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FEATURE

# Legacy sediment erosion hot spots: A cost-effective approach for targeting water quality improvements

Patrick M. Fleming, Dorothy J. Merritts, and Robert C. Walter

As federal and state governments seek to address nonpoint source (NPS) water pollution, billions of dollars will be spent to implement conservation practices known to reduce sediment and nutrient runoff. Nonpoint source pollution has proven to be a "wicked" challenge for policymakers, characterized by uncertainty and complex interactions among socioeconomic, hydrologic, and other geodynamic systems along multiple dimensions (Shortle and Horan 2017). A recent summary of research indicates, in fact, that the adoption of conventional NPS conservation practices is not directly linked to measurable pollution reduction in most streams in the Chesapeake Bay watershed (Keisman et al. 2018). A primary reason cited for this disconnect is the temporal dynamic by which water quality improvements are delayed or offset by the ongoing effects of legacy pollutants in soils and groundwater (Keisman et al. 2018). (Legacy pollutants are those that remain in the geosphere decades to centuries after the pollution occurred.)Innovative approaches to NPS pollution reduction may be needed to address these legacy pollutants, and thereby meet goals for improved water quality, such as the Chesapeake Bay total maximum daily load (TMDL).

One such approach that has received increasing attention is legacy sediment (LS) mitigation. As shown in the research of Walter and Merritts (2008), LS and associated nutrient pollution accumulated for decades (and sometimes centuries) behind milldams and other historic stream impediments. As these impediments are removed, intentionally or otherwise, long-term elevated pollution loads have been left behind along numerous stream systems in the mid-Atlantic region. These loads are concentrated at LS "hot spots," characterized by near-vertical stream banks carved into the previously accumulated sediment (figure 1). (Here, we consider LS erosion hot spots as stream lengths that produce above 0.05 tn $ft^{-1}$ $yr^{-1}$ [0.15 Mg $m^{-1}$ $y^{-1}$] of sediment erosion over at least a span of 2,000 ft [610 m]). Subsequent research has shown that LS mitigation—through removal of sediment to restore the wetland or other aquatic ecosystem long buried behind historic stream impoundments (Hartranft et al. 2011)—is a highly effective form of sediment, phosphorus (P), and nitrogen (N) abatement when implemented at identifiable LS erosion hot spots (Sharpley et al. 2013; Inamdar et al. 2017). However, less is known about the cost-effectiveness of LS mitigation projects in terms of their cost per unit of pollution reduced, especially in comparison to other NPS reduction practices.

In this article, we summarize the results of a recent study of the cost-effectiveness of LS mitigation in the Chesapeake Bay watershed in comparison to agricultural practices that are commonly considered low-cost forms of abatement, such as cover crops and grass and forest riparian buffers. We then describe two broader policy implications of these findings, using recently available technology to identify hot spots at a landscape scale. The importance of legacy pollutant sources has long been recognized—from P in soils, to nitrates ($NO_3$) in groundwater, to LS and nutrients along stream banks (USGS 2003; Garnache et al. 2016). As technology increasingly allows policymakers to identify LS erosion hot spots, we emphasize that greater awareness of LS mitigation should be promoted as a cost-effective tool in the suite of options available to reduce NPS water pollution.

## LEGACY SEDIMENT MITIGATION

The problem of LS impaired waters is ubiquitous in the mid-Atlantic United

**Figure 1**

Erosion of legacy sediment 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.


**Patrick M. Fleming** is an assistant professor of economics and public policy at Franklin & Marshall College in Lancaster, Pennsylvania. **Dorothy J. Merritts** is Harry W. and Mary B. Huffnagle professor of geosciences at Franklin & Marshall College in Lancaster, Pennsylvania. **Robert C. Walter** is a professor of geosciences at Franklin & Marshall College in Lancaster, Pennsylvania. The authors are researchers with the Water Science Institute, Lancaster, Pennsylvania.

States, including the Chesapeake Bay watershed. Census data indicate that over 65,000 water-powered mills existed every 1.2 to 1.9 mi (2 to 3 km) on many streams in the eastern United States by 1840 (Walter and Merritts 2008). With colonial settlement patterns tethered to waterways along which gristmills, sawmills, and forges were established, LS stream bank erosion has been found to contribute as much as 50% to 100% of current suspended sediment loads in Piedmont watersheds (Massoudieh et al. 2012; Voli et al. 2013; Gellis and Brakebill 2013; Walter et al. 2017).

One of these LS impaired waters, Big Spring Run (BSR) in Lancaster County, Pennsylvania, has been closely monitored over a 15 year period—before, during, and after LS mitigation—for its sediment, P, and N loads and numerous other environmental indicators (http://www.bsr-project.org/). Average prerestoration rates of stream bank erosion at this study site averaged 875 tn $yr^{-1}$ (sd 614 tn [794 Mg $y^{-1}$, sd 557 Mg]), or approximately 0.3 tn $ft^{-1}$ (0.89 Mg $m^{-1}$) (Langland 2019). This represents 186 tn $ac^{-1}$ (417 Mg $ha^{-1}$) of restored area. By comparison, an acre of cropland in Lancaster County produces about 0.6 tn (0.5 Mg) sediment, according to the Chesapeake Assessment Scenario Tool (CAST) used to track progress toward Chesapeake Bay TMDL goals. Legacy sediment also contains nutrient pollutants of P and particulate N. Based on the average concentrations of these nutrients found in LS at the BSR site—i.e., 2.3 lb total P $tn^{-1}$ and 2.9 lb total N $tn^{-1}$ (0.95 kg total P $Mg^{-1}$ and 1.19 kg total N $Mg^{-1}$) of LS (Walter et al. 2013)—this site also contributed loads of 428 lb P $ac^{-1}$ and 540 lb N $ac^{-1}$ (479 kg P $ha^{-1}$ and 605 kg N $ha^{-1}$) annually through stream bank erosion, not including leaching of N into groundwater at the prerestoration site. (For comparison, an acre of cropland in Lancaster County produces about 2 lb P and 94 lb N [2.24 kg P $ha^{-1}$ and 105 kg N $ha^{-1}$] in the CAST model.) These loads are typical of LS erosion hot spots in the region.

Legacy sediment mitigation involves the removal of LS to restore aquatic ecosystem characteristics and processes that existed prior to the accumulation of sediment behind the historic stream impoundment. Wetland restoration is often a critical component of these aquatic ecosystem restorations, given that wetland soils and anastomosing channels were often buried by LS in the Chesapeake region (Walter and Merritts 2008; Voli et al. 2009; Hartranft et al. 2011). Like wetland restorations in general, or riparian buffer plantings, the load reductions from LS mitigation come from both (1) load source conversion (the annual reduction of existing load by converting the land use on the restoration site) and (2) efficiency reduction (the filtration of upland/upriver loads by the restored site). For example, at the BSR study site, annual abatement due to load source conversion is nearly equal to the elevated on-site loads prior to restoration, since the loads produced by the restored wetland are negligible. Further, the annual abatement due to efficiency reduction depends on the quantity of load entering the restoration site and the ability of the restored wetland to capture that load. Using the Chesapeake Bay Program's (CBP) Wetland Expert Panel (2016) report (CBP 2019), restored wetlands like that at BSR (Piedmont-floodplain wetlands) remove 31%, 40%, and 42% of sediment, P, and N, respectively, from 3 ac (1.2 ha) upland. Using CAST model loads for upland agricultural land uses in the region, annual abatement from efficiency reduction is an additional (albeit smaller) 0.8 tn sediment $ac^{-1}$, 0.9 lb P $ac^{-1}$, and 53.8 lb N $ac^{-1}$ (1.8 Mg sediment $ha^{-1}$, 1 kg P $ha^{-1}$, and 60.3 kg N $ha^{-1}$). Combining abatement from load source conversion and efficiency reduction results in substantial annual abatement of LS mitigation—187 tn sediment $ac^{-1}$, 429 lb P $ac^{-1}$, and 592 lb N $ac^{-1}$ (419 Mg sediment $ha^{-1}$, 480 kg P $ha^{-1}$, and 663 kg N $ha^{-1}$)—when implemented at identifiable hot spots such as the BSR site. This reduction far surpasses that of other conservation practices. For example, the P abatement benefits of just 1 ac (0.4 ha) of LS mitigation require the equivalent of 361 ac (146 ha) of forest buffer, 928 ac (376 ha) of grass buffer, or 279 ac (113 ha) of wetland restoration at sites not characterized by elevated LS stream bank erosion, based on CAST model parameters (Fleming 2019). However, policymakers concerned with finding practicable strategies for meeting water quality goals must consider not only per-acre efficiency, but also cost-effectiveness in terms of dollars spent per unit of pollution reduced.

## THE COST-EFFECTIVENESS OF LEGACY SEDIMENT MITIGATION

The cost-effectiveness of LS mitigation was recently analyzed as part of a USDA Natural Resources Conservation Service (NRCS) Conservation Innovation Grant administered by the Water Science Institute (Fleming 2019). This analysis included not only upfront costs of practice adoption, but also ongoing maintenance costs, opportunity costs borne by landowners who may remove land from production, and potential regulatory costs of LS mitigation. The same set of costs were gathered for several comparison best management practices (BMPs)—grass and forest riparian buffers, cover crops, and wetland restorations at sites not characterized as LS erosion hot spots. However, cover crops do not involve maintenance or opportunity costs, and regulatory costs were only significant for wetland restorations. For the comparison practices, data were drawn from USDA NRCS and Farm Service Agency program payment schedules, and supplemented with published cost information when available (Wieland et al. 2009; Jones et al. 2010; Kaufman et al. 2014).

Upfront costs of LS mitigation are relatively higher than most agricultural BMPs. Data from design and restoration firms indicate current costs of US$350 $ft^{-1}$ (US$1,148 $m^{-1}$) of stream length, including implementation, permitting, and other regulatory costs. In addition, landowner compensation for wetland easements (which are exclusively granted in perpetuity in Pennsylvania) is US$6,546 $ac^{-1}$ (US$16,175 $ha^{-1}$) of cropland removed from production, based on NRCS Wetland Reserve Enhancement payments. Maintenance at the BSR site was budgeted at US$10,000 total, and primarily used to control invasive species in initial years of wetland establishment. In sum, implementing LS mitigation today—using the BSR study site as a benchmark for the ratio of stream length-to-restoration acreage—would require upfront costs of about US$220,000 ac$^{-1}$ (US$543,613 ha$^{-1}$).

It is necessary to place these costs in annualized terms for purposes of comparison with conservation practices that are implemented annually, like cover crops. To convert one-time payments to annual ones, economists typically use discount rates, which represent the opportunity cost of capital. The US Environmental Protection Agency recommends using social discount rates, as opposed to individual discount rates, for economic analyses involving environmental investments that reap future benefits (USEPA 2010). Social discount rates are often evaluated empirically based on the cost of government borrowing, which has averaged approximately 2% to 3% over recent decades (USEPA 2010). Thus, at a 2% discount rate, the annualized cost of LS mitigation is US$4,437 ac$^{-1}$ (US$10,964 ha$^{-1}$; calculated as US$221,865 ac$^{-1}$ [US$548,221 ha$^{-1}$] multiplied by 0.02). By comparison, the annual cost of rye (*Secale cereale* L.) cover crops in the region is US$88 ac$^{-1}$ (US$217 ha$^{-1}$), and the costs of forest and grass riparian buffers, placed in annual terms, are US$834 and US$618 ac$^{-1}$ (US$2,061 and US$1,527 ha$^{-1}$), respectively. Complete details and sources for these cost calculations can be found in Fleming (2019).

With annual costs and abatement benefits per acre, cost-effectiveness for practice $k$ and pollutant $p$ is simply calculated as:

$$CE_{kp} = c_k \div a_{kp}\,, \tag{1}$$

where $c_k$ is the implementation cost per acre, and $a_{kp}$ is the abatement per acre achieved by that practice. Despite the relatively high cost per acre of LS mitigation, the *cost per pound of abatement* ($CE_{kp}$) remains low when considering the large annual reduction of sediment, P, and N achieved when implemented at LS hot spots. For sediment and P runoff, LS mitigation reduces loading rates at a substantial cost advantage (figure 2). The sediment abatement obtained by LS mitigation at US$0.03 lb$^{-1}$ (US$0.07 kg$^{-1}$) is one-sixteenth the cost of the next most cost-effective practice for sediment (grass riparian buffers). Legacy sediment mitigation reduces P loads at approximately US$19 lb$^{-1}$ (US$42 kg$^{-1}$), one-sixty-eighth the cost of the next most cost-effective practice (forest riparian buffers). 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.

The cost-effectiveness of LS mitigation is consistently driven by the large load reductions available at LS hot spots, such as the BSR study site—that is, the large denominator of equation 1. Using different geographic regions, agricultural land uses modeled in CAST, and higher discount rates used to annualize costs, the qualitative results are unchanged. Legacy sediment mitigation retains a substantial cost advantage for sediment and P reduction, and is competitive for N abatement, in comparison to low-cost agricultural practices. For detail on these sensitivity checks, see Fleming (2019).

## POLICY IMPLICATIONS FOR NONPOINT SOURCE POLLUTION ABATEMENT

The above results have important implications for NPS abatement policy in many US regions, including the Chesapeake Bay watershed. First, there is an opportunity for improved targeting of NPS reductions as technology advances policymakers' ability to identify LS erosion hot spots. Second, the response of landowners to information on legacy pollutants such as LS erosion hot spots presents both opportunities and risks for current NPS abatement programs.

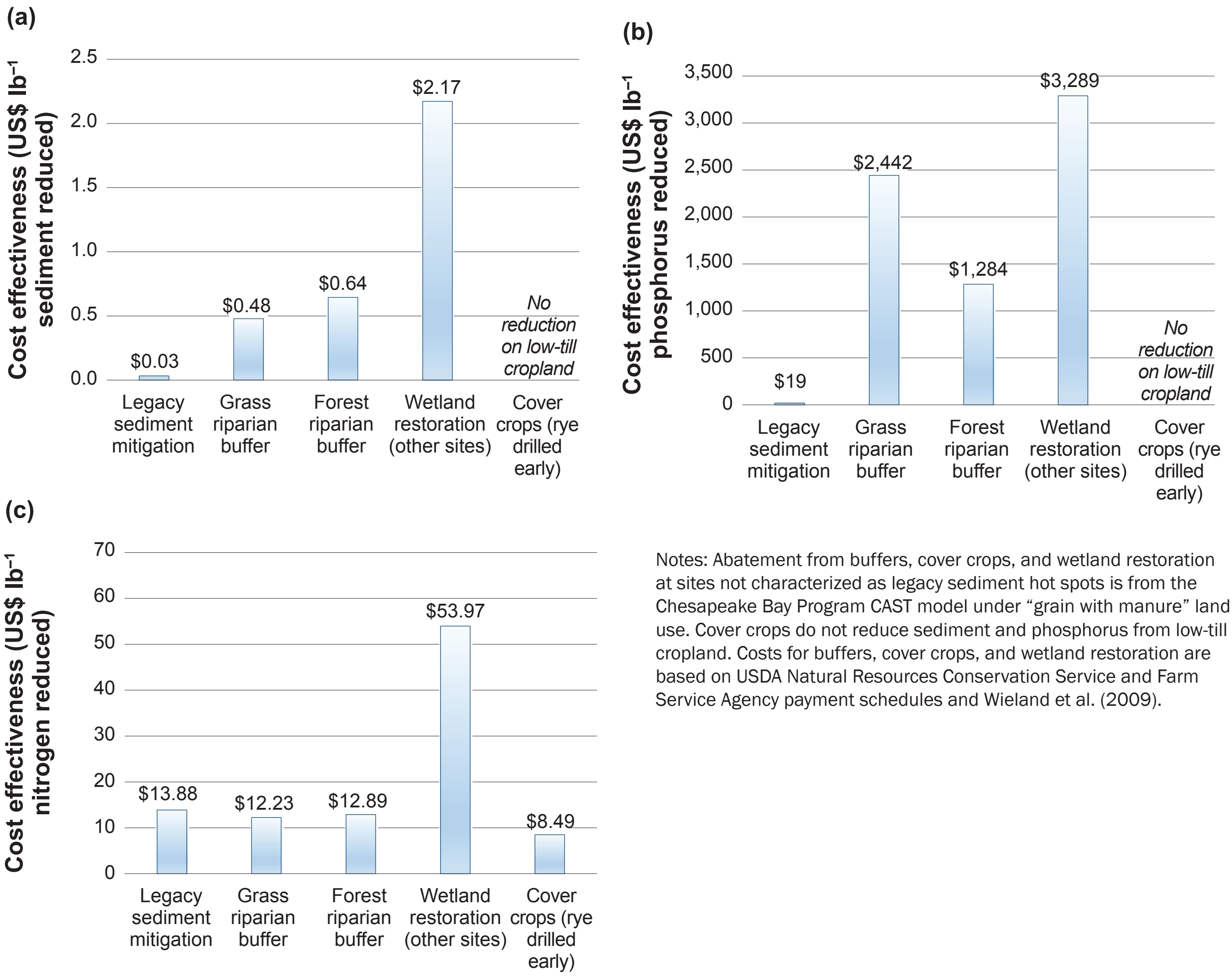
***Opportunities for Targeting.*** The Clean Water Act of 1972 has largely focused on point sources, and policymakers interested in reducing NPS pollution have primarily needed to rely on voluntary payment mechanisms to subsidize the adoption of qualifying conservation practices. As policymakers are increasingly able to identify LS erosion hot spots, LS mitigation should receive further attention as a practice eligible for cost-share funding from existing conservation programs.

Improvements in the quality of airborne light detection and ranging (LiDAR) data have made it possible to locate and quantify elevation change—and hence stream bank erosion—through digital elevation model (DEM) differencing. The identification of hot spots begins at the stream level, where highly eroding stream lengths stand out from those with more typical erosion rates. For example, figure 3 shows aerial identification of LS erosion, with red coloration indicating stream bank erosion between April of 2008 and December of 2014. With an average loss of 1,640 tn yr$^{-1}$ (1,487 Mg y$^{-1}$) on 3,133 ft (955 m) of stream length, this map clearly identifies an erosion "hot spot" according to the definition set forth above. The classification of hot spots at the individual parcel or stream level provides a guide for targeting the most severe erosion problems in a watershed. Figure 4 shows 18 LS erosion hot spots in the Mill Creek watershed where the BSR study site is located (indicated by the blue marker in figure 4). Each of these sites has comparable erosion rates to BSR prior to restoration, and together generate an estimated 8,524 ± 2,146 tn sediment yr$^{-1}$ (7,731 ± 1,946 Mg sediment y$^{-1}$) based on DEM differencing of LiDAR data. This includes an associated 20,458 lb P and 24,720 lb N (9,288 kg P and 11,223 kg N) annually, at average nutrient concentrations. Since these sites primarily run through agricultural land, these loads are often ascribed solely to agricultural sources despite their actual genesis from shear stress of flowing water and freeze-thaw cycles on stream banks (Inamdar et al. 2017).

If LS mitigation were implemented at these 18 sites, the immediate reduction of sediment load by converting the LS hot spots to restored wetlands would be approximately equal to the prerestoration loads (approximately 8,524 tn sediment yr$^{-1}$ [7,731 Mg sediment y$^{-1}$], with associated P and N), since loads produced at a restored wetland are negligible. This is an astonishing quantity of abatement, representing in itself about 5% of the remaining progress toward the Chesapeake Bay TMDL sediment goals for agriculture in Pennsylvania (see https://www.chesapeakeprogress.com/clean-water/watershed-implementation-plans). Assuming a ratio of stream length to restoration area that is consistent with the BSR site, this quantity of abatement would be achieved by restoring approximately 99 ac (40 ha) of land at

**Figure 2**

Cost effectiveness of (a) sediment and (b and c) nutrient abatement in the Chesapeake Bay watershed, showing legacy sediment mitigation versus other management practices.




Notes: Abatement from buffers, cover crops, and wetland restoration at sites not characterized as legacy sediment hot spots is from the Chesapeake Bay Program CAST 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 Resources Conservation Service and Farm Service Agency payment schedules and Wieland et al. (2009).



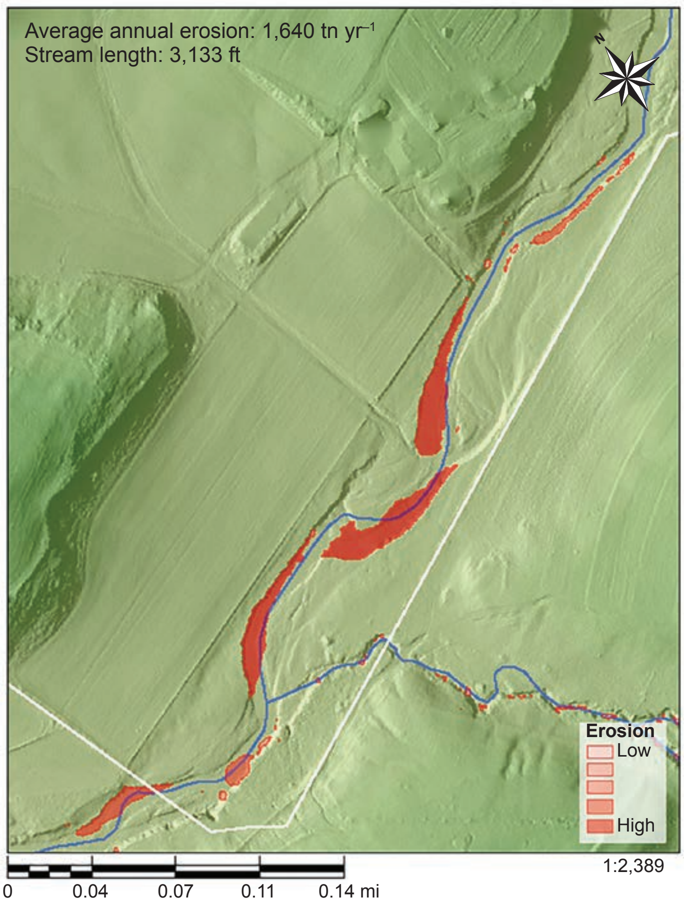
an annualized cost of about US$441,000, applying per-acre cost data of Fleming (2019). (Note this estimate assumes that LS mitigation has similar implementation costs on both tributaries and the main stem of Mill Creek. The BSR study site is on a tributary, while several of the other hot spots in the watershed are located on the main stem.) Other practices require substantially more restoration acreage and cost to achieve equivalent reductions (figure 5). For example, over 4,800 ac (1,942 ha) of buffer plantings or wetland restoration at areas not targeted as hot spots would be required to make the same progress, at much higher costs including annual per-acre rental payments to landowners.

***Landowner Response to Information on Legacy Sediment Hot Spots.*** An important consideration in any analysis of targeting is landowner participation. Legacy sediment mitigation at erosion hot spots would require the cooperation and participation of landowners at these sites, just as landowner participation is required for nearly all conservation practices that reduce NPS pollutants. The number of landowner contracts required to obtain similar abatement through cover crops and forest or grass buffers is substantially larger, due to the smaller abatement per acre of these practices. Focusing outreach efforts on several high load sites presents an opportunity to reduce transaction costs of program enrollment (McCann and Claassen 2016).

In other contexts, information provision and social comparisons at a household or property level have been shown to significantly increase willingness to invest in conservation (Allcott 2011; Ferraro and Price 2013). The improved mapping technology highlighted here may also provide a low-cost form of informational outreach to landowners. Parcel-level maps like that in figure 3 may "nudge" landowners at hot spots to do something about erosion problems on their properties, especially when those problems are among the most severe in a watershed. A targeted approach to NPS abatement has long

**Figure 3**

Legacy sediment "hot spot" identified at the parcel-level by digital elevation model (DEM) differencing of light detection and ranging (LiDAR) imagery.




been recognized as a means for improving the cost-effectiveness of policy. The identification of LS erosion hot spots at a watershed scale presents an opportunity to implement targeted policy in practice.

At the same time, NPS abatement policies that ignore legacy pollutants may become increasingly vulnerable politically. Substantial progress has been made through decades of implementation of upland agricultural or urban BMPs, yet this progress is masked by the ongoing and often substantial loads generated by legacy pollution sources, like LS hot spots. For example, figure 5 implies that the sediment and nutrient load produced by the 18 hot spots—if not addressed—offsets the sediment reduction produced by at least 4,800 ac (1,942 ha) of forest or grass riparian buffers annually. Landowners' willingness to implement and maintain conservation practices is related to how much impact they think their actions will have on water quality (Wilson et al. 2014). Ignoring legacy pollutant sources will render less visible the progress that has been made by subsidizing upland urban and agricultural practices, perhaps leading to increased political scrutiny on the effectiveness of these subsidy programs.

## CONCLUSION

The legacy of prior land use decisions has powerful implications for the design of cost-effective water quality policy today. This includes not only LS sites, but other well-known temporal dynamics in water pollution—including legacy P in soils, N in groundwater, and the problem of combined sewage overflows in many urban areas resulting from prior development decisions. Yet in the case of LS sites, the cost-effectiveness of the restoration actions highlighted in this article, together with the improved ability to identify hot spots, suggests that opportunities for targeted mitigation are increasingly available.

Given the large number of LS hot spots 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 to meet TMDL goals, strategies for achieving the TMDL should encompass a broader set of management practices that includes mitigation of LS impaired waters. In contrast, strategies that rely heavily on upland practices may be insufficient, and even limit the salience of progress made by upland NPS practices. Fortunately economic decision-making and improved technology now provide an innovative alternative to confront a "wicked" policy challenge.

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**Figure 4**

Legacy sediment "hot spots" identified in the Mill Creek watershed of Lancaster County, Pennsylvania. Legacy sediment hot spots are defined here as stream lengths that produce above 0.05 tn $ft^{-1}yr^{-1}$ of sediment erosion over at least a span of 2,000 ft.

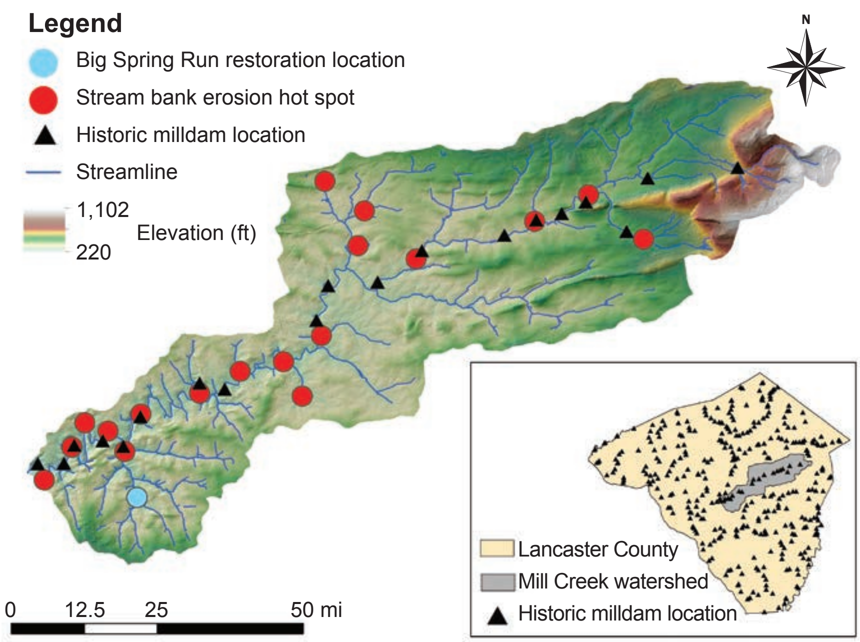
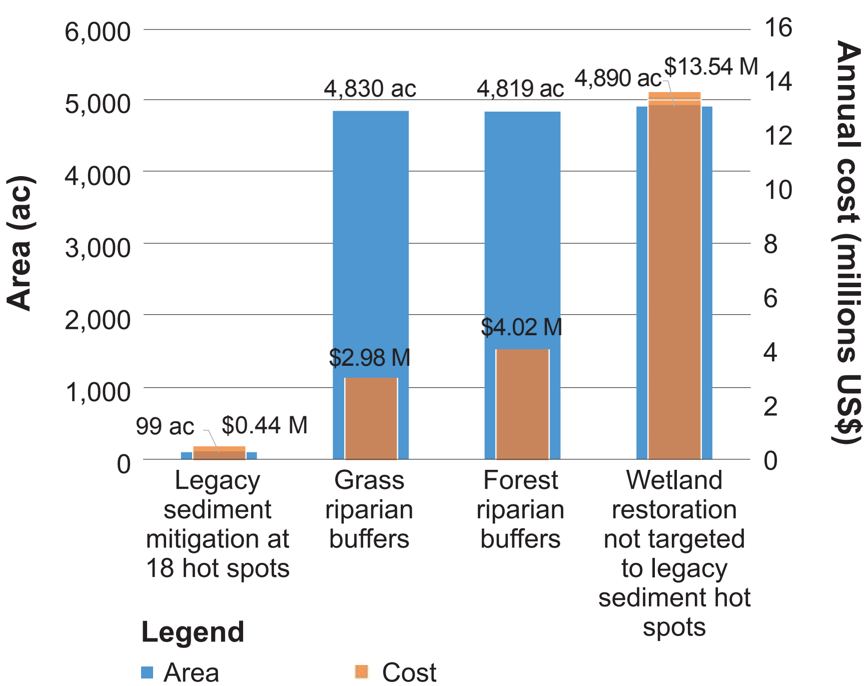



**Figure 5**

Annual cost and total restoration acreage required to achieve 5% of Chesapeake Bay total maximum daily load (TMDL) sediment goal for Pennsylvania agriculture (17 × $10^6$ lb abatement annually).





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