marshes had filled in ~9% of the North River estuary present above Riva Bridge in 1846 by 1991 (Marcus and Kearney 1991). Now there are tidal areas exposed to low dissolved oxygen and this fuels algal blooms in tidal waterways. Michelsen inferred that some of the marsh growth occurred at locations where sediment supplied to tidewater was derived from legacy sediments released by breaching of mill dams whose remnants are visible in LiDAR images of upstream tributaries. Historical sedimentation patterns in tidewater areas documented by Hilgartner and Brush (2006) in a Harford County wetland system show a very stable open-water configuration with limited marsh for a long time, followed by rapid encroachment of deposition features that are now covered by riparian forest with marsh and delta deposits extending into the waterway.

The "broken" stream systems function as major sources and conveyors of sediment and phosphorus into tidal waterways, with maximum distance from divide to tidewater of just a few miles. Suburban watersheds have rapidly eroding stream banks, as do some of the rural watersheds. The sediment and nutrient TMDLs guide management practices and are driven by BMP efficiencies set by the states though these often lag behind the science. Impervious cover is an important driver.



Comparative Cost Effectiveness of Various Stormwater Practices

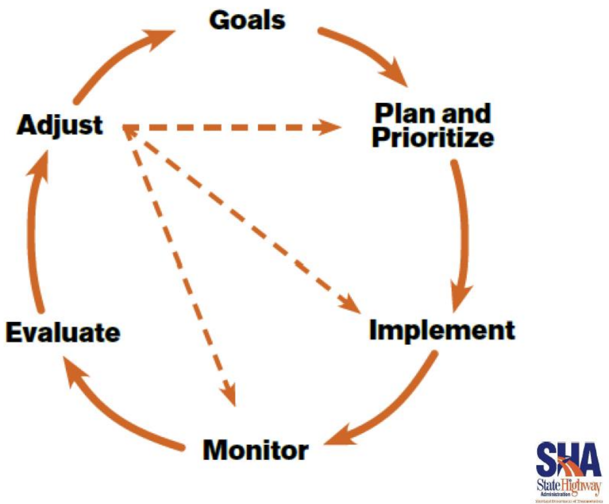
Comparing LID and Stream Restoration - Medina & Curtis, 2011 (Fairfax Co, VA)

Practice	Pollutant	$/Unit Reduced	Avg Additional Cost
LID	Nitrogen	$14-23 k/lb	$6 k/lb
Stream Restoration	Nitrogen	$5-19 k/lb	
LID	Phosphorus	$70-122 k/lb	$54 k/lb
Stream Restoration	Phosphorus	$17-67 k/lb	
LID	Sediment	$224-358 k/ton	$258 k/lb
Stream Restoration	Sediment	$13-53 k/ton	

"[S]tream restoration can confer additional benefits, such as aquatic ecosystem restoration and reconnection of streams with their floodplains."

In comparing cost-effectiveness of Low-Impact Development (LID) stormwater practices with stream restoration, costs per pound of sediment or phosphorus reduction from stream restoration practices are just a fraction of the cost per pound for LID practices, and costs for nitrogen are comparable or slightly lower even though restoration is more expensive on a project basis. Unit costs of stream restoration per acre of impervious surface are lower in Maryland counties than LID, stormwater ponds, or bioretention retrofits. However there are other considerations related to new research coming out that references the percent of sediment yield and nitrogen coming from different sources. Groundwater sources of nitrate, particularly leaking sanitary sewers at baseflow, pose a challenge that is difficult to tackle.

However, there are opportunities for cooperation between agencies for cost share and better overall outcomes, and in some projects managers find that if they stabilize the system properly they may set the stage for natural processes of recovery, including colonization by beavers.



Flow chart for developing control measures and restoration plans to mitigate effects of impervious cover on stormwater and sediment yield.

Ryan Cole of the Maryland State Highway Administration (SHA) began his presentation by pointing out that the SHA Chesapeake Bay Restoration Program has much in common with the program described by Erik Michelson. Steps in their process include setting of goals, planning and prioritization, implementation, monitoring, evaluation of results, and adjustment to what is learned. SHA is in a permit cycle right now that began in 2015 and is looking for a combination of control measures. They are looking for scientists to help inform the program to set up these controls. The agency has a balanced approach to stormwater management, stream restoration, tree planting and (hopefully) living shorelines. Accomplishing all of this on a 5-year cycle is very difficult.

SHA carries out a desktop assessment and GIS analysis for each project before going out to the field to rate a site. The protocol includes utilities, adjacent land use, floodplain use and construction analysis. Landowner permission is often the limiting factor; success rate with approaching a landowner and completing a project is about 10-20% and slows down the process greatly. Another constraint: SHA has responsibility for 11 counties across the entire state. They believe they have projects in a variety of places that are good, including places outside of counties with MS4 permits. But figuring out where to focus attention is a challenge. The approach now is to maximize stormwater treatment of impervious areas, plant trees where SWM is not possible, carry out stream restoration near roads where possible and move offsite when necessary for additional stream restoration projects.

However, information is needed to answer questions such as:

- Where, when, and how do we put in projects?
- Do we do SWM first and stream restoration later? Do we do it all together?
- How do we handle potential lag times?
- What about local benefits vs benefits to the Bay?
- What restoration types are appropriate and is that another physiographic region consideration? Should we work elsewhere or focus closer to the Bay?

The presentation by Denise Clearwater summarized the elements of MDE’s Wetlands and Waterways Program (WWP) in reference to restoration practices. The WWP program implements three main statutes and regulations:

- Changes to course, current and cross sections in nontidal waters and floodplains (1933, primarily engineering and safety based)
- Tidal wetlands (1970)
- Nontidal wetlands (1989, first implementation in 1991)

If you are designing a restoration project you probably need an authorization based on one of these statutes. In evaluating applications, MDE talks about water quality, water quantity, habitat/other natural resource values, economic considerations, public need, recreational use, scenic/aesthetic resources, marine commerce, navigation, loss of life or high value property, increased risk of flooding, safety, danger from natural hazards, cultural resources, and public comment. For legacy sediment removal and stream restoration in general, the following issues arise: Potential of increased flooding on adjacent property, loss of trees due to construction, loss of existing resource benefits, and disposal of removed material.

The local flood insurance program must agree to manage and maintain all activities in floodplains. Applicants must notify FEMA and the local community of changes and receive approval; failure to do this may result in local community suspension from the FEMA flood insurance program and may not qualify for federal disaster aid. Consider what would happen in Ellicott City, MD site of devastating floods over many years, if participation were suspended.

The Wetlands and Waterways Program is not opposed to legacy sediment removal, but hopes they are designed and implemented in appropriate areas. Projects are authorized mostly in agricultural or open areas to avoid concern about loss of tree and other resources. To address issues of adjacent flooding, applicants conduct Hydrology & Hydraulics analysis; purchase land or easements or obtain signed statement of agreement from affected property owners; re-design as needed; and notify FEMA and the local community before receiving approval.

Some sediment should be transported as part of the natural functioning of the system. Too much accumulation may render designs ineffective; too little sediment transported could result in more degradation from headcuts and degradation to tidal wetlands.

Some general guidelines to minimize impacts on Chesapeake Bay include:

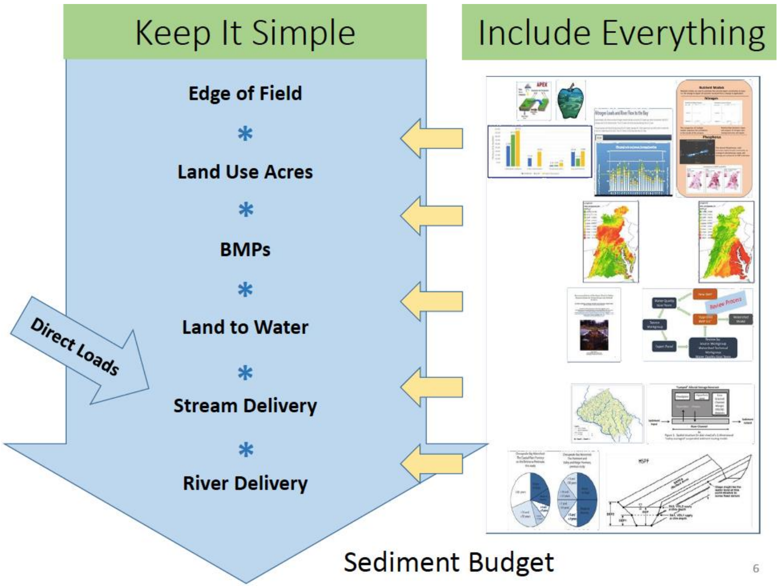
- Do not force a preferred BMP/design on every site. Often practitioners have selective expertise.
- Select the practice and the extent of the project based on the condition of the reach and causes of degradation. Install practices close to the source of the problem where practicable. Consider additional goals for stream health, riparian buffers and wetlands in addition to modeled credit reductions; pursue crediting for ecological benefits, whether existing or restored.
- Costs and constraints that influence ability to implement practices include other relevant regulatory requirements, remaining function benefits or values at the restoration site, improper design for the site, and potential increase in flood risk. Additional information that managers need to inform their choices includes understanding of regulatory requirements, early consultation with regulatory agencies, and assessment of existing resource conditions and reasons for degradation.

Gary Shenk spoke about sediment simulation in the Chesapeake Bay watershed model. The model is used to assess sediment and nutrient loads for different Bay tributaries based on current and prospective scenarios, and these in turn inform the limits under the Bay TMDL requirements. The TMDL was necessitated by failure to meet water quality standards for dissolved oxygen, water clarity and chlorophyll, and it sets limits on N, P, and sediment.

We know how to model water well, we can model nitrogen well, we can model phosphorus reasonably well, and we model sediment not as well owing to a number of difficult technical challenges (many already discussed in this workshop). N and P are the most critical Baywide; and the TMDL was set up so that if you met your expectation for P for implementation at the state and basin level, you would also meet the sediment load requirement.

The timeline for the TMDL includes a 1999 lawsuit by the American Canoe Association and the American Littoral Society; the formal implementation of the TMDL in 2010; the 2017 Midpoint Assessment requiring that 60% of the management practices should be implemented, models should be improved, and any mid-course corrections identified. The TMDL is supposed to meet its goal by 2025 with 100% of the management practices implemented. By that date there should also be another upgrade of the modeling suite.

The Phase 6 Watershed Model was formally adopted in December 2017[3]. Modification of the model was carried out with input from the Bay partnership and included the following:



Structure of the time-averaged version of the Phase 6 Chesapeake Watershed Model

The Water Quality Goal Implementation Team (WQGIT) requested that the model should be more transparent and easier to understand by local partners to ensure successful engagement. On the other hand, the Scientific and Technical Advisory Committee (STAC) requested the use of multiple models, simulation of complex reservoir dynamics, and simulation of fine-scale processes; in other words, include everything. This led to a Phase 6 model structure that employs a simple approach using multiplicative factors in the way it is designed and explained, but informed by components that incorporate more complex and finer-scale process representation. It is important to remember that this is not a research model but a management model. The time-averaged model employs steady-state assumptions with the following formula:

> Edge of field * land use acres * BMPs * land to water * stream delivery (w/ direct loads) * River delivery factor

where “stream delivery” and “river delivery” are separated by scale. The “include everything” part is that each of the values in this multiplicative formula is the product of many different models or analyses rather than just one single model, all put together to generate those coefficients. An example was illustrated to show how the Chesapeake watershed K factor (relative susceptibility of soil to sheet and rill erosion in the Revised Universal Soil Loss Equation, RUSLE2) and connectivity metric were derived from analysis at 10-m resolution over the entire watershed. The stream delivery component of the model includes delivery from field to stream with modification by exchange with either stream banks or the floodplain.

Some elements involved in calculation of these exchanges were summarized in the presentation by Greg Noe as part of panel A1. Others use the USGS SPARROW model. Stream restoration credits are incorporated in the model using one of four protocols (prevented sediment; nutrient processing; floodplain reconnection; dry channel regenerative stormwater conveyance (RSC)) or default values in

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[3] All documentation and supporting materials in reference to the Phase 6 Watershed Model is accessible at: https://www.chesapeakebay.net/who/group/water_quality_goal_implementation_team

pounds per linear foot for sediment, nitrogen and phosphorus. Up to this point 100% of permits have used the default values and none have used the protocols.

At the time of the workshop the model was in the process of undergoing review by STAC[4]. STAC's recommendation was that new model structures should be created that account for the variety of potential sediment sources in the watershed and the wide distribution of timescales for sediment delivery. A coordinated modeling and field data collection program will be needed to support such an effort to really capture the distribution of sources and timescales and this will require new research funding. There are research models and accounting models; what we have here is an accounting model and we have a ways to go as a community of researchers, research modelers, and accounting modelers in order to get to the point where we really would like to be.[5]

In evaluating the effects of sediment on the Bay, we recognize that coarse sediments are needed for establishment of wetlands, whereas fine sediments block light for aquatic vegetation. There are different transport mechanisms for fine and coarse sediment and these need to be separated from the standpoint of management.

The synthesizer team for theme C, speaking individually, emphasized the following key points.

Ann Swanson, Chesapeake Bay Commission: We listened from the lens of a policymaker looking for something definitive we could change into an actionable item. We listened from three very different perspectives.

1. The title of this workshop report should be "It Depends." We heard that legacy sediment sources are ubiquitous and that we need a common definition of what the term means.
2. There is high spatial heterogeneity and temporal variability for deposition and erosion and these matter deeply, and therefore the more uniform approaches we can take with N and P are very different and the sediment world is very different.
3. Bank erosion as a source is a far bigger deal than previously calculated and this will change the way the bay program assigns values.

Actionable items:

1. We need monitoring both before and after projects or we proceed in ignorance. We understand the costs but not the stackable benefits. Ecosystem services may be one of our most compelling arguments.
2. We need to separate knowledge of sources from knowledge of storage.
3. We are not separating, to the degree necessary, the difference between coarse and fine sediments.

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[4] STAC's Review of the Phase 6 Chesapeake Bay Watershed Model is accessible at: http://www.chesapeake.org/pubs/379_Easton2017.pdf

[5] The STAC-sponsored visioning workshop held in January 2018 on the future of the Chesapeake Bay modeling framework recommended the formation of a working group to provide recommendations for the next generation of sediment modeling. http://www.chesapeake.org/stac/workshop.php?activity_id=278

4. We need to improve our data sets for decision making and we are mapping with NHD but not with the first- and second-order drainage network scale where we should be.
5. Location matters in terms of sediment. There will be local effects for local reasons and it is not just about N, P and sediment – one must also consider impervious surface. One needs to identify local benefits along with the costs. Fine vs coarse comes up again and again when you start to have these conversations.
6. We need to improve regulations that distinguish between development and restoration projects. One is disturbance with a purpose and one is disturbance without. We need to favor regulations that install practices closer to the source of the problem and approaches that dampen the hydrograph or slow the water down.

Target

1. Using LIDAR differencing to identify storage locations sounds very useful, but we have to track back to the sources and hot spots and develop compelling communication tools to convey the importance to private landowners.
2. We need incentives for landowners if we want to convince them to allow a treatment on their property and packages that provide financial incentives for landowners making choices we want them to make for the greater good of water.

<u>Lisa Wainger, STAC Chair [in April 2017] and University of Maryland Center for Environmental Science</u>:

1. We need metrics to judge a full suite of net benefits and tradeoffs, including environmental uplift, key tradeoffs, echoes through time of decisions made today (short and long term), and capacity to achieve total goal (TMDL cap) – i.e., are there enough places to implement a particular practice on the landscape?
2. We should be optimizing from the perspective of the Bay TMDL, but also keep in mind local TMDLs and other goals (e.g., habitat, flooding aesthetics)
3. Human loss aversion and concerns create constraints; considerations include the need to avoid, minimize, mitigate or “first do no harm,” and to evaluate risk-weighted benefits (e.g., beaver habitat)
4. We need to promote flexibility and creativity through measures such as those listed here:
    a. Keep flexibility in the policy system, policy goals are currently ahead of the science and when the science comes up with new results it can surprise managers (i.e. “we thought the science was settled, now you’re telling us it’s not”)
    b. There are likely to be different solutions that are effective in different places
    c. Cost-effective sediment controls might come from completely different practices than we are currently envisioning; for example, instream vs out of stream efforts
    d. Different knowledge is needed for the Chesapeake Bay Watershed accounting model vs. developing site-specific recipes. We need to consider whether initial simple conceptual models can be used without creating biased decisions. We need also to recognize that coarse and fine sediments may be moved under different conditions that need to be recognized and managed separately

5. BMP-site cost effectiveness results need to be considered – one can plot cost vs. net removal. An example would be development of a marginal cost curve for total nitrogen in the Susquehanna Basin – for every pound how does the cumulative cost increase for different kinds of sources (e.g. agricultural, urban, point sources)?
6. Use ecosystem services values to compare implementation options and ability to meet the total cap considering least cost vs maximized benefits.

Conclusions

1. Economic analysis and decision support tools can be used to assess benefits and tradeoffs of different policies
2. New research can support policy by improving understanding of cost-effectiveness of BMP/site combinations and total capacity to meet goals
3. Different information is needed for the accounting model vs. the demonstration or the research model

Dave Goerman – Pennsylvania Department of Environmental Protection

1. The regulatory process needs adapted restoration permitting and TMDL allocation; the current process seems rigid in approach and not as adaptive as it might be. In allocating loads we should acknowledge that legacy contributions are not sector driven. We are looking for ways to incentivize and account for the benefits associated with ecosystem benefits from legacy sediment removal projects.
2. Remove traditional silo approaches and allow crediting across regulatory frameworks including compensatory mitigation, stormwater, water quality, etc.
3. The level of funding that will be needed to deal with the problem is astounding – given the uncertainty in the science this makes the problem even more concerning.
4. Better communicate complexity of problem and time scales. This requires dedicated third party funding for basic research as well as applied research. It also requires better-coordinated research efforts across disciplines and jurisdictions (otherwise policymakers may cherry-pick research results to justify what they already want to do)
5. Change the point of measuring progress from watershed outlet to more local scales – for sediment you cannot measure progress toward success at the bottom end.

We have to be able to sit on a witness stand in front of a judge and defend decision-making; the public expects science to provide simple and easy solutions to problems, but they may take a long time and take generations to accomplish.

Summary of Findings

Physical Characteristics and Implications of Legacy Sediment Deposits

Legacy sediment definition and distribution: For the purposes of the Bay management effort, legacy sediment is defined as sediment stored in upland and lowland portions of the Bay watershed as a byproduct of accelerated erosion caused by landscape disturbance following European settlement. Legacy sediments exist throughout the region but are most recognized in the Piedmont and Coastal Plain provinces. Much sediment eroded during this historical period is still stored on footslopes, but the most visible legacy sediments are those stored on valley floors and exposed in stream banks. Greater thicknesses of legacy sediment are observed upstream of sites where thousands of historical mill dams were or are still located.

The distribution of legacy sediments varies within a river system. Between 60 and 80% of the total drainage network length is composed of low-order channels, and most legacy sediment exposed in stream banks is stored along these headwater tributaries.

Valley-bottom legacy deposits are commonly fine-grained sediments (<sand size) that can be efficiently delivered to streams through channel incision and bank erosion, and transported primarily as suspended load. Nutrient concentrations (P and bioavailable N) in legacy deposits vary with valley location. Because historical deposits pre-date the post-WWII period of intensive application of chemical fertilizers and concentrated animal feeding operations, expected nutrient concentrations would normally be lower than those at sites affected by these activities.

Erosion potential of valley legacy deposits is considered highest where dams are intact or have recently been breached. Some studies show very high rates of sediment evacuation during initial decades after breaching, with potential to trigger incision propagating upstream for decades. Large numbers of intact dams, especially in Pennsylvania, are regarded as potential sediment source hotspots; but mill dams that were partially breached 50 or more years ago often exhibit slow long-term channel migration and erosion (≤ two or three channel widths).

Relative contributions to watershed sediment yield: There is spatial and temporal heterogeneity in relative contributions of different sources to watershed sediment yield, residence times of stored sediment, and lag times for delivery to tidewater. Some workshop presentations indicated that sediment yields (sediment load per unit drainage area, e.g. tons/km^2/year) from slopewash, gullies and stream channels at low-order headwater sites are much greater than those from higher-order drainages. Others found that bank erosion is a dominant source and that fine-grained sediment from bank erosion at downstream locations would likely reach tidewater more quickly than from upstream sources.

Sediment storage is a large component of most sediment budgets, but sites vary among watersheds due to their geomorphic characteristics; some have substantial storage potential downstream of valley legacy sediment erosion sites whereas others do not (e.g., tributaries to the Lower Susquehanna). Although valley legacy sediment deposits are regarded by some researchers as net sources, valley-floor deposition of sediment is still active even at some sites underlain by legacy sediment. Where storage is active, a large fraction of sediment in transport may be trapped on valley floors in downstream portions of the watershed. Sediment trapping close to the head of tide as rivers approach the estuary is also an important storage mechanism that limits the fraction of watershed-derived suspended sediment reaching the Bay proper, thus limiting siltation and burial of tidal wetlands.

Investigations of sediment transport also reveal heterogeneity among watersheds. One set of studies suggested that even fine particles typically do not move more than about 10 km before being deposited, with median storage times of ~100 years and potential lag times of centuries to millennia for delivery to tidewater. Nonetheless, the well-known "Wolman diagram," depicting early 20th-century decreases in sediment yield, was in part based on measured changes in reservoir sedimentation rates driven by changing upstream land cover and land use. Observations of ~50% reduction in sediment yield on the lower Susquehanna River at Marietta between the periods 1941-1950 and 1991-2012 have been attributed to reduction of mining activity, farm abandonment, and new sediment controls.

The implication of all of these findings is that no one set of assumptions about all of the processes described above can be applied universally across the Chesapeake Bay watershed.

Mitigation strategies and management issues

An important theme that emerged from the workshop is that, just as no one set of assumptions about dominant processes can be applied universally, no one mitigation strategy is universally applicable across the entire Bay watershed and site-specific approaches are needed. This is true both for legacy sediment and for other sediment sources.

Legacy sediment removal: Practices involving removal of valley-bottom legacy sediment may improve local ecosystem services through reconnection of surface and subsurface hydrologic systems, increased base flow, restoration of wetland complexes to encourage biodiversity, or retention of nutrients and sediment. These might reduce downstream fluxes to tidewater depending on location and geomorphic setting. Ongoing projects show promising local results, but there is not yet a large enough number of studies to quantify long-term engineering reliability or benefits across the Chesapeake Bay watershed.

Other mitigation practices: Regardless of issues related to legacy sediment in valley bottoms, N and P concentrations are high in modern agricultural soils and and in sediment eroded from those soils. Phosphorus derived from modern upland sources can become sorbed to fine-grained sediment, including legacy sediment, during transport. Keeping existing topsoil in place remains critically important. Mitigation techniques considered to be potentially effective include cover crops, engineered swales, and forested riparian buffers, and these are essential components of any management strategy. In developed watersheds, effective stormwater management is essential to controlling loads and reducing fluxes from both upland and valley sources.

General observations from managers: Managers operate in a complex environment with a web of regulatory requirements and budget constraints, local vs watershed-scale concerns, and uncertainty about what combination of choices will be most effective. They want information about relative merits of different options (e.g. stormwater management vs stream restoration, coarse vs fine sediment), where to target projects within and among watersheds, variations in effectiveness by location, and expected lag times before benefits appear. Other considerations include weighing expected benefits relative to disturbance involved in restoration projects such as loss of trees, existing resources or potential of projects to increase flooding on adjacent properties.

Policy goals should drive new research and provide more flexible, adaptive permitting processes that allow for integration of new scientific results when they become available. Managers described a need to allow crediting across regulatory frameworks, where warranted, including compensatory mitigation, stormwater, water quality, etc. Economic analysis and new decision support tools (such as use of high-resolution mapping techniques and new modeling approaches) can be used to assess benefits and tradeoffs of different policies. New research can support policy by improving understanding of cost-effectiveness of BMP/site combinations and total capacity to meet goals. Better-designed incentives are needed for landowners so that they will be willing to install or permit installation of BMP practices in order to assure better water-quality outcomes.

Recommendations

Nonpoint source pollution: We recommend a continued primary focus on avoidance, minimization, and mitigation of nonpoint source water quality problems in uplands. Consideration should be given to management of valley legacy sediments where their influence on Bay water quality is determined to be substantial.

Stormwater and riparian vegetation management strategies: New knowledge of legacy sediment deposits does not support fundamental changes to existing policies and investments related to upland stormwater management or to riparian vegetation restoration efforts.

Legacy Sediment Site Evaluation: The varied prevalence and relevance of valley legacy sediment deposits to Chesapeake Bay water quality requires strategic investments in watershed assessment and long-term engineering performance evaluation. Legacy sediment deposits are spatially variable, but research supports adoption of consistent approaches to evaluate locations where legacy sediment management is most likely to mitigate Bay water quality problems.

Water quality outcomes from legacy sediment management activities have been quantified in several locations, but more information is needed to refine water quality load reduction crediting for Bay TMDLs. Protection or enhancement of sediment storage locations needs to be considered as a management strategy rather than focusing solely on erosion. Whereas erosion management may be focused on “hot spots,” storage locations are more widely distributed within watersheds. Design life performance information related to legacy sediment management practices is essential to long term maintenance, cost considerations, water quality load reduction performance, and nonpoint source pollution management decisions.

Comprehensive data collection: Varied legacy sediment deposit conditions, contributions to Bay water quality problems, and management approaches support development of a comprehensive, spatially explicit database of sediment characteristics and nutrient concentrations to guide mitigation decisions.

Site-specific evaluation criteria: Due to watershed heterogeneity, there is no uniform set of TMDL credit values that can be applied throughout the Chesapeake Bay watershed. We recommend that research on restoration at legacy sediment sites be continued and evaluated in order to further develop and refine guidelines for TMDL development. Until such time as there is more complete information to inform decision-making, we recommend the following principles be applied at individual sites where a project plan is being developed. Such estimates should also be applied to other forms of restoration and mitigation where appropriate.

1. Identify current rates of erosion in terms of mass of sediment per year per unit channel length, including estimates of fine-grained fractions, and measure concentrations of N and P from samples representative of the vertical bank profile. These should be used to calculate net mass of N and P contributed annually by bank erosion under existing conditions. Lab analysis techniques should be standardized and specified so data can be compared across sites and across jurisdictions. For sites behind intact dams that might breach in the future, predictions about

sediment and nutrient fluxes should be based on what is known about the range of variation for similar deposits remobilized under different breaching conditions in different watershed settings and the decay rate of sediment remobilization following initial breach of a dam deposit.

2. Each valley legacy sediment site should be evaluated with respect to its location within the watershed drainage network. Given uncertainty about the probability and residence time of intermediate storage as a function of distance upstream, sites with closer functional proximity (e.g., potential for transport, storage, and delivery) to tidewater should be weighted more heavily than sites that are farther from tidewater or that have a lower probability of delivery to tidewater. Additional research should be funded to develop predictive relationships for the typical fractions of sediment, N and P going into intermediate storage or reaching tidewater within some specified time period, and the expected response time needed to detect a net reduction in sources.

3. BMP effectiveness is widely understood to be highly variable across the Bay watershed and measurable improvements at larger watershed scales over short time periods are elusive. Projects should ideally be justified based largely on local water-quality benefits or other management objectives and only secondarily on contributions to meeting Bay TMDL requirements.

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Appendix A – Workshop Agenda

“Legacy” Sediment, Riparian Corridors, and Total Maximum Daily Loads

A Scientific and Technical Advisory Committee (STAC) Workshop

April 24-25, 2017
Workshop Location: Westin Annapolis, 100 Westgate Circle, Annapolis MD 21401
http://www.chesapeake.org/stac/workshop.php?activity_id=276

This STAC workshop will be structured around panel discussions on each of three themes as outlined below, with four-five experts on the panel who will be asked to address specific questions and cite key evidence (~10 minutes per panelist). These will be followed by Q&A and group discussion. Following all panels, individuals designated as “synthesizers” will come up with discussion points to summarize or respond to the panel. Panelists will be asked to prepare notes with reference citations that can be used by the steering committee in preparing the workshop proceedings.

DAY 1:

9:30 – 10:00 am Sign-In and Coffee (provided)
10:00 – 10:30 am Welcome, Introductions, Overview of workshop Objectives and Outcomes – *Andy Miller, UMBC*

Theme A: State of the Science

10:30 – 12:00 pm **A1 Panelists**: *Allan James (University of South Carolina), Sean Smith (University of Maine), Dorothy Merritts (Franklin and Marshall), Greg Noe (USGS)*

- How should legacy sediment be defined in the context of the Chesapeake Bay management effort?
- What is the importance of legacy sediments compared to other sediment sources affecting Bay conditions?
- To what extent do legacy sediments provide an important source of nutrient contributions by comparison with other sources?

12:00 – 12:45 pm Lunch (provided)

12:45 – 2:15 pm **A2 Panelists**: *Jim Pizzuto (University of Delaware), Cliff Hupp (USGS, retired), Allen Gellis (USGS), Karl Wegmann (North Carolina State University)*

- How do the distribution, characteristics and relative magnitude of legacy sediment vary with watershed scale or geographic location?

- To what extent are lag times for sediment delivery and intermediate floodplain storage processes relevant to our assessment of the problem?

2:15 pm Break

<u>Theme B</u>: Mitigation Approaches and Assessment of their Effectiveness

2:30 – 3:45 pm **B1 Panelists**: *Art Parola (Stream Institute, University of Louisville), Solange Filoso (University of Maryland Center for Environmental Science), Drew Altland (RK&K), Tess Thompson (Virginia Tech)*

- What do we know about the engineering reliability and water-quality effectiveness of practices designed to mitigate the potential downstream impacts of legacy sediment at the watershed scale?

3:45 pm Break

4:00 – 5:15 pm **B2 Panelists**: *Don Weller (Smithsonian Environmental Research Center), Bern Sweeney (Stroud Water Research Center), Peter Kleinman (USDA-ARS), Kathy Boomer (The Nature Conservancy)*

- What do we know about the relative effectiveness at the watershed scale of practices designed to retain or prevent mobilization of sediment and associated nutrients from sources other than legacy sediment?

5:30 pm Adjourn Day 1

<u>DAY 2:</u>

8:30 – 9:00 am Light breakfast (provided)
9:00 – 9:30 am Recap Day 1

<u>Theme C</u>: Management, Policy, and Decision-making

9:30 – 12:00 pm **Panelists**: *Kevin Smith (Maryland Department of Natural Resources), Stu Schwartz (UMBC), Erik Michelson (Anne Arundel County Dept. of Public Works), Gary Shenk (USGS/CBPO), Ryan Cole (MD State Highway Administration), Denise Clearwater (Maryland Department of the Environment)*

- How do we decide on the appropriate combination of controls from Theme B (both in design and number) to reduce impacts on Chesapeake Bay?

- What are costs and constraints that influence ability to implement practices?
- What additional information do managers need to inform their choices?

12:00 – 12:45 pm Lunch (provided)

<u>Panel Synthesis</u>

12:45 – 1:30 pm Theme A Panel Response and Discussion –
A1 Synthesizers: *Mike Langland (USGS), Andy Miller (UMBC), Bob Walter (Franklin and Marshall)*
A2 Synthesizers: *John Brakebill (USGS), Katie Skalak (USGS), Dorothy Merritts (Franklin and Marshall)*

1:30 – 2:15 pm Theme B Panel Response and Discussion –
B1 Synthesizers: *Scott Lowe (McCormick Taylor), Mike Trumbauer (Biohabitats, Inc.), Sean Smith (University of Maine), Jeff Hartranft (PA Department of Environmental Protection)*
B2 Synthesizers: *Karen Prestegaard (University of Maryland), Matt Baker (UMBC), Tom Schueler (Center for Stormwater Protection)*

2:15 – 3:00 pm Theme C Panel Response and Discussion –
C Synthesizers: *Ann Swanson (Chesapeake Bay Commission), Lisa Wainger (University of Maryland Center for Environmental Science), Dave Goerman (PA Department of Environmental Protection)*

3:00 – 3:30 pm Concluding Thoughts and Next Steps

3:30 pm Adjourn

Appendix B – Summary of questions and discussion points raised during the workshop

Questions raised in the introductory presentation included the following:

- How do we define and characterize these deposits?
- How much is out there and where is it?
- What kinds of nutrient concentrations are there?
- How much of this material is being removed from storage per year and where is it going?
- How does this amount compare with other (e.g. upland) sources?
- How much is redeposited, how much leaves the watershed per year, and how long does it take to reach Chesapeake Bay?
- Is this a problem for the Bay? If so, what should be done about it?

Points raised in audience discussion after panel presentations and synthesizer presentations included the following:

Theme A: State of the Science

- It was pointed out that when we think about water quality and habitat concerns, there is often a lot of focus on fine sediment (e.g. silt and clay). This led to a question: are we able to constrain our conversation to focus on where fine-grained sediments are generated in the landscape and how they are managed?

- It was suggested that we should not measure bank erosion rates based only on comparison of topographic data sets, especially where rates are slow; this led to the recommendation that we consider the whole suite of possible techniques. Various participants weighed in both on the value of new high-resolution remote-sensing techniques for quantifying geomorphic change, and on the importance of checking these against other approaches, some of which are "low-tech" but highly reliable. Similar statements were made about measurement of sediment flux and storage using different approaches and comparing results.

- There was active discussion of the issue of sediment travel time and residence time in storage and the extent to which it affects the potential for sediment BMPs to affect loads reaching tidewater over the time scale of years to decades. Some of the work on storage probabilities and residence times suggested that even fine-grained sediment is unlikely to travel very far before going into storage, and that storage on valley floors may have a very wide range of residence times with arrival times that might be measured in centuries to millennia. Some of those raising questions about this work were of the opinion that fine-grained sediment remobilized from storage by bank erosion should be able to travel as wash load and reach tidewater more rapidly. Several participants talked about the importance of understanding local geomorphic conditions that might affect opportunities for intermediate storage of eroded sediment.

- Although we are on the verge of being able to make much better measurements to quantify sediment budgets at high resolution over large areas, we are still developing the analytical procedures to do so, and especially to quantify error. Furthermore we need to develop the modeling frameworks in concert with the data collection effort so we can incorporate the modeling needs into the data collection design. Most of the large-watershed sediment budgets compiled to date are based on a considerable amount of supposition and we have not yet been able to fully account for uncertainty in the predictions. And since we are in the business of trying to make predictions about the efficacy of practices in the landscape, we can't rely just on measurements, we do have to be able to make quantitative predictions.

- In predicting erosion of cohesive banks, we are still developing and evaluating models of bank erosion, and we don't yet have a way to fully address the strong dependence of bank erosion on temperature, pH, salinity, etc. to make effective predictions.

- It's relatively easy to measure erosion, particularly when it's rapid, but measuring storage is more difficult especially when it is deposited as thin but widespread amounts on large floodplain areas. The only data we have yet are the unpublished data from the USGS Chesapeake Floodplain Network. Work in the South River watershed indicates that floodplain deposition there accounts for three times as much sediment as bank erosion.

- The question of whether there is a single valid model of pre-colonial stream systems in the mid-Atlantic Piedmont was one that engendered active debate. Some participants believed that there were no truly alluvial single-thread meandering streams with floodplains built by point-bar migration and overbank deposition, and that the conceptual model described in presentations by Parola and Altland, based to a considerable extent on previous research by Merritts and Walter and their collaborators, is the default condition that should be recognized as a restoration target. Others believed that even if this conceptual model is applicable at some sites, characterizing it as universally applicable across the Piedmont would be an overly broad assumption about regional geomorphology that has not been subjected to rigorous review.

Theme B: Mitigation Approaches and Assessment of Their Effectiveness

- Audience discussion included a focus on the question of whether we can make educated guesses about possible variability in performance of legacy-sediment removal projects. Variability is observed both spatially and over time, either due to sequencing of weather events or to changes that occur due to natural processes as a project ages. There may be unforeseen dynamics and complex processes associated with attempts to generate successful ecological restoration in a lowland environment; as one example, projects that retain sediment and reduce the flux of nitrogen may also lead to desorption of phosphorus which then becomes more mobile. In upland streams restoration approaches may rely more on structural designs intended to reduce stormwater impacts and control velocity of potentially erosive flows.

- The importance of reforestation and retention or protection of trees in restoration efforts was also discussed. Some participants suggested that protection of trees does not prevent erosion of steep, high banks underlain by thick silt-rich legacy sediment deposits that have been incised by streams eroding back to base level, and that the best management option in this situation is removal of the legacy sediment. An alternative view was that forested streams are naturally wider than streams with grass and herbaceous vegetation cover, so that tree planting leads to channel widening with some loss of trees occurring as a byproduct of widening. According to this view, once the forest shades out the grasses and the stream attains a stable width, the functionality of reforested reaches will be significantly better than the functionality of the deforested reach. There was general agreement that even if trees are removed at some restoration sites, reforestation and maintenance of forest buffers is still an important part of a broader management strategy.

Theme C: Management, Policy, and Decision-making

- Several questions were raised in response to Kevin Smith's presentation.
    - One had to do with the balance of sediment transported by overland/upland flow vs. streambank erosion. Clearly there is no universal ratio that applies in all locations or all watersheds and we need to address geographic differences that depend on land use and landscape characteristics, but we can agree that there are diverse sources and all need to be considered. Fine-grained particles are the most important and some amount of fine-grained sediment does get through agricultural BMPs. It was also observed that slowing down the hydrograph without promoting hyporheic flow may enhance primary production more than denitrification, and therefore mitigation of the hydrograph peak is not by itself a simple, straightforward recipe for success.
    - This led to further questions about whether we should go back to look at the pre-colonial condition as a reference for promoting hyporheic exchange. Smith agreed that things were undoubtedly "better" at that time and that there was much less erosion in the landscape, notwithstanding evidence of disturbance by Native Americans. But it was also pointed out that Grace Brush's work shows clear evidence of disturbance by fires and floods in the system prior to European settlement, and that we live in an environment with high ratios of the 100-year flood peak to the presumed 1-2 year bankfull flood owing to regional hydrometeorology, with higher weathering rates and frequent large storms driving erosion. So not all erosion is a result strictly of contemporary human disturbance.
    - A final observation was that even in completely forested watersheds we may still see headcuts migrating upstream through the landscape and banks may be high; the suggestion was that neither traditional management approaches or stormwater control are likely to be successful in preventing some of the persistent sources of erosion.

- These issues were raised in discussion following the presentation by Stu Schwartz:
    - With respect to the use of tracers to identify sediment sources, there sometimes are differences in bedrock and mineral composition that allow us to fingerprint the original source of the sediment sample, but this doesn't necessarily tell us where the sediment was mobilized from most recently (e.g. intermediate floodplain storage), how many stops it made along the way and how long it took to reach the sampling location, or how many BMPs would be required in which locations to accomplish the desired effect. Therefore tracing the original source may not be sufficient to identify the spatial array of management actions needed to have a significant impact at the mouth of a large watershed.
    - There is stratigraphic evidence from sediment cores in Chesapeake Bay indicating that there were dramatic increased in sedimentation rates over time, thus demonstrating that at least some sediment moved through the system rapidly even if a large fraction might have gone into intermediate storage. A question was asked as to whether this might be relevant to policy on management of sediment. The answer provided was that rapid increase in sediment supply may increase watershed sediment yield, but this does not mean that a rapid reduction would be equally likely with improved control of sediment sources because of the slower rates of remobilization from widely dispersed storage sites.

- In response to Erik Michelsen's presentation several additional points were raised:
    - There was a question as to whether encroachment of marsh on tidal creeks in recent decades is a problem. The answer was that the newly developed marshes are not really a problem, but that they are probably transient features that result from past disturbance and as such are probably not worth investing significant resources to maintain them. On the other hand, research on freshwater marshes elsewhere has shown that freshwater marshes are a type of sediment storage site that has expanded as a result of upstream disturbance and that they are helpful with ecosystem services like denitrification potential and might therefore be worth preserving.
    - Another question was raised as to whether cost/benefit analysis has been carried out for legacy sediment removal and whether the benefits can be documented. However that level of analysis has not been carried out in Anne Arundel County yet.
    - Another set of questions was asked about the connections between changing sediment supply, sea-level rise, and impacts on freshwater floodplains and either nontidal or tidal wetlands. We know that many nontidal wetlands were lost as a result of changes in land use following European settlement (both through draining for agriculture and through filling by sediment from upstream disturbance). High sediment loads may also have affected survival of submerged aquatic vegetation and wetland productivity. The balance between sedimentation rate, effects of sediment on water quality in shallow water, growth of tidal wetlands and associated ecosystem services on newly deposited materials, and the effects of sea-level rise in eroding or drowning tidal marshes are all topics that require more attention.
    - A question was raised about regulatory impediments to implementing BMP practices. The response was that most of the regulatory apparatus was set up with the hierarchy of avoid-minimize-mitigate, and that some of the mitigation measures proposed raise

    concerns with regulators because of their temporary impacts. A regulatory framework that recognizes a difference between restoration impacts and development impacts would be helpful in meeting restoration goals.
    - A final question was asked about the relative merits of legacy sediment removal compared with other approaches to stream restoration. The response was that the setting matters: conditions are more complicated in urban areas than in areas where there is cropland or pasture extending to the edge of the stream, because many urban streams are bordered by forested riparian buffers that are also valued as important. An alternative approach in these areas is to raise the bed to increase frequency of floodplain inundation. Because there is an expected increase in the number of projects being built, it would be useful to have more "surgical" interventions to reduce costs through such means as local grade control with a system profile that does not require bank armoring along the entire length of the stream.

- The discussion in response to Ryan Cole's presentation included the following questions and comments:
    - How do you deal with the need for landowner agreements to install practices? Much of the land in Maryland is private; the state makes agreements with local governments but needs data and stronger justification to argue for changes on private property, with information identifying erosional hot spots and their potential impacts on a downstream water body. Some agricultural land is not extremely valuable but there may be issues where the landowner cannot spare even an extra foot for a riparian buffer; there are also issues with a lack of trust in government. When necessary the state pays for easements.
    - Regarding the relative importance of benefits to the Bay vs. local benefits, it was explained that there is always a concern for both site-level and downstream effects. There are both local and Baywide TMDLs and the state needs to respond to both; even if a project is designed in response to the Bay TMDL the local site concerns still have to be considered.
    - An additional set of questions concerned both the economics of the appraisal process and the potential for changes in state policy that would be helpful. With regard to appraisal, there is a uniform code imposed by the Federal Highway Administration and appraisal is potentially the slowest process. Land is not condemned for TMDL projects, unlike what is done with roads. Getting permission from landowners requires major effort on the part of state employees working with real estate and rights of way. With regard to state policy the main concern is to have a template that incorporates evidence for benefits of stream restoration and helps in prioritizing projects that maximize those benefits.

- Following Denise Clearwater's presentation the following points were raised.
    - In the presentation it was mentioned that loss of trees is a consideration when projects are evaluated. Is this owing to aesthetic concerns or does it have more to do with hydrologic impacts? It would have to do with an overall change in resource benefits. Maryland values trees and forests for water quality benefits, shade, moderation of temperature, corridors for wildlife, forest interior dwelling birds, and additional considerations.

  - If a stream is incised and eroding and undercutting a forest, is there value in fixing this even if it means removing trees? The answer depends on local conditions. A site that is deeply incised and losing some trees is different from something that is not very incised and is also forested wetland. Those tradeoffs need a lot of discussion. We are working on metrics and assessment approaches with the U.S. Fish and Wildlife Service. The functional uplift approach is not yet very strong on the riparian component. As a general rule, if you have existing benefits, first do no harm. One participant mentioned that Chesapeake Bay Trust will likely be funding research directed at this specific question.
  - With regard to the issue of enhanced flooding, one participant stated that he had rarely seen evidence of increased flooding on adjacent properties when creating a lower floodplain surface. But according to Denise Clearwater, this is often what we see; and if someone's property is flooded more often, they have to give permission for it to happen. There have been national court cases that have dealt with this issue. There could also be claims of harm from smaller events experienced by a landowner, not only by the 100-year flood, which is why some form of easement and acknowledgement by the landowner is needed.

- These questions and comments were raised following Gary Shenk's presentation but some appear to be addressed to the group as a whole.
  - What are the greatest research needs? We need to understand more about where sediment ends up and how far it moves when it is mobilized, and we need to have some way of tracking both fine and coarse sediment. The future of the sediment component of the Chesapeake Bay Watershed Model will be discussed at another STAC workshop in January 2018. We know that more research is needed to inform the model.
  - Where did the numbers in the approved credits come from? There were 12-15 studies available that helped to inform these numbers, which may need to be revisited in future if new data sources become available. The value of pounds of removal in TMDL credit for streambank sediment comes from protocol 1, tempered by a delivery ratio curve depending on where that sediment is coming from in the watershed. The time scales for the measurements on which those numbers are based are very short and there needs to be more validation.
  - We have done large watershed-scale monitoring primarily in large agricultural watersheds where monitoring was done for over 10 years pre- and post-BMPs and they saw no changes. You need to do this over a period of multiple decades.
  - Why is there not more money invested in assessing the effectiveness of BMPs? The nutrient and sediment TMDL is one part of the Bay program and this is just one part of the sediment TMDL. The Bay program doesn't have a lot of money to devote to the basic research. A lot of numbers are included in the model and some are well supported and others are not. The original 40% N reduction target from the 1980's was poorly supported but it still turns out to have been extremely useful.
  - What would be most useful to the Chesapeake Bay model? Actual measurements to better establish response at the watershed scale would be helpful so we can say more about where sediment is being stored and where it is being eroded. That by itself does not solve the nutrient problem. However, research on the processes at a particular location

has to be generalizable to the entire Bay watershed before it makes its way to the management.

- Time does not seem to be on our side. The TMDL is due soon and there is a long lag between when we do something up in a first-order stream and when we see a result coming into Chesapeake Bay. Conowingo Dam stores 100 million+ tons of sediment. Papers coming out in the last year show there has been a significant reduction in sediment input to Conowingo in the last decade or more, yet the output reaching the Bay has not gone down because Conowingo is full so storm events do excavate sediment.
- How do costs compare for different mitigation approaches? Pennsylvania's experience is that we need to start by identifying what is wrong with the system first before deciding on what practice to approve. Pennsylvania finds that the costs are very comparable – stream restoration per linear foot costs about as much as valley-bottom restoration, but the benefits are significantly different. This information has not yet been released but should be available in the near future.
- With respect to valley-bottom removal, remember that regional facilities that were essentially valley-bottom treatment facilities were deemed inadmissible in Maryland many years ago under the terms of the Clean Water Act. Where does the issue of valley-bottom removal land in that conversation? *Erik Michelsen*: To the question of whether these practices are accredited, they are. MDE's evolution on the strategy, and the Corps to some extent too, are to be able to demonstrate effectiveness. The bifurcation of SWM vs healthy system is harmful if we ignore the health of the system and we are moving toward a more integrated approach. *Denise Clearwater*: The requirements for avoid-minimize- mitigate are for adverse impacts, but the activities in construction can occur in restoration projects and this is usually considered just part of the project. In some cases those consequences might be an issue because of an existing resource that needs to be protected. The reason regional facilities were rejected still holds true today because of all the other pollutants that ran downstream for miles.
- If we shut off the nutrients and let the sediment go, do we still have a nutrient problem? You still have to address clarity issues. The goal lines are really about DO and clarity even though they don't appear in the TMDL.
- In Pennsylvania's Big Spring Run and other restoration sites, the goal is not to get rid of legacy sediment, it's to provide a larger ecological service which is really about restoring wetlands to generate a larger benefit. There is also an argument that the storage of legacy sediment creates a real effect on the hydrograph peak. We reverse that trend – while the peak was significantly diminished, the bigger story is that we increased the tail of the recession curve.
- Is there a strategic plan? *Ann Swanson*: there is an extremely strategic plan and in order to understand it you need to go back and read the successive versions of the Chesapeake Bay agreement. In 2010 we transitioned from a largely voluntary plan to one where there was a federal intervention with the TMDL and that is why this conversation is very much influenced by that federal TMDL focused on three impairments: P, N and sediment.
- We should be concerned about whether the magnitude of the suspended sediment contribution from legacy sediments is going to increase dramatically over time especially

with another Agnes-type event. We are still early in the response to incision of legacy sediment and it will get worse over time.

- All the accrediting gives you the same credit per unit cost no matter where you apply the BMPs. There are areas very close to the Bay where you have hot spots, but incentives are to go further upstream.

Appendix C – Participants List

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