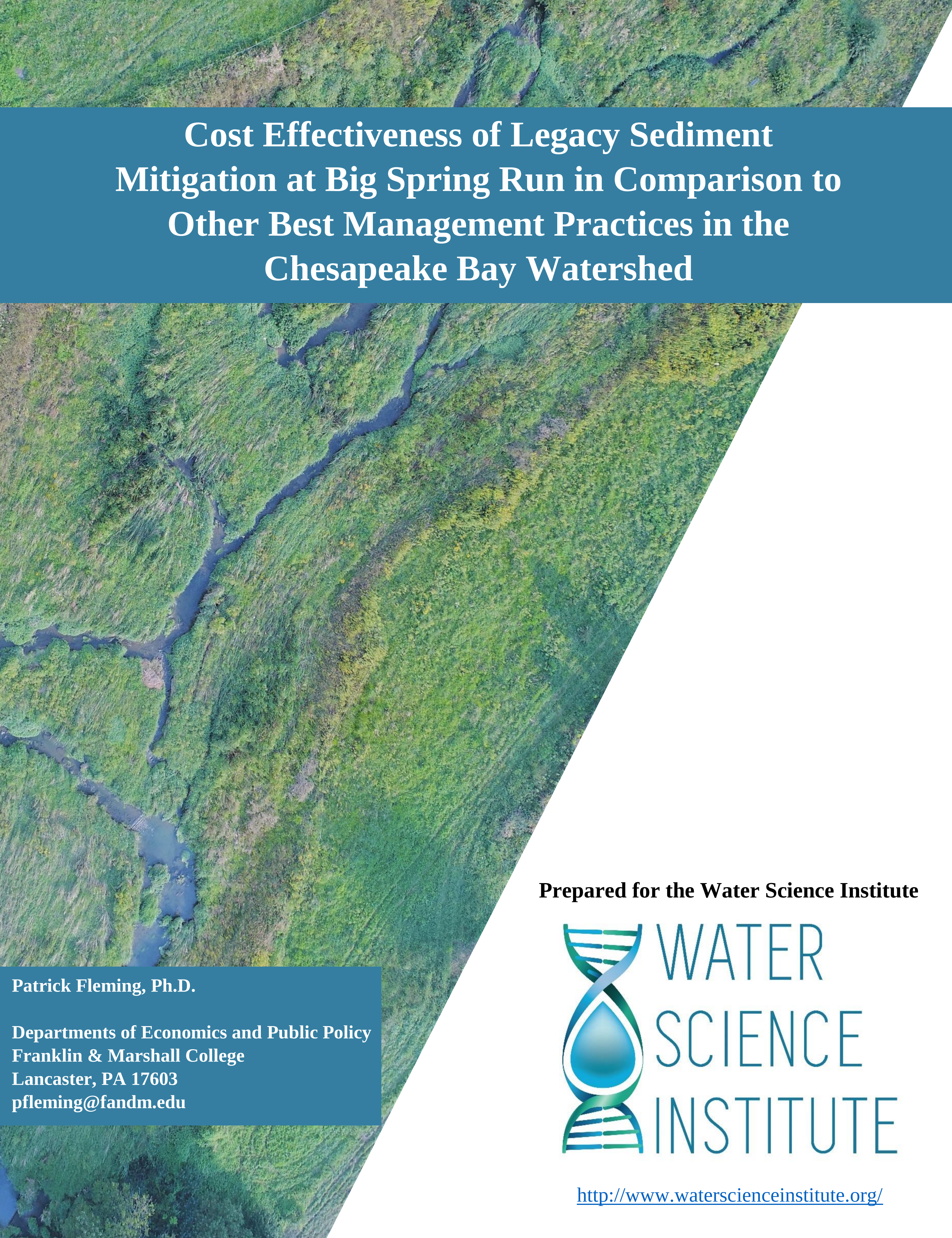

Cost Effectiveness of Legacy Sediment Mitigation at Big Spring Run in Comparison to Other Best Management Practices in the Chesapeake Bay Watershed

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Cover Photo: Post-restoration aerial view of multi-branching channel at Big Spring Run (Credit: WSI).

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I. Executive Summary

Mitigating legacy sediment impaired waters will likely be a critical strategy for meeting improved water quality goals in the mid-Atlantic region of the United States, including the Chesapeake Bay total maximum daily load (TMDL). Geologists have done pioneering work to establish that numerous historic milldams and other stream impediments have buried mid-Atlantic stream valleys in thick layers of “legacy sediment” over many decades (Walter and Merritts 2008). As time goes on and the milldams or other impediments are removed, intentionally or otherwise, this sediment is released and steep, incised stream banks are left behind which lead to long-term loading of sediment and nutrient pollution from streambank erosion (Figure 1).

Figure 1. Erosion of legacy sediments following breach of Strobers dam in Pennsylvania in 2011. Bank sediments are upstream of the breached dam and the top of the bank matches the top of the dam.

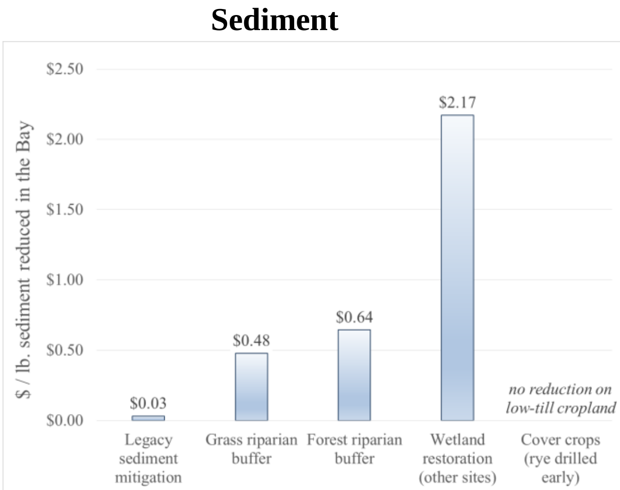
The problem of legacy sediment (LS) impaired waters is ubiquitous in the Chesapeake watershed. Census data indicates that over 65,000 water-powered mills existed every 2-3 km on many streams in the eastern U.S. by 1840 (Walter and Merritts 2008). Nearly 800 historic milldam sites have been identified in Lancaster and York Counties alone. With colonial settlement patterns tethered to waterways along which gristmills, sawmills, and forges were established to process grain, timber, and ore (De Cunzo and Garcia 1993), LS stream-bank erosion has been found to contribute as much as 50-100% of current suspended sediment loads in Piedmont watersheds (Walter and Merritts 2008; Massoudieh et al. 2012; Voli et al. 2013; Gellis and Brakebill 2013; Walter et al. 2017). In addition to sediments, recent studies have found that streambank legacy erosion could also contribute substantially to stream nitrogen loads in particulate forms (Inamdar et al. 2017), and is likely to have an even greater influence on nutrients that are preferentially bound to sediments such as phosphorus (Merritts et al. 2010; Sharpley et al. 2013).

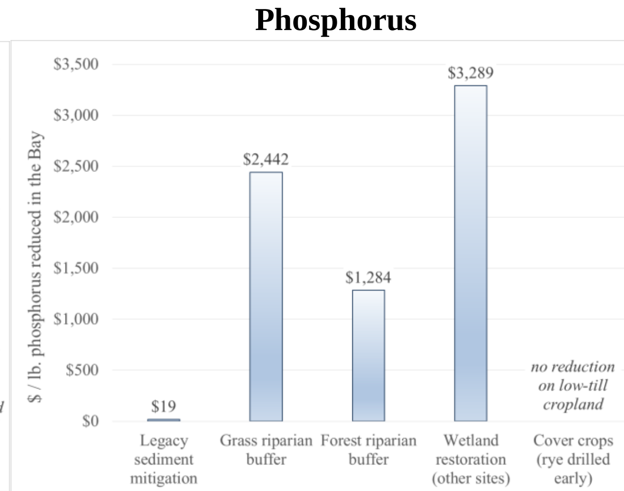
One of these legacy sediment impaired waters, Big Spring Run (BSR) in Lancaster County, Pennsylvania, has been closely monitored over a fifteen-year period—before, during and after LS mitigation—for its sediment, phosphorus (P), and nitrogen (N) loads, along with numerous other environmental indicators (http://www.bsr-project.org/). Among other findings, this test site has demonstrated that LS mitigation, in the form of legacy sediment removal to restore natural aquatic ecosystem characteristics and processes, is a highly effective means to reduce pollution loads. However, less is known about the cost-effectiveness of LS mitigation projects, in terms of its cost per unit of pollution reduced.

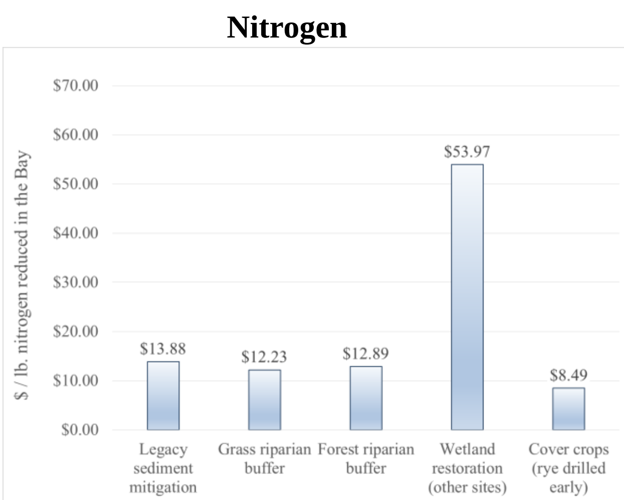
This report conducts a cost-effectiveness analysis of LS mitigation in comparison to other best management practices (BMPs) that are commonly considered low-cost, such as forest and grass riparian buffers, and cover crops on agricultural land. Data on abatement per acre for the group of comparison BMPs comes from the Chesapeake Bay Program (CBP) Phase 6 water quality model. Load reductions from LS mitigation are from measurements of sediment and nutrient abatement at the Big Spring Run study site. Practice implementation costs per acre are from United States Department of Agriculture (USDA) payment schedules (supplemented with published sources of costs). Costs per acre of LS mitigation are based on updated cost data from the Big Spring Run restoration project, along with landowner compensation required for USDA wetland easements.

As shown in summary Table 1 and Figure 2, this analysis finds that LS mitigation is a highly cost-effective abatement method. This is particularly the case for the pollutants of sediment and P. For sediment runoff, LS mitigation reduces loading rates at a cost of $0.03 per pound, or 5% to 21% of the cost of other BMPs that are commonly considered low cost. For phosphorus runoff, LS mitigation reduces loading rates at approximately $18 per pound, or 1% to 6% of cost of other BMPs. The substantial advantage in cost-effectiveness for LS mitigation remains true under different agricultural land uses and geographic regions in the CBP model, as well as different discount rates for converting practice costs to annual terms. For N reduction, LS mitigation is competitive in its cost-effectiveness, but other practices are modeled to reduce N loads at slightly lower average costs, with cover crops as the most cost-effective. For example, LS mitigation reduces N loads at $13.27 to $14.80 per pound, in comparison to $4.58 to $7.98 per pound for cover crops, under average N loading rates by agricultural land uses in the Chesapeake Bay watershed. Under various modeling scenarios, the cost-effectiveness of LS mitigation is consistently driven by the very high load reductions available at LS "hot spots" such as the BSR study site.

Figure 2. Cost effectiveness of abatement in the Chesapeake Bay watershed by practice type: Grain with manure land use







Notes: Delivery factors used to adjust for transport from edge-of-stream to the Chesapeake Bay. Abatement from buffers, cover crops, and wetland restoration at sites not characterized as LS hot spots is from the Chesapeake Bay Program watershed model "grain with manure" land use. Cover crops do not reduce sediment and phosphorus from low-till cropland. Costs for buffers, cover crops, and wetland restoration are based on USDA payment schedules, and Wieland et al. (2009). Abatement and costs for legacy sediment (LS) mitigation are from data at the Big Spring Run study site, updated engineering cost estimates, and USDA wetland easement values.

This analysis has important policy implications for reducing nonpoint source (NPS) water pollution in the United States. Since the Clean Water Act has largely focused on regulating discharges from point source emitters, the policy approach for reducing NPS water pollution has relied on voluntary subsidy programs that reduce the cost of adopting qualifying BMPs, such as the practices analyzed here. Given the cost-effectiveness of LS mitigation in comparison to practices that are commonly considered low cost, and given the high number of LS erosion hot spots in the mid-Atlantic region, this mitigation practice should receive further attention as a BMP eligible for cost-share funding from existing conservation programs. Moreover, along with considerations of cost-effectiveness, it is necessary to note that LS mitigation is the only abatement action that will address the problem of highly-incised stream banks vulnerable to erosion at the numerous legacy sediment erosion hot spots in the Chesapeake watershed. Ignoring the elevated sediment and nutrient loads from these sites will render less visible the substantial progress that has been made by implementation of upland agricultural and urban BMPs.

II. Cost Effectiveness Definition and Methodology

The general formula for cost effectiveness is based on the estimated abatement per acre, *a*, and implementation cost per acre, *c*, for each practice studied. Cost effectiveness for practice *k* and pollutant *p* is then calculated as:

(1) $$CE_{kp} = {}^{c_k}/_{a_{kp}}.$$

CE_{kp} will be expressed in dollars per unit of pollution reduced. In this report we analyze five practices: legacy sediment (LS) mitigation, forest riparian buffers, grass riparian buffers, cover crops, and wetland restoration at sites not primarily characterized by elevated loads from legacy stream impediments. LS mitigation is defined based on the project undertaken at the BSR study site (http://www.bsr-project.org/) in the Mill Creek watershed in Lancaster County, which involved removing legacy sediment to restore a wetland complex that had been buried beneath the legacy sediment. Numerous similar "hot spots" of elevated stream bank erosion exist in the Chesapeake Bay watershed, with pollutant loads comparable to those at the BSR study site prior to restoration.

The practices of forest riparian buffers, grass riparian buffers, and cover crops were chosen based on their reputation for cost-effectiveness and associated policy relevance (Jones et al. 2010). In the case of wetland restoration, this practice was selected not for its reputation for cost-effectiveness, but for purposes of comparison with wetland restoration that frequently occurs as part of LS mitigation.

The three pollutants analyzed are those targeted for reduction by the Chesapeake Bay TMDL: sediment, total phosphorus (P), and total nitrogen (N). There are other ecosystem benefits of implementing all of these conservation practices, including LS mitigation—these co-benefits include wildlife habitat, carbon storage, flood control, amenity values, and other ecosystem services. However, we focus on abatement of sediment, P, and N in order to place this analysis within the broader effort of identifying cost effective strategies and Watershed Implementation Plans (WIPs) to achieve TMDL targets.

A. Data Sources

Estimates of cost effectiveness require data on (i) the abatement benefits of practices in terms of the units of sediment, P and N reduced and (ii) the implementation costs of each practice. Abatement benefits (e.g., nutrient and sediment abatement) for the group of comparison BMPs are obtained from the Chesapeake Bay Program (CBP) Phase 6 Watershed Model. In particular, we use per-acre loads from agricultural land uses modeled in the Chesapeake Assessment Scenario Tool (CAST),[1] in combination with BMP pollution reduction efficiencies from updated Phase 6 Expert Panel Reports.[2] Sediment and nutrient abatement for LS mitigation is based on USGS gage data from the BSR test site (Langland *in prep.*).

Actual measurements from LS sites are preferable to the CBP/CAST modeled loads for the Stream Bed and Bank load source, because the highly elevated loads at LS erosion hot spots are not explicitly identified in the CAST model. For example, the Stream Bed and Bank load source in CAST is modeled to produce 306,743 lbs. sediment per year (~153 tons per year) for the entire Mill Creek river segment, using the 2017 "progress scenario" of the model. In contrast, USGS gage measurements indicate approximately 1.75 million lbs. per year (875 tons per year) for the BSR study site alone, which is just one of eighteen LS erosion "hot spots" in the Mill Creek watershed.[3] The BSR study site is the only one of these hot spots that has been restored. Thus, modeled Stream Bed and Bank loads drastically undercount this load source.

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1 http://cast.chesapeakebay.net/

2 https://www.chesapeakebay.net/who/group/bmp_expert_panels

3 For the purposes of this report, an LS erosion "hot spot" is characterized as having bank sediment erosion of at least 0.05 tons per foot per year in a stream length between 2000 and 5000 feet, using erosion rates identified by LiDAR Digital Elevation Model (DEM) differencing. Each hot spot in the Mill Creek watershed produces an average of 474 tons of sediment and associated nutrient runoff per year, and some are as large as 1147 tons sediment per year

Implementation costs for the comparison BMPs evaluated are based on information from the USDA Natural Resource Conservation Service (NRCS) and Farm Service Agency (FSA) program payment schedules, and supplemented with published information on practice costs (Wieland et al. 2009; Jones et al. 2010; Kaufman et al. 2014). We use a comprehensive metric of costs required for ongoing practice implementation, including not only the upfront cost of practice adoption but also, where applicable, permitting, ongoing maintenance, and opportunity costs borne by landowners when implementation requires removing land from production. The costs of LS mitigation are based on the costs of the restoration at the BSR study site, but adjusted to account for the costs if a similar restoration were to occur today. These costs are provided by construction firms that have implemented LS restoration practices, and are supplemented with USDA NRCS payment schedules for the opportunity costs of removing land from production.

The CBP watershed model—used for identifying abatement benefits in this report—divides the Chesapeake Bay watershed into more than 2,000 river segments, and then simulates pollution loads using more than 20 years of historical monitoring data on precipitation, stream flow and land uses.[4] While the CBP watershed model is calibrated based on historical water quality measurements, it makes certain simplifications in developing model parameters. For example, the model does not explicitly account for nonlinearities in NPS pollution generation, such as interactions between neighboring pollution sources (Rabotyagov, Valcu and Kling 2013), nor does it explicitly model legacy sediment sites with their associated high levels of erosion and nutrient runoff as separate sources of load. While the Phase 6 model does include a Stream Bed and Bank load source, the magnitudes of sediment and P load from this source are substantially lower than combined measurements at legacy sediment sites. Nonetheless, despite these limitations we use the CBP model parameters because this is the tool employed by the EPA and all state and local jurisdictions in the Chesapeake Bay watershed to monitor progress and assess cost-effective strategies toward meeting TMDL requirements. Continual improvement of the model to incorporate high load sources, such as milldam legacy sediments, is imperative for accurate model prediction.[5]

[4] Documentation on the CBP Phase 6 Model is available at: http://cast.chesapeakebay.net/Documentation/ModelDocumentation.

[5] The CBP Phase 6 model also includes BMP cost estimates. This report generally updates those estimates by using more recent source data. For example, the CBP model's costs for the comparison practices utilize 2011 NRCS payment schedules for upfront adoption costs and

B. Definition of Legacy Sediment (LS) Mitigation

While the comparison BMPs studied in this report have well-known definitions, the legacy sediment (LS) mitigation practice is not commonly known and therefore it is helpful to define it with more precision. LS mitigation involves removal of legacy sediment to restore aquatic ecosystem characteristics and processes that existed prior to the accumulation of legacy sediment behind the historic milldam or other stream impediment. Given that wetland soils and anastomosing channels were often buried by legacy sediment in the Chesapeake region, wetland restoration (as defined by the BMP Phase 6 Expert Panel Reports) often is a critical component of these aquatic ecosystem restorations (Walter and Merritts 2008; Voli et al. 2009). However, depending on site-specific conditions, other types of restoration may be appropriate following partial removal of accumulated sediment, including floodplain restoration or riparian buffers. The removed sediment has an economic value as fill for construction firms, and may have other higher-value uses including rehabilitation of brownfield sites and topsoil additive.[6]

The remainder of this report will focus on outlining the methods for calculating abatement achieved by each practice (Section III), and the associated costs of implementation (Section IV). In Section V, we summarize results and test the sensitivity of these results to a number of modeling scenarios.

III. Practice Abatement per Acre

Table 2 shows the abatement per acre for each practice analyzed in this report. Abatement from LS mitigation is based on measured pre-restoration loads at Big Spring Run and subsequent filtration of upland loads by the restored wetland at that site, using parameters from the CBP Phase 6 Model. For all comparison BMPs, abatement is based on the CBP Phase 6 model. The calculation of these estimates is described below for each practice in turn.

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opportunity costs borne by landowners, whereas this report updates that information with 2018 NRCS payment schedules. In a few cases, however, the underlying cost assumptions differ between the CBP model's costs and those derived in this report (e.g. the discount or "annualization" rate). In these cases, the modeling decisions used in this report are explained, and sensitivity checks are performed where appropriate.

[6] For example, the sediment from BSR was used in a brownfield rehabilitation in Lancaster (https://www.fandm.edu/about/community-matters/railyard).

A. Legacy Sediment (LS) Mitigation

LS mitigation achieves abatement both by (i) a change of land use and (ii) the filtration of upland acreage. Change in land use refers to the conversion of an incised stream bank into a restored wetland complex or other natural aquatic ecosystem. Prior to restoration, loads are highly elevated due to bank erosion; after restoration, these loads are negligible. The second type of abatement is through the filtration of upland acres achieved by the restored wetland complex or other natural aquatic ecosystem. Each is discussed in turn.

(i) Change of land use. The average rate of stream bank erosion prior to restoration activity at BSR, over a three-year period from USGS water years 2009-2011, was 875 tons per year (Langland *in prep.*).[7] Comparable erosion hot spots have been identified at numerous LS sites in the Piedmont region (including sites on Chiques Creek, Little Conestoga Creek, and Conoy Creek, as shown in Walter et al. (2007), Tables 2 and 4; Merritts et al. 2011; and Merritts et al. 2013). Using average nutrient concentrations from this and other LS sites in the study region—2.9 pounds N per ton and 2.3 pounds P per ton (Walter et al. 2013)—sediment stream bank erosion resulted in corresponding annual loads of N and P of 2,538 pounds and 2,013 pounds, respectively.[8]

For the purpose of comparing with other practices, it is necessary to convert these loads to their per-acre equivalents. This can be done in one of two ways: either based on the total acreage of the restoration site, or based on the restored stream length multiplied by an average width of aquatic ecosystem restoration. In this report, per-acre loads are based on the restoration site area of 4.7 acres.[9] Therefore, prior to mitigation efforts at BSR the annual per-acre loads of legacy sediment, P, and N were 372,340 pounds (about 186 tons), 428 pounds, and 540 pounds, respectively.

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[7] See Appendix A for a discussion of the data and methods used to obtain the pre-restoration load at Big Spring Run.

[8] Annual loads for P and N are measures of nutrient loading due to bank erosion. To the extent that nutrient runoff prior to restoration occurred through other avenues (such as leaching into groundwater, particularly for N), these estimates represent lower bounds of nutrient load generated at the pre-restoration site.

[9] Note that the pre-restoration BSR site contained 2,731 linear feet of stream length—an average bank width of 37 feet per side is approximately equivalent to the 4.7 acre site.

After LS mitigation at the BSR site, on-site pollution loads are almost entirely eliminated. The BSR site restored a wetland complex that generates negligible loads in the CBP Phase 6 Model. In particular, after LS mitigation at BSR, annual loads per acre of sediment, P, and N are modeled to be 31, 0.1, and 1.4 pounds, respectively, based on average CBP model loads for non-tidal floodplain wetlands in the Chesapeake Bay watershed. This is consistent with measurements at the BSR test site, which show negligible loads following restoration.
Thus, the difference between annual pre-restoration and post-restoration loads represents the abatement due to change in land use. This indicates annual pounds abatement per acre of 372,309 for sediment, 428 for P, and 538 for N, due to change in land use (Table 3).

(ii) Filtration of upland acres following restoration. The second type of abatement by LS mitigation is through filtration of upland acres following aquatic ecosystem restoration, including a wetland complex with anastomosing stream channels. The sites of historic milldams often contain wetland soils beneath the accumulated sediment, which makes them well-suited for wetland restoration (Walter and Merritts 2008; Voli et al. 2009; Hartranft et al. 2011). Based on the CBP Wetland Expert Panel Report (2016)[10], the sediment and nutrients removed by wetlands from water flowing into them varies by the physiographic subregion of the wetland, and whether or not the wetland is located in a low-lying floodplain (see Table 12 of CBP Wetland Expert Panel Report). These factors determine the number of upland acres filtered by the wetland, which is intended to approximate the retention time of water as it flows through the wetland (Jordan, Simpson and Weammert 2007). In low-lying floodplains in the Piedmont physiographic region, where the BSR study site is located,[11] the model assigns three upland acres as treated by wetland restoration, with load reduction efficiencies of 31%, 40%, and 42% for sediment, P and N, respectively.

In the CBP Phase 6 Model, the load reduction efficiencies for wetlands are multiplied by the loads generated by land uses upland of the wetland. Thus, the modeled abatement per acre will vary based on the land use patterns above the wetland. Mathematically, wetlands with surrounding land uses that generate higher loads will be modeled as reducing more pollution per wetland-acre, and vice versa.

[10] https://www.chesapeakebay.net/documents/Wetland_Expert_Panel_Report_WQGIT_approved_December_2016.pdf
[11] Email correspondence with Robert Walter, November 12, 2017.

Table 4 shows the CBP Phase 6 Model loads per acre from various agricultural land uses (columns [1] to [3]), averaged across all river segments in the Bay watershed. We focus on agriculture because that is a dominant land use in Lancaster County, and commonly considered a major contributor to Sediment, P, and N pollution in the watershed.[12] Columns [4] to [6] of Table 4 show the associated abatement due to filtration of upland acres by restored floodplain wetlands in the Piedmont subregion, as estimated in the CBP Phase 6 Model.

For purposes of comparison with other BMPs, the land use of "grain with manure" (gwm) was selected, since this is a typical agricultural land use in the region. Thus, abatement per acre from filtration of upland acres at the BSR site results in annual abatement per acre of 1,695, 0.9, and 53.8 pounds of sediment, P, and N, respectively. However, as noted, actual abatement achieved will vary based on the land uses surrounding a given legacy sediment project, as well as the presence of high-load LS sites upstream.[13] Section V.A describes how the results are affected when considering other agricultural land uses in the CBP model.

(i) + (ii). Total abatement per acre. Combining load reduction due to change in land use and filtration of upland acres, the total abatement per acre of LS mitigation is over 374 thousand pounds for sediment, 429 pounds P, and 592 pounds N (Table 2). While making certain simplifications regarding the abatement process resulting from LS mitigation, this method is intended to be transparent and replicable, serving as a lower bound on abatement obtained at the legacy sediment BSR site.

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[12] In the case of the Big Spring Run site, upland land uses contain a mix of developed spaces (approx. 48%), agricultural cropland (26%), agricultural pasture or hay (22%), and forest (4%). (Email correspondence with Dorothy Merritts, November 12, 2017.)

[13] Load estimates from USGS gage data at the BSR study site allow for cross-checking the CBP modeled reductions. For example, from water years 2013 to 2015 after wetland restoration at BSR, average total sediment loads at the upstream gages were 1,797 tons annually (with corresponding nutrient loads of 4,134 lbs. TOTP and 5,213 lbs. TOTN). The average sediment load at the downstream gage was 427 tons annually (982 lbs. TOTP, and 1,238 lbs. TOTN) during the same time period. This indicates a percentage load reduction of approximately 76%, substantially larger than the 31%, 40%, and 42% reductions indicated in the CBP Wetland Expert Panel Report. Moreover, the absolute quantity of reductions / deposition measured with USGS gages is much larger than the CBP model's estimates because the upland loads (or more precisely, the upland and upstream loads, given the presence of LS erosion hot spots upstream) are substantially higher than the CBP's upland agricultural load sources, such as "grain with manure." (See Appendix A and Table A1 for more details on the USGS gage data.)

B. Forest and Grass Riparian Buffers

Like LS mitigation, the abatement achieved by either forest or grass riparian buffers occurs through both (i) land use change and (ii) filtration of upland acres following establishment of the buffer area.

(i) Change of land use. Prior to buffer establishment, the loads generated per acre will depend on the particular land use upon which the buffer will be planted. For the purpose of consistent comparison, we use a representative agricultural cropland use of "grain with manure" (gwm), which is the same land use we model as surrounding the legacy sediment site in the preceding section. In the CBP Phase 6 Model, grain with manure is modeled with average per-acre loads across the Bay watershed of 1,823, 0.7, and 42.7 pounds for sediment, P, and N, respectively, as shown in Table 4. (Section V.A shows sensitivity checks with the loads from different land uses in the CBP model.)

After establishment of a forest riparian buffer, the loads generated will be negligible. The CBP Riparian Buffer Expert Panel Report (2014)[14] recommends using modeled loads per acre from the "true forest" (for) land use for buffers (an average of 34.7, 0.1, and 1.5 pounds for sediment, P, and N). For grass riparian buffers, the Phase 6 model uses loads per acre from "agricultural open space" (aop) (43.0, 0.8, and 3.8 pounds for sediment, P, and N). Since loads generated by both "true forest" and "agricultural open space" land uses are generally lower than those generated by cropland, the difference between loads per acre before and after buffer establishment represents the abatement due to land use change.

(ii) Filtration of upland acres following buffer establishment. Abatement due to filtration of upland acres varies by geographic region. As shown in the CBP Riparian Buffer Expert Panel Report (2014), buffer reduction efficiencies applied to load generated by upland acres will vary by hydrogeomorphic region. For purposes of comparison with the BSR site, we use reduction efficiencies in the Piedmont (schist/ gneiss) region, which is the region where BSR is located. Sediment and P reduction efficiencies are modeled in the same way for forest and grass buffers (48% and 36%, respectively), whereas the N reduction efficiency varies (46% for forest buffers,

[14] https://www.chesapeakebay.net/documents/Riparian_BMP_Panel_Report_FINAL_October_2014.pdf

32% for grass buffers). Both forest and grass buffers are modeled as filtering two upland acres for sediment and P, and four upland acres of N. (See Table 1 of the CBP Riparian Buffer (2014) report.)

(i) + (ii). Total abatement per acre. As shown in Table 2, the combined abatement per acre of forest riparian buffers is 3,538 pounds, 1.2 pounds, and 120 pounds for sediment, P, and N, respectively. For grass riparian buffers, the corresponding per acre abatement is 3,530 pounds, 0.5 pounds, and 94 pounds for sediment, P, and N. The two practices reduce a similar amount of sediment per acre, but forest buffers are modeled to reduce substantially more P and N per acre than grass buffers.

C. Wetland Restoration at Other Sites

Wetland restoration operates through the same two types of abatement as LS mitigation and riparian buffers: (i) change in land use and (ii) filtration of upland acres. Since the BSR legacy sediment practice involved wetland restoration, the primary difference in abatement between LS mitigation and wetland restoration at other sites is due to the substantial difference in *pre-restoration* loads between legacy sediment sites and other sites not characterized by accumulated sediments caused by historic milldams or other impediments.

(i) Change of land use. The particular land use in place prior to wetland restoration will largely determine subsequent abatement caused by land use change. We restrict ourselves to agricultural land uses for the purposes of comparison, and as with the other practices described above we use loads per acre from “grain with manure” (gwm) as a representative agricultural load prior to BMP implementation. To the extent that wetland restoration occurs on land uses that generate different quantities of pollution, the subsequent abatement per acre for wetland restoration will differ.

In the CBP Phase 6 Model, loads per acre from grain with manure are 1,823, 0.7 and 42.7 pounds per acre for sediment, P, and N, respectively, averaged across the Bay watershed (see Table 4). After wetland restoration, loads per acre are negligible. Non-tidal floodplain wetlands are modeled, on average, to have loads of 31, 0.1, and 1.4 pounds per acre for sediment, P, and N in the CBP Phase 6 Model. Abatement due to land use change is then calculated as the difference between the pre-restoration and post-restoration loads.

(ii) Filtration of upland acres. Abatement obtained by filtration of upland acres is modeled in the same way as wetland restoration at legacy sediment sites such as BSR. As with other practices, the abatement obtained by filtration of upland acres is sensitive to the choice of upland land use. For the sake of consistent comparison with other practices, we use loads per acre from grain with manure, a typical agricultural land use in the region. As described, the CBP Wetland Expert Panel Report (2016) recommends that a wetland restored in the Piedmont region surrounding BSR filters three upland acres for sediment, P, and N at a rate of 31%, 40%, and 42%, respectively, resulting in abatement of 1,695, 0.9, and 53.8 pounds.

(i) + (ii). Total abatement per acre. Combining both types of load reduction results in total abatement per acre of wetland restoration at other sites (not characterized as legacy erosion hot spots) of 3,486, 1.5, and 95.1 pounds, for sediment, P, and N, respectively (Table 2).

D. Cover Crops

Unlike the other practices analyzed, cover crops operate through the reduction of runoff on working land acres. That is, cover crops do not involve a change in land use, but are planted on cropland in the fall in order to provide soil cover through the winter, as well as live root systems that absorb nutrients remaining in the soil after the growing season. This reduces nutrient leaching into groundwater, and also minimizes sediment runoff. Cover crops are particularly effective at soaking up residual nitrogen remaining after the growing season.

The CBP Cover Crop Expert Panel Report (2016) indicates that the load reduction efficiency for cover crops varies by species, planting date, planting method and physiographic region.[15] For the purpose of this analysis, we use the reduction efficiency associated with traditional rye planted early in the Piedmont region, using low-till planting methods (drilled). This type of cover crop and planting method is typical in the agricultural areas surrounding the BSR site.

[15] See https://www.chesapeakebay.net/documents/Phase_6_CC_EP_Final_Report_12-16-2016-NEW_TEMPLATE_FINAL.pdf , Figure 1. Nutrient and Sediment Reduction.

The abatement obtained per acre will vary in the CBP Model based on the agricultural land use on which the cover crop is planted. According to the Phase 6 Expert Panel Report, cover crops reduce N on all agricultural land uses, but only reduce sediment and P on land uses that are considered "high till" (low residue): in the Phase 6 Model, these include "silage with manure", "silage without manure", "specialty crop high", and "other agronomic crops". All other crop land uses are considered "low till", and therefore cover crops are not modeled as reducing sediment and P on these other crop land uses—including "grain with manure", the representative agricultural land use utilized in this report.

Thus, the load reduction efficiency for traditional rye cover crops drilled early is 45% for N only, with no reductions credited for sediment and P on the grain with manure land use. Multiplying the load reduction efficiency by the modeled loads per acre on the "grain with manure" land use results in abatement per acre of 19.2 pounds N per acre for cover crops planted in the same region as the BSR site (Table 2).

E. Comparison of Abatement per Acre by Practice

Along with modeling the cost-effectiveness of these practices, it is helpful to make direct comparisons of the abatement potential of each practice in terms of the acreage required to achieve a given target. For example, pre-restoration measurements from the BSR project combined with the CBP Phase 6 modeled loads from wetland restoration (as described in Section III.A) indicate that the 4.7 acre project has led to about 879 tons of sediment abatement per year.[16] How many acres of each BMP would be required to match this level of abatement for each pollutant? This comparison can provide a sense of the scale of landowner outreach required to match the abatement potential of one representative LS mitigation project.

The results are summarized in Table 5. Four hundred ninety-seven acres of forest buffers, and 498 acres of grass buffers, would be required to match the sediment reduction from the BSR restoration project, according to the CBP watershed model's parameters. Wetland restoration at other sites (not characterized by highly elevated loads from legacy sediment) would also require substantially more treated acreage, given the lower pre-restoration loads. Similarly, the amount of acreage required to match phosphorus abatement observed at the BSR site is substantial, at

[16] Calculated as LS mitigation abatement per-acre (374,004 pounds) multiplied by the 4.7 acres of the BSR site (about 1.76 million pounds, or 879 tons of sediment abatement per year).

1,698 acres of forest buffers or 4,362 acres of grass buffers. The acreage needed to match the nitrogen abatement observed at BSR is relatively smaller (23 and 30 acres respectively for forest and grass buffers), and 145 acres of cover crops, according to the parameters of the CBP Phase 6 model.

These results are relevant for policymakers considering ways to reduce the transaction costs of achieving abatement through voluntary conservation by landowners. For example, the probable number of landowner contracts required to match the phosphorus or sediment abatement from a single LS mitigation project through the use of other BMPs is very high. These results do not yet incorporate the implementation costs of each practice, but are indicative of likely program and outreach costs in order to obtain a given level of abatement. We now turn to a comparison of costs per acre for each practice.

IV. Practice Implementation Costs per Acre

The implementation cost per acre is intended to be comprehensive, including several cost components for each practice: (i) upfront cost of practice adoption; (ii) upfront costs of permitting (when applicable); (iii) ongoing maintenance costs (when applicable), and (iv) ongoing opportunity costs in cases when practice implementation requires removing land from production. A detailed discussion of these estimates is contained below for each practice.
For ease of comparison, the annualized implementation cost per acre of each practice is shown in Table 6. We report costs from the BSR restoration project for LS mitigation, updating those costs to account for price increases since the BSR restoration took place. For the comparison practices, we calculate costs from information obtained through the USDA Natural Resource Conservation Service (NRCS) and Farm Service Agency (FSA) payment schedules, as well as published information from prior cost-effectiveness studies in the Chesapeake Bay region (Wieland et al. 2009).

A. Legacy Sediment (LS) Mitigation

LS mitigation includes both upfront and ongoing costs. (i) Upfront practice adoption costs include partial removal of sediment, streambank grading, and planting of wetland plants; as well as permitting, design and other regulatory costs; (ii) potential maintenance and monitoring costs to sustain vegetative health; and (iii) ongoing opportunity costs for land account for the loss of land from agricultural production (extending back from the streambank as part of wetland restoration).

We use updated costs from the BSR restoration for (i), including information obtained from the construction firm, LandStudies, Inc. (which implemented the BSR restoration), review of MS4 cost estimates, and discussions with other practitioners.[17] For (ii), we use data from the BSR restoration supplemented with information from the CBP Wetland Expert Panel Report (2016). For (iii) we use landowner compensation rates from the NRCS Agricultural Conservation Easement Program (ACEP), which is the primary program used to compensate landowners for wetland restoration in the state. We address each type of cost in turn. A summary of costs is shown in Table 6.

Note that legacy sediment sites typically contain wetland soils buried beneath the valley-bottom sediments, which makes them particularly well-suited for wetland restoration (Walter and Merritts 2008; Voli et al. 2009; Hartranft et al. 2011). For this reason we focus on wetland restoration as an integral part of the mitigation activity that takes place on legacy sediment sites.

(i) Upfront practice adoption costs. Upfront restoration costs for LS mitigation are significant, and they include both construction costs (partial removal of sediment, streambank grading, and planting of wetland plants) as well as permitting, design and other regulatory compliance costs. The engineering firm *Land Studies, Inc.*, which implemented the Big Spring Run restoration, estimates that a similar restoration practice today would cost about $350 per linear foot of stream length.[18] This includes practice implementation and regulatory costs, but not post-restoration maintenance and monitoring, nor any landowner compensation required. To complete another LS mitigation practice of the same size as Big Spring Run would thus require upfront costs of $955,850 (or $350 per linear foot multiplied by 2,731 feet of pre-restoration stream length).

Regulatory costs primarily include permitting and design, but also closing costs and titling for the wetland easement. These costs are not insubstantial for practices such as LS mitigation which involve extensive regulatory compliance, long-term contracts or easements, and

[17] Cost estimates of LS restorations in York County provided by the engineering and design firm Johnson, Mirmiran, & Thompson, Inc. are also approximately $350 per linear foot of stream length.

[18] Email Communication with James M. Kreider, Director of Field Operations & Environmental Scientist, LandStudies, Inc., June 21, 2018.

thus it is necessary to include such costs in the overall assessment of LS mitigation.[19] While analyses of BMP cost-effectiveness have not always explicitly included this component of cost (e.g. Wieland et al. 2009), such regulatory costs can be considered part of the transaction costs of practice adoption. Transaction costs have gained increasing attention in economic literature on NPS abatement practices (e.g. McCann et al. 2005; Peterson et al. 2014), and are an important component of overall practice adoption costs.

Note that approximately 22,000 tons of sediment were removed from the BSR site. This sediment was sold for $3 per ton as part of a brownfield restoration in Lancaster ($66,000 in revenue). The removed sediment may serve as a commodity to partially offset practice implementation costs. It is expected that this cost offset will be available in future restorations, since all legacy sediment sites will require the partial removal sediment. However, in order to be conservative in the cost estimates of the LS mitigation practice, we do not include this possible revenue stream.[20]

In order to compare the gross practice implementation cost with other comparison practices, it is necessary to place it in terms of a cost per acre. Given the 4.7 acre BSR restoration site, the practice adoption cost is $203,372 per acre for a LS mitigation practice completed today, of similar size and scope as that completed at Big Sprig Run. The upfront costs for LS mitigation are more than five times those reported for wetland restoration at sites not primarily characterized by legacy sediment. For example, Wieland et al. (2009) report a cost of $40,000 per acre for wetland restoration that requires moving two feet of soil and planting wetland plants on 18 inch centers ($40,000 per acre (p. 26). The higher costs observed at BSR were due to the need to remove substantially more than two feet of soil from the exposed stream bank. To the extent that LS mitigation at different sites requires lesser or greater quantities of soil removal, the upfront costs for restoration will differ accordingly.

For purposes of comparison with other practices, it is also necessary to convert upfront costs per acre to *annualized* costs per acre. The CBP Wetland Expert Panel Report (2016) does not make a specific recommendation for the expected lifetime of wetlands, however regulatory

[19] For the BSR project, regulatory costs (particularly permitting and design, but also closing costs and title for easement) amounted to approximately $100,000, or $21,277 per acre.
[20] Similarly, for the sake of consistency we do not include potential revenue streams which may arise from the use of any of the practices analyzed in this report.

policies in relation to wetlands in the region almost exclusively utilize easements in perpetuity.[21] The expectation is that established wetlands will continue to provide ecosystem benefits—including sediment and nutrient load reduction—for the foreseeable future. The standard economic approach to account for benefits or monetary payments in perpetuity is to discount those payments to present value terms using a discount rate, r. That is, the total present value (*PV)* of an annual series of payments continuing in perpetuity (C), is expressed as:

(2) $$PV = C / r$$

Importantly, a one-time payment can also be converted to *an annual series of payments* by reversing the equation, such that:

(3) $$C = PV \cdot r$$

Specifically, the cost per acre for LS mitigation in the present time period, *PV*, was described above as $203,372 per acre. In order to place this cost in annualized terms, the primary empirical question becomes the choice of discount rate, r.

Guidelines provided by the U.S. EPA for cost-benefit analyses involving future benefits or costs suggest using a *social discount rate* based on the shadow price of capital, which represents how society trades and values consumption over time (US EPA 2010). Empirical evaluations of the shadow price of capital typically use low-risk, historical rates of return on "safe" assets such as U.S. Treasury securities or the cost of government borrowing. The average cost of government borrowing was estimated by the Congressional Budget Office (CBO) to be 2 percent, which is also the discount rate used by the CBO itself in analyses of future costs and benefits of U.S. policies (US EPA 2010, p. 6-10). We likewise use a social discount rate $r_s = 0.02$ for this analysis (see Section V.C for a sensitivity check using a range of discount rates).

Under the social rate of discount of $r=0.02$, the annualized upfront practice adoption cost of LS mitigation (not including ongoing maintenance or payments for the opportunity cost of land) is $4,067 per acre, calculated as in equation (3). We follow the guidelines of the U.S. EPA in concluding that the lower discount rate of $r=0.02$ is more appropriate for investments that involve environmental benefits accruing over a long time period, such as LS mitigation. This reflects the greater importance of future benefits to society as a whole.

[21] Email correspondence with Hathaway Jones, USDA NRCS, December 19, 2017.

Nonetheless, sensitivity checks using higher discount rates are shown in Section V.C. For example, a discount rate of $r_h = 0.05$ results in annualized adoption costs (not including ongoing maintenance or opportunity costs) of $10,169 per acre. Higher discount rates tend to decrease the relative cost-effectiveness of LS mitigation in comparison with shorter-lived conservation practices like cover crops, because the value of future benefits are discounted more steeply. However, the use of a higher discount rate does not alter the ranking of cost-effectiveness found in this report. Even using $r_h = 0.05$, LS mitigation is still more cost-effective in terms of sediment and phosphorus abatement than the other practices analyzed below.

(ii) Maintenance and monitoring costs. In addition to the upfront construction and regulatory costs, it is necessary to consider potential ongoing costs of maintenance and monitoring for proper wetland functioning. According to the Wetland Expert Panel Report, restored wetlands in agricultural or wooded areas—as opposed to constructed wetlands in (sub)urban areas—typically do not require ongoing maintenance such as periodic dredging (CBP Wetland Expert Panel Report 2016). Nonetheless, the BSR restoration included post-restoration maintenance and monitoring as part of its budget, primarily for control of invasive species. This cost for post-restoration maintenance and monitoring was approximately $10,000. Beyond the first five years, no ongoing maintenance has been required. For completeness, we include the maintenance and monitoring cost of $10,000 in this report. This amounts to $2,128 per acre on the 4.7 acre wetland site. We place this cost in annualized terms using the same methodology described above.

(iii) Opportunity cost of land. The final cost component for LS mitigation is the opportunity cost of land. Since land restored to a wetland may have had value to its owner as productive farmland (in this case, land extending back from the stream bank of the legacy sediment site), the opportunity cost represents the market value that could have been obtained by farming it.

When determining compensation paid to landowners for wetland easements in Pennsylvania, the NRCS ACEP-Wetland Reserve Enhancement (WRE) program conducts an analysis of market land values under various uses: including cropland, pasture, and wooded/other. For fiscal year 2018, this market analysis resulted in a value per acre of $6,890 for cropland in Lancaster County.[22] Wetland easement payments are then made according to a Geographic Area Rate Cap (GARC) of 95% of the market analysis value, or $6,546 for cropland in Lancaster County.

Since the WRE easement payments represent the value of agricultural production rights foregone by the landowner in perpetuity, it must be converted to an annualized value through a discount rate. In this case, the higher individual discount rate of $r_h = 0.05$ is most appropriate, as opposed to the social discount rate, since the easement payment reflects individual foregone investment opportunities for the landowner. At this discount rate, the easement value of $6,546 per acre results in an implied annual opportunity cost of $327 per acre—which is very similar to average cash rental rates for farmland in the region. Thus, we use the NRCS WRE easement values to estimate the opportunity cost of land for wetland restoration, since this is the NRCS program that would most likely be used to compensate landowners for wetland restoration in the study region.

(i) + (ii) + (iii) + (iv). Total cost per acre. Combining the four cost components for LS mitigation, we obtain a total annualized cost of $4,437 per acre per year for this practice. A summary is shown in Table 6.

B. Forest and Grass Riparian Buffers

Like other BMPs that involve land use change, forest and grass riparian buffers require consideration of (i) upfront practice adoption costs, (ii) maintenance costs, and (iii) opportunity costs of land.

(i) Upfront practice adoption costs. For forest riparian buffers, upfront practice adoption costs will vary based on planting rates, chemical control for plant competition, and the use of tree shelters as protection against herbivore browsing.[23] Wieland et al. (2009) find practice adoption costs of approximately $800 per acre based on planting rates of 435 trees (10’ by 10’ spacing)

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[22] Email correspondence with Hathaway Jones, January 30, 2018. The list of Pennsylvania NRCS ACEP Geographic Area Rate Caps in FY 2018 are shown in Appendix B. The market value in Lancaster County is $4,470 for pasture, and $3,810 for wooded.

[23] Regulatory compliance costs for forest or grass buffers are negligible.

and spot herbicide treatments. Adding tree shelters for 200 trees would roughly double the per-acre cost (p. 18). For grass buffers, upfront practice adoption costs are generally lower than for forest buffers. These include site preparation, seed costs, and seeding. Wieland et al. (2009) estimate practice adoption costs of $325 per acre for cool season grasses, and $425 per acre for warm season perennial grasses.

Nonetheless, after outlining the itemized costs for buffer adoption, Wieland et al. (2009) use USDA Conservation Reserve Enhancement Program (CREP) incentive payments as the best general approximation of the practice adoption costs for both forest and grass buffers. We follow a similar approach, using the average cost-share payment per-acre in south-central Pennsylvania for forest buffers in 2017 and 2018, which was $1,812 per acre for CP22 (forest riparian buffers).[24] This number is consistent with the itemized cost reported by Wieland et al. (2009) when tree shelters are utilized. For grass buffers, we were not able to obtain similar USDA CREP payment information for recent years in Pennsylvania, and we therefore use the per-acre practice cost cited in Wieland et al. (2009) of $377 per acre.[25] This number is within the range of the itemized costs described above for cool season and warm season grasses.

As with LS mitigation, these upfront adoption costs must be expressed in annual terms in order to compare with other practices. The CBP Riparian Buffer Expert Panel Report (2014) recommends a lifetime of 40 years for forest buffers, and does not provide a specific recommendation for the lifetime of grass riparian buffers. However, riparian buffer establishment does not typically involve easements in perpetuity, like wetland restoration. Rather, typical CREP/CRP contract lengths are 15 years for forest buffers, after which point the continued effectiveness of the buffer is uncertain. Therefore, we distribute the upfront cost of forest buffer establishment over the 15-year contract period, and distribute the grass buffer establishment cost over a 10-year period (which is a more typical contract length utilized for grass buffers).[26] This results in annualized establishment costs of $121 and $38 per acre for

[24] Calculated as the FSA cost-share payment, plus the Pennsylvania State cost-share payment, including one-time Practice Incentive Payments.
[25] Note that the CBP / CAST upfront cost for grass buffers—based on 2011 NRCS payments for the practice in Pennsylvania—are similar ($393 per acre). See CAST cost data here: https://cast.chesapeakebay.net/Documentation/BMPsModelsGeography
[26] Communication with Alexis Tirado, Agricultural Program Specialist, USDA FSA, March 2, 2018. Note that Wieland et al. (2009) also use a 15-year contract period to distribute the costs of forest buffers, and a 10-year contract period for grass buffers.

forest and grass buffers, respectively. The upfront establishment costs are distributed evenly over the contract period for the sake of simplicity; if we had incorporated an opportunity cost of current-period spending for these practices—i.e. a discount rate greater than zero—their annualized per acre costs would slightly increase.

(ii) Maintenance costs. Maintenance costs for buffer establishment and for continued ecosystem functioning of buffers also need to be considered. This is especially the case in the initial phases of establishment of forest riparian buffers. The USDA's *Landowner Guide to Buffer Success* (USDA CREP 2007), shows that the first five years of forest buffer growth require regular maintenance. This includes checking shelters for damage, monitoring for invasive species and herbivory, applying herbicide, and removing nets and shelters at the appropriate time. At a minimum, this ongoing monitoring and maintenance is expected to require 20 hours of landowner time per year, for each acre of forest buffer during the first five years of establishment.[27] At a custom rate for skilled agricultural labor of $20 per hour (see Pennsylvania custom rate guide, USDA NASS 2016), this corresponds to annual maintenance costs of $400 per acre for the first five years of establishment ($2000 total). In annualized terms, this maintenance cost can be spread out over the fifteen-year forest buffer contract to $133 per acre per year. Maintenance costs for grass buffers are considered to be negligible when properly seeded, and therefore not included here.

(iii) Opportunity cost of land. Forest and grass riparian buffers require land to be removed from agricultural production for their establishment to occur. As with wetland restoration, the opportunity cost of the foregone production on this land therefore represents an important aspect of total practice cost.

When determining compensation paid to landowners for riparian buffers in Pennsylvania, the FSA CREP program pays what is considered a fair market rate to offset the value of foregone agricultural production, as well as to provide additional incentive to landowners. In Lancaster County, CREP annual payments for riparian buffers range from $290 to $580 per acre.[28] Each landowner contract is determined on an individual basis, however typical soil types in Lancaster

[27] Communication with Peter Hoagland, State Forester, USDA NRCS, March 14, 2018.
[28] Communication with Stephanie Hartz, USDA FSA, December 13, 2018.

County imply a per acre payment that often falls on the upper range of this scale, at $580 per acre. Note that CREP payments differ from landowner incentive payments offered by USDA-NRCS programs. We use the USDA-CREP incentive payments to estimate opportunity costs because CREP is the program actually used to compensate landowners for buffer implementation in the study region.

(i) + (ii) + (iii). Total cost per acre. Combining the three relevant cost components for forest and grass riparian buffers, we obtain a total annualized cost of $834 per acre per year for forest buffers, and $618 per acre per year for grass buffers. A summary is shown in Table 6.

C. Wetland Restoration at Other Sites

The cost structure of wetland restoration is similar to that of LS mitigation, since restoration of LS erosion hotspots often involves restoration of aquatic ecosystems including wetlands. The cost amounts are different, however, due to the larger upfront costs of LS mitigation with removal of sediment and streambank grading. However the basic structure of costs remains (i) upfront costs for practice adoption, (ii) maintenance costs, and (iii) opportunity costs of land.

(i) Upfront practice adoption cost. Wieland et al. (2009) estimate upfront costs for restoration using publicly funded program costs, but they note that these costs are much lower than that reported by firms that undertake wetland restoration. For example, using CREP funding for CP23 (wetland restoration) and CP30 (marginal pasture wetland buffer), they find an average CREP payment of $3,290 per acre over a ten-year period in Maryland. In contrast, information provided by the firm Environmental, Inc., which undertakes wetland restoration projects in Maryland, indicates that wetland restoration costs easily rise to $40,000 per acre if such restoration requires excavation, grading, and subsequent planting wetland plants at $1.00 to $1.50 per plug (on 18 inch centers).

Note that the wide range of upfront costs in restoring wetlands is indicative of the wide range of specific implementation methods. However, these specific methods are not specified in the description of this BMP or, generally speaking, in the accounting of their nutrient reduction.[29] Even when focusing on wetland restoration at sites not identified as legacy sediment / erosion hot-spots, a wide range of implementation practices still exist.[30]

According to communication with the firm LandStudies, Inc., which implements wetland restoration in the study region, the estimates provided by Wieland et al. (2009) significantly understate the cost of wetland restoration. This firm has observed a range of costs for wetland restoration from $75,000 per acre to as high $160,000 per acre, for projects less than an acre to 15 acres in size, with an average of approximately $120,000 per acre.[31] These costs must be placed in annualized terms for the purpose of comparison across practices. As with LS mitigation, the standard economic approach in these cases is to use a discount rate to infer the annual costs implied by the one-time payment. Following the same method described above in the section on costs of LS mitigation, we use a social discount rate of $r_s=0.02$ to obtain annualized costs of $2,400 per acre, based on the one-time payment of $120,000 per acre (Table 6).

(ii) Maintenance and monitoring costs. The maintenance and monitoring costs required to ensure the ecosystem function of restored wetlands are expected to be similar to those required for wetland restoration as part of LS mitigation. Therefore, we use the same maintenance and monitoring cost per acre as that observed at Big Spring Run, of $2,128 per acre. This cost is primarily incurred in the first five years following restoration. Spreading out this cost over the wetland easement period, using the same discount rate described above of $r_s=0.02$, results in annualized costs of $43 per acre per year. Unlike created wetlands in urban or suburban areas, ongoing maintenance such as dredging is not expected for restored wetlands in rural areas (CBP Wetland Expert Panel Report 2016).

(iii) Opportunity cost of land. Finally, the opportunity cost due to foregone production on land previously in crops or pasture would once again be the same for this practice as for LS mitigation, since both practices involve the purchase of wetland easements from landowners. We

[29] The Wetland Expert Panel Report distinguishes nutrient reduction potential by physiographic subregion, and whether or not the wetland is in a floodplain.
[30] Separately modeling the effects of wetland restoration at legacy sediment sites is a critical step in the direction of accounting for heterogeneity in wetland restoration.
[31] Email communication with James M. Kreider, LandStudies, Inc., June 21, 2018.

therefore use, as before, the USDA-WRE Geographic Area Rate Caps (GARCs) for cropland in Lancaster County ($6,546 per acre). This results in an annual opportunity cost of $327 per acre, which is the same as the opportunity cost for LS mitigation involving wetland restoration.

(i) + (ii) + (iii). Total cost per acre. Combining the four cost components for wetland restoration at other sites, we obtain a total annualized cost of $2,770 per acre per year for this practice. A summary is shown in Table 6.

D. Cover Crops

Unlike the previous conservation practices analyzed, cover crops are implemented on working land, and so do not involve opportunity costs for foregone production. Moreover, as an annually implemented practice, the costs are already expressed in annualized terms and do not involve ongoing maintenance. The only cost component to consider, therefore, is upfront practice adoption in the form of seed and planting costs.

Cover crop establishment costs vary based on the type of seed purchased, and the planting method used. Different planting methods—no-till drill, aerial broadcasting, and others—involve slightly different amounts of labor, fuel, and equipment costs. However, for a given seed mix, the planting costs are very similar. For example, Wieland et al. (2009) show a range of costs of $31.40 to $34.80 per acre for rye, $32 to $35.50 for barley, and $33.40 to $37.30 for wheat. For the sake of consistency, we consider the costs of drilled rye as a reference point, which correspond to the cover crop nutrient-reduction levels reported in the previous section, and are a typical cover crop and planting method used in Lancaster County. Wieland et al. (2009) show a cost of $31.40 per acre for drilled rye, based on seed prices and custom planting rates from 2008.

It is important to observe that most cost-sharing programs for cover crops provide a substantially higher per-acre payment than the implementation costs identified by Wieland et al. (2009). For example, the Maryland Agricultural Cost Share (MACS) program—which subsidizes the adoption of cover crops on over 40% of the harvested cropland in the state—uses a base payment of $45 per acre for rye cover crops, with an added bonus of $20 per acre if the rye is planted early (MACS Annual Report 2016). The USDA Environmental Quality Incentives Program (EQIP) lists a payment of $66.03 per acre for single-species cover crop planting in

Pennsylvania, which is designed to cover 75% of practice adoption costs. The EQIP payment schedule implies a cost of $88.04 per acre in Pennsylvania. We therefore use a cover crop cost of $88.04 per acre, to correspond with planting a single-species cover crop in the study region.

One reason that this cost per acre is higher than that estimated by Wieland et al. (2009) is that seed costs have risen substantially over the past ten years. For example, fall 2017 seed costs for cereal rye were $16 per bag from a representative seed distributor in Lancaster County, which results in seed costs of $48 per acre at recommended planting rates.[32] When also considering the cost of time, fuel, and capital (equipment), the cost of $88 per acre implied by current cost-share rates is closer to a farmer's total cover crop implementation costs than the numbers reported in 2009.[33]

V. Cost Effectiveness Summary and Robustness Checks

Data on the cost and abatement per acre is utilized to calculate the cost effectiveness of conservation practice implementation in terms of the cost per pound of sediment, P and N reduced for each practice. Following equation (1) above, once the necessary data is in hand the cost-effectiveness calculation becomes a straightforward application of division.

Table 7 summarizes the cost effectiveness results. LS mitigation is the most cost effective practice analyzed for sediment and phosphorus reduction, by a substantial margin. This practice reduces sediment loads at approximately 1/18th of the unit cost of grass riparian buffers, the next most cost-effective practice. For phosphorus loads, the results are similarly stark, with LS mitigation reducing phosphorus pollution—which tends to bind tightly to soil particles—at 1/68th the unit cost of the next most cost-effective practice, forest riparian buffers. Since the LS mitigation practice faces high upfront costs, this result is clearly driven by the extremely high sediment and phosphorus loads that have been measured at legacy sediment erosion hot spots such as Big Spring Run. The pollution reduction actually obtained by addressing the LS load source is substantially higher, per dollar spent, than that from by the most cost-effective upland conservation practices, using the parameters given by CBP water quality model. For nitrogen

[32] Conversation with King's Agriseeds, June 4, 2018. Recommended planting rates are 168 pounds per acre, and rye seed is sold in approximately 56 pound bags.
[33] Note that the Wieland et al. (2009) cost also does not consider discing or turbo-tilling land prior to planting in the fall. If land preparation is required after harvest, the costs would increase.

abatement, cover crops are the most cost effective mitigation practice. This practice has relatively low upfront costs, does not require removing land from production (and therefore does not require annual compensation to landowners), and is known to be effective at reducing nitrogen leaching to the groundwater. However, other practices analyzed are competitive with cover crops in their cost effectiveness. LS mitigation, and grass or forest riparian buffers are each approximately only 1.5 times the unit cost of cover crops, with grass riparian buffers as the second most cost-effective practice based on CBP model parameters.

Estimates of cost-effectiveness for any NPS pollution reduction practice rely on several key modeling decisions. For example: (i) What is the surrounding or existing land use that produces the load to be treated by the practice; (ii) What geographic regions are considered most relevant for the analysis; and (iii) for investments that involve an upfront cost with future benefits, what discount rate should be used to convert one-time payments to annualized terms. The above results are tested against each of these decisions in turn.

A. Robustness of Results to Different Land Uses

Different land uses will produce different amounts of sediment, P, and N pollution load. For "efficiency" BMPs such as cover crops, which remove a percent of load from an existing tract of land, the land use on which the practice is implemented will determine how much load is available to be treated. For "load source conversion" BMPs such as riparian buffers, wetland restoration, or—as described in this report—LS mitigation, the prior land use which the conservation practice replaces likewise determines the abatement potential of the practice. Finally, practices that combine both the "load source conversion" and "efficiency" BMP characteristics—such as riparian buffers, wetlands, and LS mitigation, which all remove a percent of load from upland (or upriver) sources—both the existing land use and surrounding land uses are critical determinants of the practice's abatement potential.

In this report, the land use that was utilized was "grain with manure" (gwm) in the CBP model. This was chosen as representative of crop agriculture in the region, given the predominance of corn in the region, and the common practice of applying manure as a fertilizer in Lancaster County. For the purpose of calculating cost-effectiveness, it was also important to focus on an agricultural land use since agricultural conservation practices are typically considered to have the lowest unit cost of NPS pollution reduction. Yet the CBP water quality model includes a number of other agricultural land uses aside from "grain with manure", both for crop agriculture (soybeans, small grains, etc.) and livestock (pasture, and riparian pasture deposition).

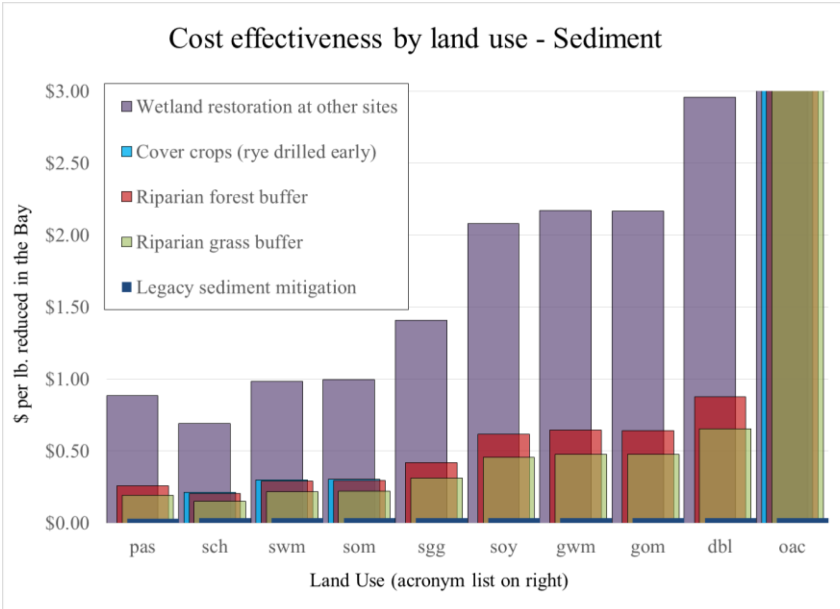
Figures 3 to 5 show how the cost-effectiveness results for sediment, phosphorus, and nitrogen change under different agricultural land uses in the CBP water quality model. The land-use acronyms utilized in the model are described on the right-hand panel of each figure. Results are quite consistent across land uses. The overall ranking of practices in terms of cost-effectiveness does not change, and while the absolute magnitudes of unit costs vary considerably (lower unit costs arise when the practices are applied to higher-polluting land uses, and vice versa), the relative magnitudes of unit costs across practices are consistent. LS mitigation reduces sediment loads at approximately 1/6th the cost of other practices when the surrounding land use is pasture, 1/14th for grain with manure, and 1/20th for other agronomic crops such as tobacco or sweet corn. The relative cost advantage for LS mitigation in terms of phosphorus reduction is similarly consistent across land uses, ranging from approximately 1/10th to 1/70th the cost of other practices. For nitrogen, unit costs are also consistent across land uses, with cover crops as the most cost-effective practice, but generally only 1 to 2 times more efficient than the other practices (except for pasture and associated animal riparian deposition, a land use to which cover crops do not apply). In sum, the results of this report are robust to different land uses in the CBP model, and the cost-effectiveness of LS mitigation in comparison to other practices is not driven by the choice of a particular surrounding land use.

B. Robustness of Results to Different Geographic Regions

Geographic variation is accounted for in the CBP model by dividing the Chesapeake Bay watershed into over 2,000 river segments, each with uniquely modeled amounts and types of load. Each load source in the CBP water quality model may produce varying amounts of load in different river segments.

In this report, average loads across all river segments in the Bay watershed were utilized to estimate abatement. Since streams throughout the mid-Atlantic region are characterized by the legacy of mill dams and other historic impediments, it was important to consider the cost-effectiveness of addressing this load source in the watershed as a whole. However, the Big Spring Run restoration that exemplified the LS mitigation practice in this report is in Lancaster

Figure 3. Cost effectiveness of sediment abatement in the Chesapeake Bay by land use

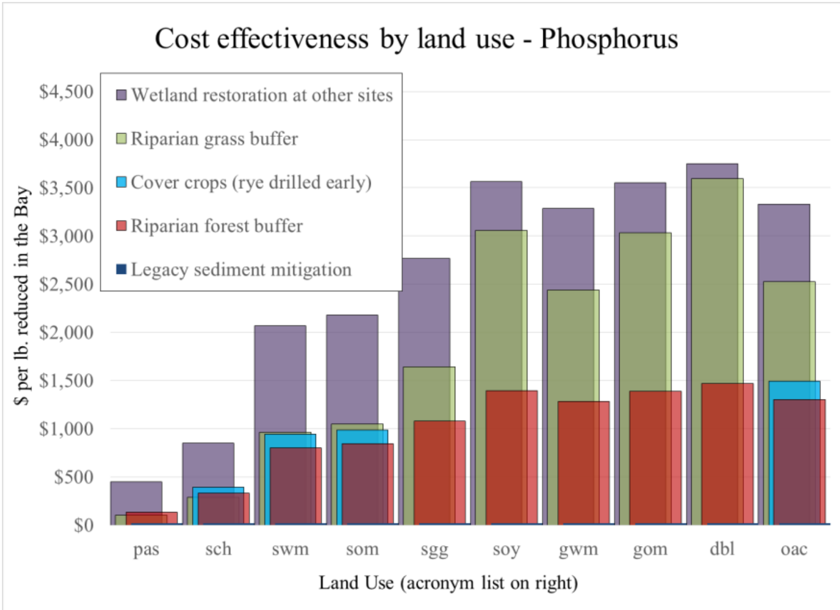


Land Use Acronyms
pas = pasture*
sch = specialty crop high (vegetables)
swm = silage with manure
som = silage without manure
sgg = small grains & grains
soy = full-season soybeans
gwm = grain with manure
gom = grain without manure
dbl = double-cropped
oac = other agronomic crops (sod, sweet corn, tobacco)

**Pasture includes animal riparian deposition load source*

Notes: For legacy sediment mitigation, land uses determine the upland loads filtered by the restored wetland / aquatic ecosystem. For riparian buffers (both grass and forest) and wetland restoration at other sites, land uses determine both the pre-existing load prior to practice implementation, as well as the upland loads filtered by the practice. For cover crops, land uses determine the loads to which the cover crop efficiency factor is applied. Cover crops are modeled to reduce sediment and phosphorus on the following land uses only: sch, swm, som, and oac. Pounds reduced in the Bay accounts for percent delivery factor from edge-of-stream to the Chesapeake Bay.

Figure 4. Cost effectiveness of phosphorus abatement in the Chesapeake Bay by land use



Land Use Acronyms
pas = pasture*
sch = specialty crop high (vegetables)
swm = silage with manure
som = silage without manure
sgg = small grains & grains
soy = full-season soybeans
gwm = grain with manure
gom = grain without manure
dbl = double-cropped
oac = other agronomic crops (sod, sweet corn, tobacco)

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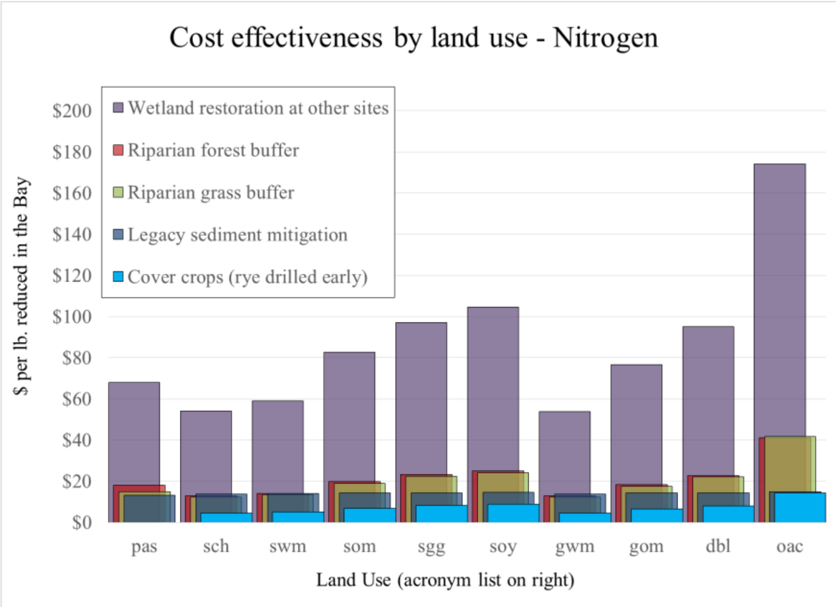
Figure 5. Cost effectiveness of nitrogen abatement in the Chesapeake Bay by land use



Land Use Acronyms

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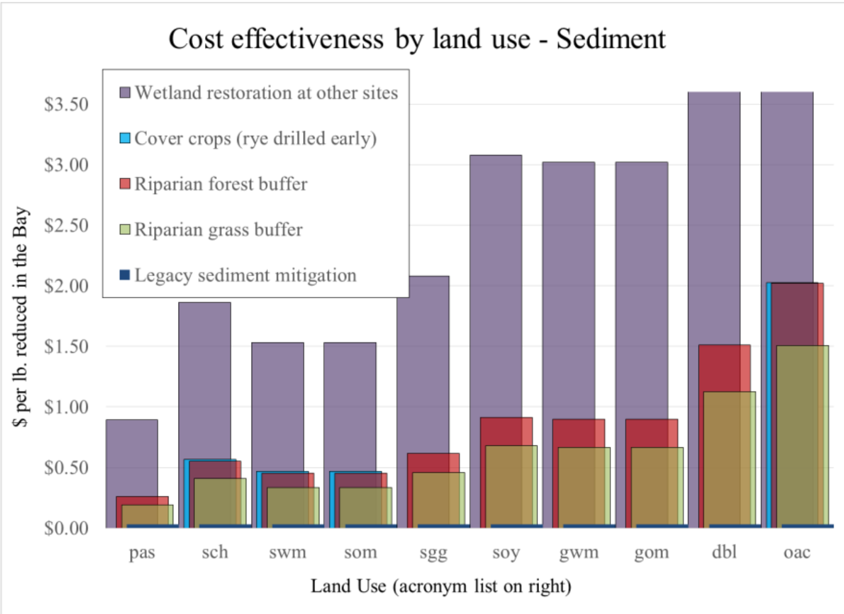
County, which contains fifteen river segments in the Susquehanna River basin. Sediment loads from most agricultural land uses in these fifteen river segments are modeled to be slightly lower than those in the watershed as a whole, while phosphorus and nitrogen loads are generally modeled 2-3 times higher for most agricultural land uses in the County. However, the load source of riparian pasture deposition is modeled to be about 11 times higher in Lancaster County than the watershed as a whole, for all three pollutant types.

As a robustness check, Figures 6 to 8 show the cost-effectiveness when using the loads modeled in Lancaster County's river segments, for various agricultural land uses. Results are consistent to what they were when using Bay-wide loads. Due to the higher modeled phosphorus and nitrogen loads, riparian buffers and cover crops take on relatively lower unit costs in Lancaster County, however the ranking of practices by unit cost is the same. LS mitigation remains the most cost-effective means of sediment and phosphorus abatement, with unit costs 6 to 35 times lower than the next most effective practice for sediment, and 5 to 27 times lower for phosphorus. Cover crops reduce nitrogen loads at the lowest unit cost in Lancaster, at 2 to 6 times lower than the cost of the other practices. In sum, while the magnitude of cost-effectiveness changes, the qualitative results of this study are unchanged when using Lancaster County loads.

C. Robustness of Results to Different Discount Rates

To place future cost or benefits in present-value terms, one of the primary empirical modeling decisions is the choice of discount rate, *r*. Discounting is a critical piece of both cost-benefit and cost-effectiveness analyses by expressing monetary values in present, annualized terms.
Using guidelines provided by the U.S. EPA for environmental analyses involving future costs or benefits, in this report a social discount rate was utilized. Social discount rates are lower than private discount rates, because they represent a lower willingness to trade-away future benefits for current consumption, whereas private discount rates represent an individual's trade-offs between present and future consumption based on that person's investment opportunities. For this reason, use of a social discount rate is generally preferred in economic analyses involving societal decisions, and it implies that future benefits are discounted less, or valued more highly, when considering society as a whole.

Figure 6. Cost effectiveness of sediment abatement in Lancaster County by land use



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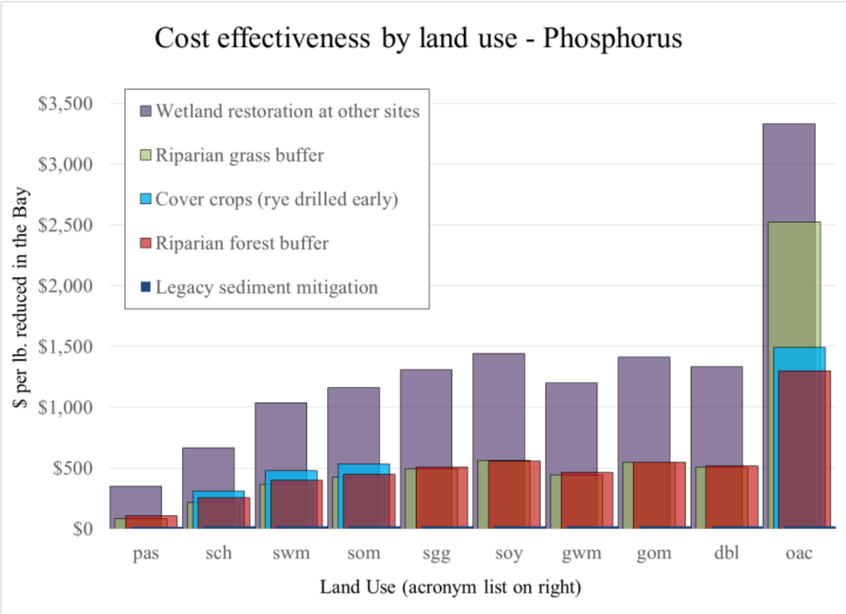
**Pasture includes animal riparian deposition load source*

Notes: For legacy sediment mitigation, land uses determine the upland loads filtered by the restored wetland / aquatic ecosystem. For riparian buffers (both grass and forest) and wetland restoration at other sites, land uses determine both the pre-existing load prior to practice implementation, as well as the upland loads filtered by the practice. For cover crops, land uses determine the loads to which the cover crop efficiency factor is applied. Pounds reduced in the Bay accounts for percent delivery factor from edge-of-stream to the Chesapeake Bay.

Figure 7. Cost effectiveness of phosphorus abatement in Lancaster County by land use



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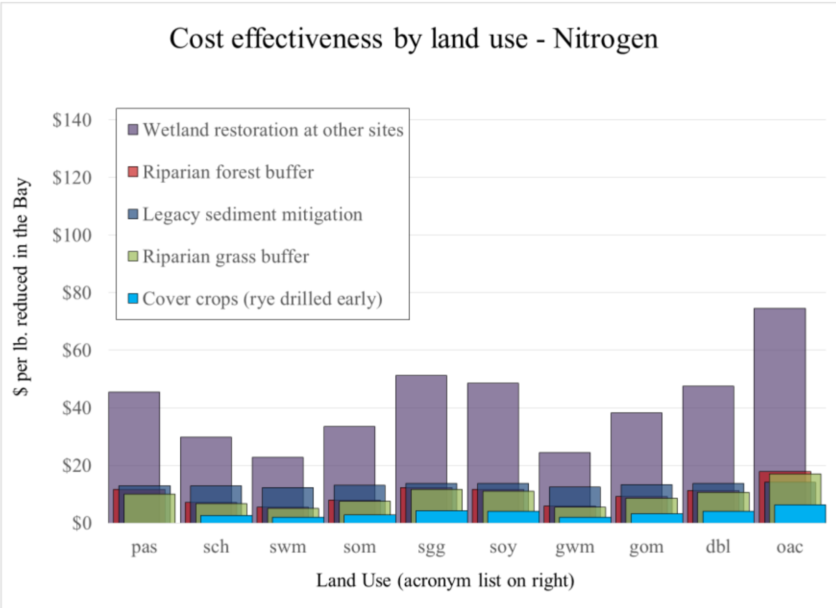
**Pasture includes animal riparian deposition load source*

Notes: For legacy sediment mitigation, land uses determine the upland loads filtered by the restored wetland / aquatic ecosystem. For riparian buffers (both grass and forest) and wetland restoration at other sites, land uses determine both the pre-existing load prior to practice implementation, as well as the upland loads filtered by the practice. For cover crops, land uses determine the loads to which the cover crop efficiency factor is applied. Pounds reduced in the Bay accounts for percent delivery factor from edge-of-stream to the Chesapeake Bay.

Figure 8. Cost effectiveness of nitrogen abatement in Lancaster County by land use



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Notes: For legacy sediment mitigation, land uses determine the upland loads filtered by the restored wetland / aquatic ecosystem. For riparian buffers (both grass and forest) and wetland restoration at other sites, land uses determine both the pre-existing load prior to practice implementation, as well as the upland loads filtered by the practice. For cover crops, land uses determine the loads to which the cover crop efficiency factor is applied. Pounds reduced in the Bay accounts for percent delivery factor from edge-of-stream to the Chesapeake Bay.

The primary results of this analysis were based on a social discount rate of $r_s = 0.02$, the same rate used by the CBO in analyses of national policies involving future costs and benefits. Some practitioners use a social discount rate of $r_s = 0.03$. Additionally, it can be useful to test the sensitivity of results to the use of higher, private discount rates such as $r_p = 0.05$.

Tables 8 and 9 show the sensitivity of results to the choice of different discount rates. Using a higher social discount rate of $r_s = 0.03$, the cost of LS mitigation increases to $6,492 per acre, from $4,437 per acre under the lower social discount rate of 0.02. When using the private discount rate ($r_p = 0.05$), the annualized cost per acre increases further to $10,602, representing a higher opportunity cost of current spending (Table 8). Nonetheless, even under the private discount rate, the overall results are unchanged insofar as LS mitigation remains the most cost-effective form of phosphorus and sediment abatement by a wide margin, and maintains unit costs of nitrogen abatement within a similar magnitude as the other low-cost practices (Table 9). Practices such as cover crops and riparian buffers—which both do not require permanent easements—become relatively more cost-effective when a higher discount rate is used, yet the qualitative results of this report are consistent. Social discount rates are the most defensible choice in economic analyses of investments that affect future generations as a whole, including environmental investments, yet it is important to verify that the primary cost-effectiveness results of this report are robust to a range of discount rates.

Any cost-effectiveness analysis of NPS pollution reduction practices will depend in part upon certain modeling specifications and assumptions. In this report, the overall qualitative results are robust to a variety of specifications, including the use of loads from different agricultural land uses, different geographic regions, and higher discount rates. LS mitigation remains a cost effective practice under various modeling scenarios, and the consistency of this result is due to the particularly large water quality benefits that arise from directly addressing the elevated loads found at legacy sediment hot spots.

VI. Conclusion

To address NPS water pollution, federal and local governments will likely spend hundreds of millions of dollars in the coming years in order to incentivize the adoption of additional best management practices. However, NPS pollution has proved to be a "wicked" challenge for policymakers to address, characterized by uncertainty and complex interactions of economic and hydrologic systems along multiple dimensions (Shortle and Horan 2017). A recent summary of research indicates, in fact, that the adoption of conventional conservation practices is not directly linked to measurable pollution reduction in most streams (Keisman et al. 2018). Novel approaches to NPS pollution reduction are needed to meet policy goals.

The data reviewed in this report indicates that LS mitigation—when implemented at appropriate locations characterized by elevated stream bank loads—produces substantial, measurable pollution reduction at a very low unit cost. For watersheds targeting phosphorus or sediment reduction, LS mitigation is markedly more cost-effective in comparison to other conservation practices commonly considered low cost. For watersheds targeting nitrogen reduction, addressing legacy sediments also reduces nitrogen loads at a similar unit cost in comparison to the other low-cost practices analyzed. These results are robust to various modeling specifications, including different land uses, geographic regions, and rates of discount.

Therefore, an implication of this review of data is that LS mitigation should be carefully considered among the suite of tools utilized to meet NPS pollution reduction goals. When applied to sites with elevated loading rates from legacy sediments, such as that found at Big Spring Run, NPS policy goals can be met at a fraction of the long-term cost by investing upfront in eliminating those loads.

The legacy of prior land use decisions has powerful implications for the development of cost-effective water quality policy today. Given the high number of legacy sediment sites in the mid-Atlantic region of the United States, greater awareness and implementation of LS mitigation should be promoted, as jurisdictions develop watershed implementation plans (WIPs) to meet water quality goals. Strategies for achieving the TMDL that exclusively focus on upland practices may be insufficient, without consideration of the opportunity for additional abatement achieved by directly addressing the elevated sediment and nutrient loads at legacy sediment sites.

References

Chesapeake Bay Program (CBP) Stream Restoration Expert Panel Report, 2013. Berg, J., Burch, J., Cappuccitti, D., Filoso, S., Fraley-McNeal, L., Goerman, D., Hardman, N., Kaushal, S., Medina, D., Meyers, M., Kerr, B., Stewart, S., Sullivan, B., R. Walter & J. Winters. 2013. Recommendations of the Expert Panel to Define Removal Rates for Individual Stream Restoration Projects.

Chesapeake Bay Program (CBP) Riparian Buffer Expert Panel Report, 2014. Belt, K., Groffman, P., Newbold, D., Hession, C., Noe, G., Okay, J., Southerland, M., Speiran, G., Staver, K., Hairston-Strang, A., Weller, D., & D. Wise. Recommendations of the Expert Panel to Reassess Removal Rates for Riparian Forest and Grass Buffers Best Management Practices.

Chesapeake Bay Program (CBP) Cover Crop Expert Panel Report, 2016. Staver, K., White, C., Meisinger, J., Salon, P., & W. Thomason. 2016. Cover Crops Practices for use in Phase 6 of the Chesapeake Bay Watershed Model. CBP/TRS-310-16.

Chesapeake Bay Program (CBP) Conservation Tillage Expert Panel Report, 2016. Thomason, W., Duiker, S., Ganoe, K., Gates, D., McCollum, B., & M. Reiter. 2016. Conservation Tillage Practices for use in Phase 6 of the Chesapeake Bay Watershed Model. CBP/TRS-308-16.

Chesapeake Bay Program (CBP) Wetland Expert Panel Report, 2016. Mason, P., Spagnolo, R., Boomer, K., Clearwater, D., Davis, D., Denver, J., Hartranft, J., Henicheck, M.,McLaughlin, E., Miller, J., Staver, K., Strano, S., Stubbs, Q., Thompson, J. & T. Uybarreta. 2016. Wetlands and wetland restoration: Recommendations of the Wetland Expert Panel for the incorporation of non-tidal wetland best management practices (BMPs) and land uses in the Phase 6 Chesapeake Bay Watershed Model. CBP/TRS314-16.

Chesapeake Bay Program, 2018. Chesapeake Bay Program Quick Reference Guide for Best Management Practices (BMPs): Nonpoint Source BMPs to Reduce Nitrogen, Phosphorus and Sediment Loads to the Chesapeake Bay and its Local Waters. CBP/TRS-323-18. https://www.chesapeakebay.net/documents/BMP-Guide_Full.pdf

De Cunzo, L., and A. Garcia, A., 1993. "Neither a Desert or a Paradise:" Historic Context for the Archaeology of Agriculture and Rural Life, Sussex County, Delaware, 1770 – 1940. University of Delaware Center for Archaeological Research, Newark. On file, Delaware State Division of Historical and Cultural Affairs, Dover.

Gellis, A.C., and J.W. Brakebill, 2013. Science summary--sediment sources and transport in the Chesapeake Bay watershed: U.S. Geological Survey web summary, available online at https://chesapeake.usgs.gov/documents/ss-sedimentsourcesandtransport.pdf.

Hartranft J.L., Merritts D.J., Walter R.C., and M. Rahnis, 2011. Big Spring Run restoration experiment: Policy, geomorphology, and aquatic ecosystems in the Big Spring Run watershed, Lancaster County, PA. Sustain 24:24–30.

Inamdar, S., E.R. Johnson, R.D. Rowland, R. Walter, and D. Merritts, 2017. Freeze-thaw processes and intense rainfall: The one-two punch for high sediment and nutrient loads from Mid-Atlantic watersheds, Biogeochemistry, https://doi.org/10.1007/s10533-017-0417-7.

Jones, C., Branosky, E., Selman, M., and M. Perez, 2010. How nutrient trading could help restore the Chesapeake Bay. Working Paper, World Resources Institute, Washington, DC.

Jordan, T., Simpson, T.W., and S.E. Weammert, 2007. Wetland restoration and wetland creation best management practices: Definition and nutrient and sediment reduction efficiencies for use in calibration of the phase 5.0 of the Chesapeake Bay Program Watershed model, Mid-Atlantic Water Program, Univ. of Md., College Park.

Kaufman, Z., Abler, D., Shortle, J., Harper, J., Hamlett, J., and P. Feather, 2014. Agricultural costs of the Chesapeake Bay Total Maximum Daily Load. Environmental Science & Technology, 48, 14131-14138.

Keisman, J., J. Blomquist, J.K. Bohlke, J. Davis-Martin, W. Dennison, C. Friedrichs, R. Murphy, S. Phillips, J. Testa, E. Trentacoste, and D. Weller, 2018. Integrating Recent Findings to Explain Water-Quality Change: Support for the Mid-Point Assessment and Beyond. STAC Publication Number 18-005, Edgewater, MD.

Langland, M.J., *in prep*. Removal of legacy sediment and effects on streamflow, nutrient, and sediment concentrations and sediment loads at Big Spring Run, Lancaster County, Pennsylvania, 2009-15: U.S. Geological Survey Scientific Investigations Report 2019-xxxx, xxp. https://doi.xxxx

Maryland Agricultural Cost Share Program, 2016. MACS Annual Report, Maryland Department of Agriculture, Office of Resource Conservation. Annapolis, MD.

Massoudieh, A., Gellis, A., Banks, W.S., and M.E. Wieczorek, 2012. Suspended sediment source apportionment in Chesapeake Bay watershed using Bayesian chemical mass balance receptor modeling. Hydrol Process. doi:10.1002/hyp.9429.

McCann, L., Colby, B., Easter, K.W., Kasterine, A., and K.V. Kuperan, 2005. Transaction cost measurement for evaluating environmental policies. Ecological Economics 52:527-542.

Merritts, D., Walter, R., and M. Rhanis, 2010, Sediment and nutrient loads from stream corridor erosion along breached millponds. Pennsylvania Department of Environmental Protection Report, 147p.

Peterson, J.M., Smith, C.M., Leatherman, J.C., Hendricks, N.P., and J.A. Fox, 2014. Transaction costs in payment for environmental service contracts. American Journal of Agricultural Economics 97:219-238.

Rabotyagov, S.S., Valcu, A.M., and C.L. Kling, 2013. Reversing property rights: Practice-based approaches for controlling agricultural nonpoint-source water pollution when emissions aggregate nonlinearly. American Journal of Agricultural Economics. 96 (2), 397-419.

Sharpley, A., Jarvie, H.P., Buda, A., May, L., Spears, B., and P. Kleinman, 2013. Phosphorus legacy: overcoming the effects of past management practices to mitigate future water quality impairment. J Environ Qual 42:1308–1326.

Shortle, J.S., and R.D. Horan, 2017. Nutrient pollution: A wicked challenge for economic instruments. *Water Economics and Policy* 3 (2): 1-39.

US Department of Agriculture CREP, 2007. Landowner guide to buffer success. Available online: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_017952.pdf.

US Department of Agriculture NASS, 2016. Pennsylvania custom rate guide. Available online: https://www.farmprogress.com/story-2016-pennsylvania-custom-rate-guide-arrives-9-141682.

US Environmental Protection Agency, 2010. Discounting future benefits and costs, Ch. 6 in *Guidelines for Preparing Economic Analyses*. Available online: https://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0568-06.pdf/$file/EE-0568-06.pdf.

Voli, M.T., Merritts, D.J., Walter, R.C., Ohlson, E., Datin, K., Rahnis, M., Kratz, L., Deng, W., Hilgartner, W., and J. Hartranft, 2009. Preliminary reconstruction of pre-European settlement valley bottom wetland, southeastern Pennsylvania. *Water Resources IMPACT* 11:11-13.

Voli, M.T., Wegmann, K.W., Bohnensteihl, D.R., Leithold, E., Osburn, C.L., and V. Polyakov, 2013. Fingerprinting the sources of suspended sediment delivery to a large municipal drinking water reservoir: Falls Lake, Neuse River, North Carolina, USA. J. Soils Sediments, 13, 1692-1707.

Walter, R.C., Merritts, D.J., and M. Rahnis, 2007. Estimating volume, nutrient content, and rates of stream bank erosion of legacy sediment in the Piedmont and Valley and Ridge physiographic provinces of southeastern and central Pennsylvania. Final Report to Pennsylvania Department of Environmental Protection.

Walter, R.C., and D.J. Merritts, 2008. Natural streams and the legacy of water-powered mills. Science 319, 299–304. (doi:10.1126/science.1151716).

Walter, R.C., Merritts, D.J., Rahnis, M., Langland, M., Galeone, D., Gellis, A., Hilgartner, W., Bowne, D., Wallace, J., Mayer, P., and K. Forshay, 2013. Big Spring Run natural floodplain , stream, and riparian wetland: Aquatic resource restoration project monitoring. Final Report to Pennsylvania Department of Environmental Protection.

Walter, R.C, Merritts, D.J., Rahnis, M., Gellis, A., Hartranft, J., Mayer, P., Langland, M., Forshay, K., Weitzman, J., Schwarz, E., Bai, Y., Blair, A., Carter, A., Sosenko Daniels, S., Lewis, E., Ohlson, E., Peck, E., Shilling, A., Schulte, K., Smith, D., Stein, Z., Verna, D. and E. Wilson, 2017. Sediment Budgets and Sources Inform a Novel Valley Bottom Restoration Practice Impacted by Legacy Sediment: The Big Spring Run, PA, Restoration Experiment, Abstract presented at 2017 Fall Meeting, AGU, New Orleans, LA, 11-15 Dec. https://agu.confex.com/agu/fm17/meetingapp.cgi/Paper/281212

Wieland, R., Parker, D., Gans, W., and A. Martin, 2009. Costs and cost efficiencies for some nutrient reduction practices in Maryland. NOAA Chesapeake Bay Office and Maryland Department of Natural Resources, Annapolis, MD.

Tables

Table 1. Summary of legacy sediment cost-effectiveness in comparison to other conservation practices for sediment, phosphorus, and nitrogen abatement

Practice Type	$ / lb. abatement, edge-of-stream			$ / lb. abatement, in the Bay		
	Sediment	Phosphorus	Nitrogen	Sediment	Phosphorus	Nitrogen
Legacy sediment mitigation	$0.01	$10.34	$7.49	$0.03	$18.90	$13.88
Grass riparian buffer	$0.18	$1,336.25	$6.60	$0.48	$2,442.19	$12.23
Forest riparian buffer	$0.24	$702.39	$6.96	$0.64	$1,283.73	$12.89
Wetland restoration (other sites)	$0.79	$1,799.82	$29.12	$2.17	$3,289.45	$53.97
Cover crops (rye drilled early)	-	-	$4.58	-	-	$8.49

Notes: Abatement and costs for legacy sediment (LS) mitigation are from data at the Big Spring Run study site. Abatement from buffers, cover crops, and wetland restoration at sites not characterized as LS hot spots is from the Chesapeake Bay Program watershed model under "grain with manure" land use. Cover crops do not reduce sediment and phosphorus from low-till cropland. Costs for buffers, cover crops, and wetland restoration are based on USDA Natural Resource Conservation Service and Farm Service Agency payment schedules, and Wieland et al. (2009).

Table 2. Summary of annual abatement per acre by practice type

	Modeled abatement - Average across Chesapeake Bay river segments							Total abatement
	(i) Land use change			(ii) Filtration of upland acres				
	Pre-implement. load	Post-implement. load	Abatement	Upland load	Efficiency	Upland acres	Abatement	
	lb. / ac.	*lb. / ac.*	*lb. / ac.*	*lb. / ac.*	*%*	*ac.*	*lb. / ac.*	***lb. / ac.***
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
Legacy sediment mitigation								
Sediment	372,340	31	372,309	1,823	31	3	1,695	**374,004**
Phosphorus	428.2	0.1	428.1	0.727	40	3	0.9	**429.0**
Nitrogen	539.9	1.4	538.4	42.7	42	3	53.8	**592.3**
Forest riparian buffer								
Sediment	1,823	35	1,788	1,823	48	2	1750	**3,538**
Phosphorus	0.7	0.1	0.7	0.7	36	2	0.5	**1.2**
Nitrogen	42.7	1.5	41.3	42.7	46	4	78.6	**119.9**
Grass riparian buffer								
Sediment	1,823	43	1,780	1,823	48	2	1750	**3,530**
Phosphorus	0.7	0.8	-0.1	0.7	36	2	0.5	**0.5**
Nitrogen	42.7	3.8	38.9	42.7	32	4	54.7	**93.6**
Wetland restoration at other sites								
Sediment	1,823	31	1,791	1,823	31	3	1,695	**3,486**
Phosphorus	0.7	0.1	0.7	0.7	40	3	0.9	**1.5**
Nitrogen	42.7	1.4	41.3	42.7	42	3	53.8	**95.1**
Cover crops (rye planted early)				*Filtration of working land acres**				
Sediment				1,823	-	-	-	**-**
Phosphorus		*n/a*		0.7	-	-	-	**-**
Nitrogen				42.7	45.0	-	19.2	**19.2**

Sources:
*Cover crops do not further reduce P or Sediment from low-till cropland in the CBP Phase 6 Model.
[1]: For legacy sediment, measured loads at Big Spring Run. For other practices, CBP Phase 6 watershed model. Buffers, cover crops, and wetland restoration at other sites use modeled loads from the grain with manure (gwm) land use.
[2]: CBP Phase 6 watershed model. Modeled as true forest (for) land use for forest buffer; ag open space (aop) for grass buffer; and non-tidal floodplain wetland (wtp) for legacy sediment restoration and wetland restoration at other sites.
[3]: Calculated as [1] - [2].
[4]: CBP Phase 6 watershed model. Assumed upland use of grain with manure (gwm).
[5] & [6]: CBP Expert Panel Reports for Wetlands (2016) and Buffers (2014).
[7]: Calcualted as [4] x [5] / 100 x [6]. For cover crops, simply [4] x [5] / 100.
[8]: Calculated as [3] + [7].

Table 3. Abatement of legacy sediment, phosphorus, and nitrogen at the Big Spring Run site following land use change

	Pre-restoration annual loads per acre (pounds)	Post-restoration annual loads per acre (pounds)	Annual abatement per acre (pounds)
Sediment	372,340	31	372,309
Phosphorus	428.2	0.1	428.1
Nitrogen	539.9	1.4	538.4

Source: Langland (*in prep.*) and CBP Phase 6 Model. Abatement due to land use change refers to the reduction of load by converting legacy sediment erosion hot spot to a restored wetland or aquatic ecosystem. Pre-restoration loads are elevated due to stream bank scouring; post-restoration loads are negligible.

Table 4. Chesapeake Bay Program Phase 6 model agricultural loads per acre, and associated abatement from filtration of upland acres by wetland restoration and forest riparian buffers

Land Use Description	**Land use code**	**Chesapeake Bay Watershed averages Loads per acre (pounds)** Sediment			**Reduction of Load from Upland Acres (pounds)** **Per acre of wetland restoration** Sediment			**Per acre of forest riparian buffer** Sediment		
		Sediment	Phosphorus	Nitrogen	Sediment	Phosphorus	Nitrogen	Sediment	Phosphorus	Nitrogen
		[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]
Percent upland load reduced by wetlands and forest buffers:					31%	40%	42%	48%	36%	46%
Number of upland acres treated by wetlands and forest buffers:					3	3	3	2	2	4
Ag Open Space	aop	43	0.79	3.8	40	0.95	4.8	41	0.57	7.1
Double Cropped Land	dbl	1,342	0.64	24.5	1,248	0.77	30.9	1,289	0.46	45.1
Full Season Soybeans	soy	1,904	0.67	22.4	1,771	0.81	28.2	1,828	0.48	41.1
Grain with Manure	**gwm**	**1,823**	**0.73**	**42.7**	**1,695**	**0.87**	**53.8**	**1,750**	**0.52**	**78.6**
Grain without Manure	gom	1,828	0.68	30.3	1,700	0.81	38.2	1,755	0.49	55.8
Legume Hay	lhy	157	0.39	7.1	146	0.46	8.9	150	0.28	13.0
Other Agronomic Crops	oac	272	0.72	13.7	253	0.86	17.3	261	0.52	25.2
Other Hay	ohy	43	0.44	11.0	40	0.53	13.9	41	0.32	20.3
Pasture	pas	37	0.95	10.3	34	1.14	13.0	35	0.68	19.0
Silage with Manure	swm	3,997	1.14	39.1	3,718	1.37	49.2	3,838	0.82	71.9
Silage without Manure	som	3,954	1.08	28.1	3,677	1.30	35.4	3,795	0.78	51.7
Small Grains and Grains	sgg	2,802	0.86	24.0	2,606	1.03	30.2	2,690	0.62	44.2
Specialty Crop High	sch	5,705	2.73	42.7	5,305	3.28	53.8	5,477	1.97	78.5
Specialty Crop Low	scl	5,893	2.67	10.5	5,480	3.20	13.3	5,657	1.92	19.4

Source: CBP Phase 6 Model (2017 progress scenario). Loads per acre averaged across river segments in the Bay watershed. CBP Expert Panel Reports for Wetlands (2016) and Riparian Buffers (2014).
In the Piedmont region, non-tidal floodplain wetlands are modeled as filtering 3 upland acres of sediment, phosphorus, and nitrogen at rates of 31%, 40%, and 42%, respectively.
In the Piedmont (schist/gneiss) region, forest riparian buffers are modeled as filtering 2 upland acres of sediment and phosphorus and 4 upland acres of nitrogen at rates of 48%, 36% and 46%, respectively.
Column [4] = [1] x 31% x 3 upland acres. Column [5] = [2] x 40% x 3 upland acres. Column [6] = [3] x 42% x 3 upland acres.
Column [7] = [1] x 48% x 2 upland acres. Column [8] = [2] x 36% x 2 upland acres. Column [9] = [3] x 46% x 4 upland acres.

Table 5. Acres of other BMPs required to match abatement from Big Spring Run study site

Practice type	**Acres needed for equivalent abatement to that from BSR study site**		
	Sediment	*Phosphorus*	*Nitrogen*
	[1]	[2]	[3]
Forest riparian buffer	497	1,698	23
Grass riparian buffer	498	4,362	30
Wetland restoration at other sites	504	1,310	29
Cover crops (rye planted early)	-	-	145

Notes:
[1] to [3] calculated as measured annual abatement from the Big Spring Run restoration divided by abatement per acre of each practice as modeled in CBP model (see Table 2).

Table 6. Summary of annualized implementation costs per acre by practice type

Cost Type	Upfront cost ($ / acre) [1]	Contract length (years) [2]	Discount rate (%) [3]	Annualized cost ($ / acre / year) [4]
Legacy sediment mitigation				
(i) Practice adoption	$203,372	*Wetland easement in perpetuity*	0.02	$4,067
(ii) Maintenance and monitoring cost	$2,128			$43
(iii) Opportunity cost of land				$327
Total costs				**$4,437**
Forest riparian buffer				
(i) Forest buffer planting	$1,812	*15*	*n/a*	$121
(ii) Maintenance and monitoring cost	$2,000			$133
(iii) Opportunity cost of land				$580
Total costs				**$834**
Grass riparian buffer				
(i) Grass buffer planting	$377	*10*	*n/a*	$38
(ii) Maintenance and monitoring cost	-			-
(iii) Opportunity cost of land				$580
Total costs				**$618**
Wetland restoration at other sites				
(i) Practice adoption	$120,000	*Wetland easement in perpetuity*	0.02	$2,400
(ii) Maintenance and monitoring cost	$2,128			$43
(iii) Opportunity cost of land				$327
Total costs				**$2,770**
Cover crops (rye drilled)				
(i) Planting	$88.04	*Annual practice on working land*		$88
(ii) Maintenance and monitoring cost	-			-
(iii) Opportunity cost of land	-			-
Total costs				**$88**

Sources and Notes

[1]: For legacy sediment, (i) and (ii) are based on actual costs of Big Spring Run mitigation, updated to reflect current costs. For forest and grass buffers and cover crops, (i) is from USDA-FSA payment schedules. For wetland restoration at other sites, (i) is based on correspondence with LandStudies, Inc. Maintenance costs for buffers based on USDA estimates.

[2]: Contract lengths based on correspondence with Pennsylvania USDA NRCS and FSA program offices. Wetland easements are typically only granted in perpetuity in Pennsylvania.

[3]: Discount rate required to convert payments in perpetuity to present value terms based on U.S. EPA "Discounting Future Benefits and Costs." https://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0568-06.pdf/$file/EE-0568-06.pdf .

[4]: When wetland easements are used, calculated as [1] x [3]. When a contract length is specified, calculated as [1] / [2]. For all practices, opportunity costs are based on USDA NRCS or FSA annual compensation to landowners in Lancaster Co.

Table 7. Summary of cost effectiveness by practice type and pollutant

	Annual Abatement *(edge-of-stream)*	Annualized Cost	Cost Effectiveness *(edge-of-stream)*	Delivery Ratio *(to the Bay)*	Annual Abatement *(in the Bay)*	Cost Effectiveness *(in the Bay)*
	lb. / ac.	*$ / ac.*	*$ / lb.*		*lb. / ac.*	*lb. / $*
	[1]	[2]	[3]	[4]	[5]	[6]
Legacy sediment mitigatio						
Sediment	374,004		**$0.01**	0.366	136,787	**$0.03**
Phosphorus	429.0	$4,437	**$10.34**	0.547	234.7	**$18.90**
Nitrogen	592		**$7.49**	0.540	320	**$13.88**
Forest buffer						
Sediment	3,538		**$0.24**	0.366	1,294	**$0.64**
Phosphorus	1.2	$834	**$702.39**	0.547	0.6	**$1,283.73**
Nitrogen	120		**$6.96**	0.540	65	**$12.89**
Grass buffer						
Sediment	3,530		**$0.18**	0.366	1,291	**$0.48**
Phosphorus	0.5	$618	**$1,336.25**	0.547	0.3	**$2,442.19**
Nitrogen	94		**$6.60**	0.540	50	**$12.23**
Wetland restoration						
Sediment	3,486		**$0.79**	0.366	1,275	**$2.17**
Phosphorus	1.5	$2,770	**$1,799.82**	0.547	0.8	**$3,289.45**
Nitrogen	95		**$29.12**	0.540	51	**$53.97**
Cover crops						
Sediment	-		**-**	0.366	-	**-**
Phosphorus	-	$88	**-**	0.547	-	**-**
Nitrogen	19		**$4.58**	0.540	10	**$8.49**

Notes:
[1]: See Table 2.
[2]: See Table 6.
[3]: Calculated as [2] / [1].
[4]: CBP Phase 6 Model. Delivery ratio from edge-of-stream to the Bay in Mill Creek land-river segment, where Big Spring Run is located
[5]: Calculated as [1] x [4].
[6]: Calculated as [2] / [5].

Table 8. Summary of annualized costs of Big Spring Run restoration by choice of discount rate

	Cost Type	Annualized Cost Components			
		Upfront cost *$ / acre*	Contract length *years*	Discount rate *%*	Annualized cost *$ / acre / year*
		[1]	[2]	[3]	[4]
	Sensitivity check, r = 0.02				
(i)	Practice adoption	$203,372	*Wetland easement in perpetuity*	0.02	$4,067
(ii)	Maintenance and monitoring cost	$2,128			$43
(iii)	Opportunity cost of land				$327
	Total costs				**$4,437**
	Sensitivity check, r = 0.03				
(i)	Practice adoption	$203,372	*Wetland easement in perpetuity*	0.03	$6,101
(ii)	Maintenance and monitoring cost	$2,128			$64
(iii)	Opportunity cost of land	-			$327
	Total costs				**$6,492**
	Sensitivity check, r = 0.05				
(i)	Practice adoption	$203,372	*Wetland easement in perpetuity*	0.05	$10,169
(ii)	Maintenance and monitoring cost	$2,128			$106
(iii)	Opportunity cost of land	-			$327
	Total costs				**$10,602**

[1]: For legacy sediment, (i) (ii) and (iv) are from LandStudies, Inc.
[2]: Contract lengths based on correspondence with Pennsylvania USDA NRCS or FSA program offices. Wetland easements are typically only granted in perpetuity in Pennsylvania.
[3]: Discount rate required to convert payments in perpetuity to present value terms based on U.S. EPA "Discounting Future Benefits and Costs." https://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0568-06.pdf/$file/EE-0568-06.pdf .
[4]: Calculated as [1] x [3].

Table 9. Summary of cost effectiveness rankings by choice of discount rate

Practice Type	$ / lb. abatement, edge-of-stream			$ / lb. abatement, in the Bay		
	Sediment	Phosphorus	Nitrogen	Sediment	Phosphorus	Nitrogen
Social discount rate, r=0.02, for legacy sediment mitigation and wetland restoration (other sites)						
Legacy sediment mitigation	$0.01	$10	$7.49	$0.03	$19	$13.88
Grass riparian buffer	$0.18	$1,336	$6.60	$0.48	$2,442	$12.23
Forest riparian buffer	$0.24	$702	$6.96	$0.64	$1,284	$12.89
Wetland restoration (other sites)	$0.79	$1,800	$29.12	$2.17	$3,289	$53.97
Cover crops (rye drilled early)	-	-	$4.58	-	-	$8.49
Social discount rate, r=0.03, for legacy sediment mitigation and wetland restoration (other sites)						
Legacy sediment mitigation	$0.02	$15	$10.96	$0.05	$28	$20.31
Grass riparian buffer	$0.18	$1,336	$6.60	$0.48	$2,442	$12.23
Forest riparian buffer	$0.24	$702	$6.96	$0.64	$1,284	$12.89
Wetland restoration (other sites)	$1.14	$2,593	$41.96	$3.13	$4,740	$77.76
Cover crops (rye drilled early)	-	-	$4.58	-	-	$8.49
Private capital discount rate, r=0.05, for legacy sediment mitigation and wetland restoration (other sites)						
Legacy sediment mitigation	$0.03	$25	$17.90	$0.08	$45	$33.17
Grass riparian buffer	$0.18	$1,336	$6.60	$0.48	$2,442	$12.23
Forest riparian buffer	$0.24	$702	$6.96	$0.64	$1,284	$12.89
Wetland restoration (other sites)	$1.85	$4,181	$67.64	$5.05	$7,641	$125.35
Cover crops (rye drilled early)	-	-	$4.58	-	-	$8.49

Notes: Abatement and costs for legacy sediment mitigation are from data at the Big Spring Run test site. Abatement from buffers, cover crops, and wetland restoration at sites not containing legacy sediments is from the Chesapeake Bay Program (CBP) watershed model, using elevated loading rates from Lancaster County river segments. Costs for buffers, cover crops, and wetland restoration are based on Wieland et al. (2009) and USDA Natural Resource Conservation Service payment schedules.

Appendix A. Big Spring Run Pre-Restoration Load Calculations

Sediment loads in the Big Spring Run (BSR) restoration area have been studied for a number of years before, during, and after restoration activities were undertaken. Among other analytical approaches, USGS gages have been used to calculate sediment loads on a daily, monthly, and annual basis using turbidity data collected at 15-minute intervals. These data are correlated with sediment concentration data from samples collected during base and stormflow conditions to develop rating curves. Three gages are located in the BSR study area: two are upstream of the restored area (the "East Branch gage" and the "West Branch gage"), and one is downstream of the restored area (the "Downstream gage").

An annual summary of gage data is shown in Appendix Table A1 for the water years 2009 to 2015. Note the BSR restoration took place during water year 2012, which spans October 1, 2011 to September 30, 2012. From water years 2009 to 2011, representing the pre-restoration time period, average annual sediment load at the Downstream gage was 2,756 tons. Average inbound loads from the East Branch gage were 543 tons per year over the same time period. West Branch gage data were not available during this time period due to equipment and site problems, including bank erosion that affected the rating curves for regressions. However, using the average ratio of West Branch to East Branch sediment loads in the years for which data is available (2012 to 2015), the estimated inbound load from the West Branch prior to restoration is 1300 tons annually.[34] Thus, approximately 913 tons per year were added to the load between the upstream and downstream gages during the pre-restoration time period.

The USGS gages are not located directly on the boundaries of the restored area. Each gage is a short distance upstream (for East and West Branch gages) or downstream (for the Downstream gage) of the restoration endpoints. Therefore, the sediment load produced between the gages and the restored area was estimated for each of three unrestored lengths of stream and used to adjust the load calculations. This estimate was obtained by utilizing Digital Elevation Model (DEM) differencing of airborne LiDAR data of the unrestored channel sections between the gages and the restored area. The LiDAR data were acquired in April 2008 and December 2014, providing an estimate of bank erosion for a 6.6-year period from which we calculate an

[34] The average annual ratio of West Branch-to-East Branch sediment loads is approximately 2.4 from 2012 to 2015. The estimated load of 1300 tons per year prior to restoration is then calculated as the East Branch load (543 tons) multiplied by the ratio (~2.4).

annual load. As shown in Appendix Table A2, DEM differencing indicates a range of 5 to 15 tons produced annually between the East Branch gage and the restored area, and 8 to 16 tons between the West Branch gage and restored area. These combined loads were added to the inbound sediment load, and thus not considered part of the load produced within the restored area. Similarly, DEM differencing indicates a range of 10 to 22 tons produced annually between the restored area and the downstream gage. This load likewise was not considered part of the load produced in the restored area. Subtracting these load estimates from the 913 tons produced annually between gages results in an estimated 860 to 890 tons per year produced within the restored area. The midpoint of this range, 875 tons per year, is utilized in this report.

Appendix Table A1. United States Geological Survey gage data for Big Spring Run area, 2009 to 2015

Water year	Gage number	Gage name	Annual sediment load (tons)
2009	1576516	East branch	515.1
2010	1576516	East branch	592.9
2011	1576516	East branch	520.7
2012	1576516	East branch	877.0
2013	1576516	East branch	367.1
2014	1576516	East branch	584.3
2015	1576516	East branch	454.8
2009	15765185	West branch	-
2010	15765185	West branch	-
2011	15765185	West branch	-
2012	15765185	West branch	544.8
2013	15765185	West branch	1726.7
2014	15765185	West branch	1466.3
2015	15765185	West branch	793.2
2009	15765195	Downstream	2342.9
2010	15765195	Downstream	4593.5
2011	15765195	Downstream	1331.4
2012	15765195	Downstream	428.6
2013	15765195	Downstream	461.6
2014	15765195	Downstream	436.3
2015	15765195	Downstream	382.9

Source. United States Geological Survey. West branch and East branch gages are upstream of restoration area. West branch data missing in water years 2009 to 2011 due to poor relation between sediment concentration values, instantaneous discrete turbidity measurements, and instantaneous streamflows.

Appendix Table A2. Sediment load produced between USGS gages and the Big Spring Run restored area

Time period	Method	Location		Erosion Rate (tons / yr) Minimum	Maximum
				[a]	[b]
2008-2014	LiDAR DEM Differencing	East Branch, between restored area and USGS gage	[1]	10.0	22.0
		West Branch, between restored area and USGS gage	[2]	5.1	15.3
		Main Stem, between restored area and downstream USGS gage	[3]	7.9	15.7
		Total load excluded from restored area: calculated as [1] + [2] + [3]	[4]	23.0	53.0
2009-2011	USGS Gages	Total load produced between gages	[5]	913	
	USGS Gages + LiDAR DEM Differencing	Load produced within restored area:			
		Min: calculated as [5] - [4][b]	[6]	860	
		Max: calculated as [5] - [4][a]	[7]	890	
		Midpoint of [6] and [7]	[8]	875	

Appendix B. Geographic Area Rate Caps (GARCs) for Wetland Easements

Pennsylvania NRCS ACEP-WRE GARC Rates FY2018

Geographic Area By Region and County		Market Analysis	Market Analysis	Market Analysis	Market Analysis	GARC (95%)	GARC (95%)	GARC (95%)	GARC (95%)	
Region	County	Cropland $/ac	Pasture $/ac	Forest $/ac	Upland $/ac	Cropland $/ac	Pasture $/ac	Forest $/ac	Upland $/ac	
1	Allegheny	$4,555	$2,970	$2,070	na	$4,327	$2,822	$1,967	na	
1	Armstrong	$4,555	$2,970	$2,070	na	$4,327	$2,822	$1,967	na	
1	Beaver	$4,555	$2,970	$2,070	na	$4,327	$2,822	$1,967	na	
1	Butler	$4,555	$2,970	$2,070	$5,975	$4,327	$2,822	$1,967	$5,676	*
1	Fayette	$4,555	$2,970	$2,070	na	$4,327	$2,822	$1,967	na	
1	Greene	$4,555	$2,970	$2,070	na	$4,327	$2,822	$1,967	na	
1	Indiana	$4,555	$2,970	$2,070	na	$4,327	$2,822	$1,967	na	
1	Washington	$4,555	$2,970	$2,070	na	$4,327	$2,822	$1,967	na	
1	Westmoreland	$4,555	$2,970	$2,070	na	$4,327	$2,822	$1,967	na	
2	Clarion	$2,870	$1,895	$1,790	na	$2,727	$1,800	$1,701	na	
2	Crawford	$2,870	$1,895	$1,790	$5,765	$2,727	$1,800	$1,701	$5,000	**
2	Erie	$2,870	$1,895	$1,790	$5,765	$2,727	$1,800	$1,701	$5,000	**
2	Forest	$2,870	$1,895	$1,790	na	$2,727	$1,800	$1,701	na	
2	Lawrence	$2,870	$1,895	$1,790	na	$2,727	$1,800	$1,701	na	
2	Mercer	$2,870	$1,895	$1,790	$5,765	$2,727	$1,800	$1,701	$5,000	**
2	Venango	$2,870	$1,895	$1,790	na	$2,727	$1,800	$1,701	na	
2	Warren	$2,870	$1,895	$1,790	$5,765	$2,727	$1,800	$1,701	$5,000	**
3	Cameron	$2,805	$1,825	$1,715	na	$2,665	$1,734	$1,629	na	
3	Clearfield	$2,805	$1,825	$1,715	na	$2,665	$1,734	$1,629	na	
3	Elk	$2,805	$1,825	$1,715	na	$2,665	$1,734	$1,629	na	
3	Jefferson	$2,805	$1,825	$1,715	na	$2,665	$1,734	$1,629	na	
3	McKean	$2,805	$1,825	$1,715	na	$2,665	$1,734	$1,629	na	
3	Potter	$2,805	$1,825	$1,715	na	$2,665	$1,734	$1,629	na	
4	Bedford	$3,315	$2,280	$2,045	na	$3,149	$2,166	$1,943	na	
4	Blair	$3,315	$2,280	$2,045	na	$3,149	$2,166	$1,943	na	
4	Cambria	$3,315	$2,280	$2,045	na	$3,149	$2,166	$1,943	na	
4	Fulton	$3,315	$2,280	$2,045	na	$3,149	$2,166	$1,943	na	
4	Huntingdon	$3,315	$2,280	$2,045	na	$3,149	$2,166	$1,943	na	
4	Somerset	$3,315	$2,280	$2,045	na	$3,149	$2,166	$1,943	na	
5	Centre	$4,825	$3,235	$2,610	na	$4,584	$3,073	$2,480	na	
5	Clinton	$4,825	$3,235	$2,610	na	$4,584	$3,073	$2,480	na	
5	Columbia	$4,825	$3,235	$2,610	na	$4,584	$3,073	$2,480	na	
5	Juniata	$4,825	$3,235	$2,610	na	$4,584	$3,073	$2,480	na	
5	Mifflin	$4,825	$3,235	$2,610	na	$4,584	$3,073	$2,480	na	
5	Northumberland	$4,825	$3,235	$2,610	na	$4,584	$3,073	$2,480	na	
5	Schuylkill	$4,825	$3,235	$2,610	$7,395	$4,584	$3,073	$2,480	$7,025	
5	Snyder	$4,825	$3,235	$2,610	na	$4,584	$3,073	$2,480	na	
5	Union	$4,825	$3,235	$2,610	na	$4,584	$3,073	$2,480	na	
5	Montour	$4,825	$3,235	$2,610	na	$4,584	$3,073	$2,480	na	
6	Bradford	$3,302	$2,245	$2,090	na	$3,137	$2,133	$1,986	na	
6	Lycoming	$3,302	$2,245	$2,090	na	$3,137	$2,133	$1,986	na	
6	Sullivan	$3,302	$2,245	$2,090	na	$3,137	$2,133	$1,986	na	
6	Susquehanna	$3,302	$2,245	$2,090	na	$3,137	$2,133	$1,986	na	
6	Tioga	$3,302	$2,245	$2,090	na	$3,137	$2,133	$1,986	na	
6	Wyoming	$3,302	$2,245	$2,090	na	$3,137	$2,133	$1,986	na	
7	Carbon	$4,900	$3,820	$3,345	$7,685	$4,655	$3,629	$3,178	$7,301	*
7	Lackawanna	$4,900	$3,820	$3,345	na	$4,655	$3,629	$3,178	na	
7	Luzerne	$4,900	$3,820	$3,345	na	$4,655	$3,629	$3,178	na	
7	Monroe	$4,900	$3,820	$3,345	$7,685	$4,655	$3,629	$3,178	$7,301	*
7	Pike	$4,900	$3,820	$3,345	na	$4,655	$3,629	$3,178	na	
7	Wayne	$4,900	$3,820	$3,345	na	$4,655	$3,629	$3,178	na	
8	Adams	$5,475	$3,715	$3,380	$9,195	$5,201	$3,529	$3,211	$8,735	
8	Berks	$5,475	$3,715	$3,380	$9,195	$5,201	$3,529	$3,211	$8,735	
8	Cumberland	$5,475	$3,715	$3,380	$9,195	$5,201	$3,529	$3,211	$8,735	
8	Dauphin	$5,475	$3,715	$3,380	na	$5,201	$3,529	$3,211	na	
8	Franklin	$5,475	$3,715	$3,380	na	$5,201	$3,529	$3,211	na	
8	Lebanon	$5,475	$3,715	$3,380	$9,195	$5,201	$3,529	$3,211	$8,735	
8	Perry	$5,475	$3,715	$3,380	na	$5,201	$3,529	$3,211	na	
8	York	$5,475	$3,715	$3,380	$9,195	$5,201	$3,529	$3,211	$8,735	
9	Lancaster	$6,890	$4,470	$3,810	$12,490	$6,546	$4,247	$3,620	$11,866	
9	Bucks	$6,890	$4,470	$3,810	$12,490	$6,546	$4,247	$3,620	$11,866	*
9	Chester	$6,890	$4,470	$3,810	$12,490	$6,546	$4,247	$3,620	$11,866	
9	Delaware	$6,890	$4,470	$3,810	$12,490	$6,546	$4,247	$3,620	$11,866	*
9	Lehigh	$6,890	$4,470	$3,810	$12,490	$6,546	$4,247	$3,620	$11,866	*
9	Montgomery	$6,890	$4,470	$3,810	$12,490	$6,546	$4,247	$3,620	$11,866	*
9	Northampton	$6,890	$4,470	$3,810	$12,490	$6,546	$4,247	$3,620	$11,866	*

** NOTE: The $5,000 cap applies to these counties for any applicant that is NOT applying for WRE through the Bog Turtle or Massasauga Rattlesnake Initiatives*

***$5,000 cap applied per WRE policy*