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From ecosystems to ecosystem services: Stream restoration as ecological engineering

Margaret A. Palmer[a,b,c,*], Solange Filoso[c], Rosemary M. Fanelli[c,d]

[a] Department of Entomology, University of Maryland, College Park, 4112 Plant Science Building, College Park, MD 20742, United States
[b] National Socio-Environmental Synthesis Center (SESYNC), 1 Park Place, Suite 300, Annapolis, MD 21401, United States
[c] Chesapeake Biological Lab, University of Maryland Center for Environmental Science, 1 Williams Street, Solomons, MD 20688, United States
[d] Marine, Estuarine, and Environmental Science Graduate Program, University of Maryland, College Park, 1213 HJ Patterson Hall, College Park, MD 20742, United States

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ABSTRACT

Ecosystem restoration was originally founded upon recovering ecosystems using wildlands as a reference state. More recently there has been interest in shifting to the restoration of ecosystem services – the benefits that natural systems can provide to humans. This shift is resulting in new restoration goals as well as new methodological approaches. The pace at which restoration goals and methods are changing is particularly fast for running-water ecosystems, which calls for a rigorous assessment of the environmental and economic costs and benefits associated with such changes.

In this paper, we explore the environmental costs and benefits of an emerging form of urban stream restoration, in which ecosystems are vastly transformed in order to enhance specific ecosystem functions and support desirable services. These projects are usually implemented in highly incised low-order perennial, intermittent, or ephemeral stream reaches. In either case, the stream channel is transformed into a stormwater management structure designed to reduce peak flows and enhance hydraulic retention of stream flow with the goals of reducing bank erosion and promoting retention of nutrients and suspended sediments. Results to date indicate that this novel ecological design approach does modify the hydrologic responses of streams during some storm events, but there is no consistent pattern of nitrogen retention or removal that would lead to net annual benefits. While additional data are needed, results suggest there is the potential for sediment retention, at least during some flows. Ongoing work which includes monitoring both pre- and post-project implementation will help resolve this uncertainty.

If sediment retention does occur, it is likely to decrease over time making the lifespan of these highly engineered projects is finite. Furthermore, environmental impacts associated with these projects can include loss or damage of riparian forests and export of sediment pulses during construction which may offset project benefits depending on their lifespan. Therefore, the use of approaches where entire existing ecosystems are modified to enhance a few specific biophysical processes should be limited to the most degraded systems where less invasive techniques, such as upland reforestation, reduced lawn fertilization, or better stormwater management at the source of runoff generation have first been exhausted.

1. Introduction

The concept of ecosystems as life-support systems and as providers of goods and services that have quantifiable value has now become widely adopted by the scientific and management communities (Cowx and Aya, 2011). The concept has been extremely useful in educating the public about our reliance on natural systems, but it also has implications for the science and practice of restoration. Historically, the focus of restoration ecology was on how best to recover "wildlands," and the choice of reference systems or a nearby least disturbed ecosystem of similar type for guiding restoration was typically a prior condition (Swetnam et al., 1999; White and Walker, 1997). Of course, the use of such references for restoration has been challenged by two persistent questions: What past? When has a system been free of human disturbance?

These questions are particularly germane given the dramatic changes in land use that have occurred worldwide and the potential

* Corresponding author at: National Socio-Environmental Synthesis Center (SESYNC), 1 Park Place, Suite 300, Annapolis, MD 21401, United States. Tel.: +1 410 919 4810.
E-mail address: mpalmer@umd.edu (M.A. Palmer).

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impacts of climate change (Davies, 2010). But, if a wildlands concept was not to guide restoration efforts, ecologists had to come up with an alternative. A variety of options have been proposed, including restoration targeting the historical range of variability (Morgan et al., 1994) or some guiding image of that (Palmer et al., 2005), restoration to maximize biodiversity or recover a valued species (Feld et al., 2011), and restoration to recover lost ecosystem processes (Beechie et al., 2010). For river systems in particular, Dufour and Piegay (2009) suggest the use of a restoration framework that incorporates both the historical context of a site (and its potential functions as observed in reference sites) as well as the societal needs for that site when developing restoration objectives. This is an appealing perspective but may be particularly difficult to achieve since current societal needs may conflict with the services an ecosystem provided historically (Sanon et al., 2012).

At the same time that restoration ecologists were broadening perspectives on goals and guidelines for restoration, the formalization and rise in broad use of the ecosystem services concept was occurring (MEA, 2005). Initially, the term “ecosystem services” meant essentially the benefits of nature to households, communities, and economies, and most attention was placed on the valuation of these ecosystem services. More recently, however, understanding when and where specific services are produced has become of great interest in the environmental management community (Daily et al., 2009). Whereas the ecosystem services concept largely arose independent of the concept of ecological restoration, we suggest they are increasingly intersecting. An ecosystem services framework does provide a new way to think about restoration goals and interventions. However, the very act of categorizing services implies an independence of the different components that support an ecosystem (e.g., soils, wetlands, forests) and the processes that sustain it (e.g., carbon cycling, primary production) (Muridan and Rival, 2012). This assumption combined with separate valuation of components and processes (Mehan, 2009) and emerging markets for restoration of specific services has placed additional pressure on ecologists to identify which biophysical processes and ecosystem components must be restored to recover specific ecosystem types and functions (Palmer and Filoso, 2009). If we understand these relationships well and a specific service is desired then restoration can target the subset of processes and components that will lead to the production of that service; however, targeting only a subset could limit the provision of other ecosystem services (Gilvear et al., 2013). For example, work by Sanon et al. (2012) indicated that restoration specifically targeting hydraulic connectivity of an Austrian floodplain would provide habitat for native biodiversity but reduce the provision of drinking water for local citizens. There are also a number of studies that have shown loss of terrestrial ecosystem services related to biodiversity or the provision of water when reforestation restoration is undertaken to enhance carbon sequestration (Hall et al., 2012; Jackson et al., 2005).

The concept of restoration of ecosystem services differs from single- or multi-species management in that the former necessarily is focused on the human use or desire for the service, whereas the latter is often but not necessarily motivated by utilitarian objectives. In both cases, however, concerns have been raised over the potential loss or degradation of ecosystem attributes that are not the focus of management or restoration efforts. Despite these concerns, the trend to focus on ecosystem services as part of ecological restoration and management is increasing (Trabucchi et al., 2012). Oyster restoration has been recommended as a strategy to help reverse eutrophication in coastal waters, and the costs and benefits of forest and wetland restoration are increasingly being evaluated in an ecosystem services framework (Birch et al., 2010; Cerco and Noel, 2007; Jenkins et al., 2010). Adoption of this framework seems to be happening at a particularly rapid pace with respect to running-water ecosystems, in part because of the potential linkage of stream restoration to environmental mitigation markets, but also because of the strong human dependency on the services that rivers provide (Doyle and Yates, 2010; Palmer, 2009). To illustrate how ecological restoration can shift from efforts to recover whole ecosystems and the full suite of their services to efforts undertaken to recover specific attributes or processes, we focus below on Coastal Plain streams. However, this phenomenon is not unique to running-water systems. Similar shifts can be found in very different types of ecosystems and parts of the world (e.g., forest restoration shifting to managed timberland for carbon offsets (Ecotrust, 2013); biodiversity conservation and restoration shifting to habitat creation for selected bird species (Morris et al., 2006)).

2. Running-water ecosystems and restoration

Streams and their floodplains provide ecosystem services essential to human well-being (Palmer and Richardson, 2009), and have become increasingly managed to optimize these services (Tockner et al., 2011). As a result, the rate of biodiversity loss in running waters exceeds that of terrestrial and marine systems and the water quality status of the world’s rivers is declining; this is particularly evident in urban areas. Urban expansion is a major global issue (Seto et al., 2011). In some countries, point-source inputs of untreated wastewater are significant and throughout the world, nonpoint-source pollution is pervasive (Corcoran et al., 2010). Runoff from impervious surfaces has a very large impact on stream and river discharge, and in some cities the rapid routing of stormwater directly to streams exacerbates peak flows and pollutant loads (Walsh et al., 2005). Higher and more frequent peak flows can also erode stream channels (Booth and Jackson, 1997) and result in high levels of fine sediments transported to downstream waters (Paul and Meyer, 2001), which can also increase the flux of N to coastal waters (Mayer et al., 1998).

A variety of management tools are being used to address urban stream and river impairment, including better development practices, separation of stormwater and sewer systems, and riparian and wetland restoration (Walsh et al., 2005). Unfortunately, the costs associated with these projects are enormous, and jurisdictions through the U.S., Europe, Australia and other regions of the world simply cannot fund all of the needed remediation projects. Further, implementing projects in developed watersheds often involves the difficult task of working with many private-property holders to gain access to buried or difficult-to-reach structures. For these reasons, alternative approaches to correcting the underlying cause of degradation for most urban streams and rivers – uncontrolled non-point inputs – are of great interest. Search for alternative approaches to control non-point inputs has increasingly led to direct alteration of stream channels in an attempt to restore them, even though the U.S. Clean Water Act limits certain activities within streams. Impacts to ‘waters of the United States’ including any dredging or filling require permits from the U.S. Army Corps of Engineers and permittees must compensate for these impacts by restoring streams elsewhere or by purchasing credits from stream mitigation banks (Lave et al., 2010).

2.1. Process-based restoration to ecological engineering

Restoration as a management tool for improving the health of rivers and streams has grown dramatically in the last decade (Bernhardt et al., 2005; Feld et al., 2011). Indeed, it is a mandatory element of the European Framework Directive which commits EU states to achieve “good status” for their ground and surface waters (Luderitz et al., 2011) and in Japan, the number of river restoration projects has grown exponentially since the 1990s such that by 2006 the total number was comparable to that in the U.S. (Nakamura et al., 2006). Increased attention to ecological outcomes of river restoration has led to recent demands that river restoration target recovery of biophysical processes instead of just focusing on channel alteration (Beechie et al., 2010; Palmer, 2009). However, scientific understanding of exactly how to implement process-based restoration of stream is in its infancy. The most well-studied 'process-based' approaches have involved dam removal or reservoir release management to better mimic a river's historical hydrologic and sediment regimes, yet even these topics remain active areas of research often involving adaptive management (Stanley et al., 2002). Water scientists have been seeking to extend their understanding of the linkage between biophysical processes, stream biodiversity, and management options to respond to the conundrum (Palmer and Filoso, 2009).

Ecological engineering, broadly defined as the design and restoration of natural ecosystems for societal and environmental benefits, is an extension of process-based restoration and is focused on the use of engineering principles on natural systems in order to recover or replace lost biophysical processes. The word design has been used to emphasize that it is a branch of engineering but unlike many engineered structures, ecological engineering should be energy neutral, ideally leading to self-sustaining systems (Bergen et al., 2001). It differs from ecological restoration in that it includes concepts such as ecosystem creation or construction but the field still maintains a focus on sustainability – namely the ability of an ecosystem to recover or withstand most disturbances (Mitch and Jorgensen, 1989). This focus on self-sustainability also distinguishes ecological engineering from environmental engineering because the latter has historically sought to produce stable, enduring structures that do not change over time in response to disturbances (Allen et al., 2003).

The term ecological engineering was first used in the 1960s by Howard Odum, but it was the mid-1990s before the field became widely recognized (for a broad review, see Matlock and Morgan, 2011). Some have taken this concept further by suggesting that we minimize manipulation of a system but accept an 'open-ended' restoration approach in which the final system state is not predictable and it may not be anything like the historical state (Hughes et al., 2011). Others have proposed no-analog or novel ecosystems but have not necessarily advocated minimal intervention to initiate or manage the restoration process (Williams and Jackson, 2007). Indeed, Hobbs et al. (2011) have promoted the idea of "intervention ecology" in which systems are manipulated with a focus on the future and not the past. There is a tradition of referring to such approaches as ecological engineering (Hobbs et al., 2009) to emphasize that the methods are grounded in ecology; often the projects are designed to meet human needs by manipulating natural systems in the most environmentally sustainable way possible. All of these fundamentally view restoration within the lens of integrating nature with society or manipulating nature to serve human needs.

2.2. Ecosystem service production and ecosystem transformation

When the goal becomes using ecological engineering to meet human needs, it is necessarily place-based within the context of how best to deliver particular ecosystem services desired by local or regional communities. The resulting product may be the same as what would come from restoration but it need not be. Since the focus of this perspective is on engineering designs to provide one or more ecosystem services instead of restoring ecosystems that provide the full suite of services for that ecosystem type, the product may be a novel/no-analog ecosystem or a technological solution that happens to use natural materials. For instance, when technological solutions are implemented in damaged streams to enhance desired functions, the aquatic ecosystem can change dramatically from what it was historically and the production of the desired ecosystem service(s) may or may not be sustainable from an energy or environmental standpoint. To provide an example, we next describe an emerging form of urban stream "restoration" that uses ecological engineering principles to intentionally transform a stream channel to deliver specific ecosystem services. We describe the motivation, design, and preliminary results of research to monitor the effectiveness of the projects in meeting specific objectives, followed by a discussion of the implications of shifting far away from whole ecosystem restoration.

3. The Coastal Plain urban stream example

Many healthy stream ecosystems can store or remove sediment and nutrients before they reach coastal areas. However, the ecosystem processes responsible for storage and removal are closely tied to infiltration and water retention capacity of entire watersheds and may become impaired in urban tributaries. Recovery of these processes has been the motivation for many restoration projects that have led to widely variable outcomes. Increases in stream bank denitrification (Kaushal et al., 2008) and small or inconsistent changes in stream nitrogen (N) uptake rates have been reported (Bukaveckas, 2007; Klocker et al., 2009; Roley et al., 2012), but reductions in the total annual export of N to downstream waters have not been detected in traditional stream restoration projects such as those using Natural Channel Design methods (Fig. 9, top panel in Filoso and Palmer, 2011). The projects we describe transform streams and gullies into structurally engineered systems designed to enhance processes such as water storage and sediment and N removal. They have been implemented in short stream reaches at the top (headwaters) of catchments or at the freshwater outlets of coastal watersheds.

3.1. Project designs

Many urban streams in the mid-Atlantic Coastal Plain region have deeply incised channels (Hardison et al., 2009). In some cases, channel heads have also migrated upward, likely due to the shift of water from subsurface flows to surface runoff which can result in ephemeral gullies many deep. Projects implemented in streams or gullies seek to restore hydraulic retention that has been lost in the landscape and restore the energy regime of stream ecosystems by dissipating excessive erosive forces from incoming stormwater runoff (Flores et al., 2009). Two key design features are involved: (1) a constructed sand-seepage bed in the channel to provide opportunities to enhance stormwater infiltration and storage; and (2) step-pool or riffle-pool features on top of a sand-seepage bed to reduce the kinetic energy of stormwater runoff (Fig. 1). The overall design of these engineered systems varies a little from project to project, as does the terminology used by practitioners, managers, and regulators.

We are evaluating the results from monitoring work done on a number of stormwater ecosystems in the Coastal Plain physiographic province of Maryland (U.S.) to determine how effective they are at changing the hydrologic conditions in stream channels and, consequently, at reducing sediment and nutrient loads exported downstream. Three projects are discussed here (Fig. 2): two of them, Howard's Branch and Wilelinor, were designed as sand-seepage wetland systems in valley bottomland areas, and are often also intended to restore the hydrologic conditions associated with Atlantic White Cedar swamps, whose historical distribution

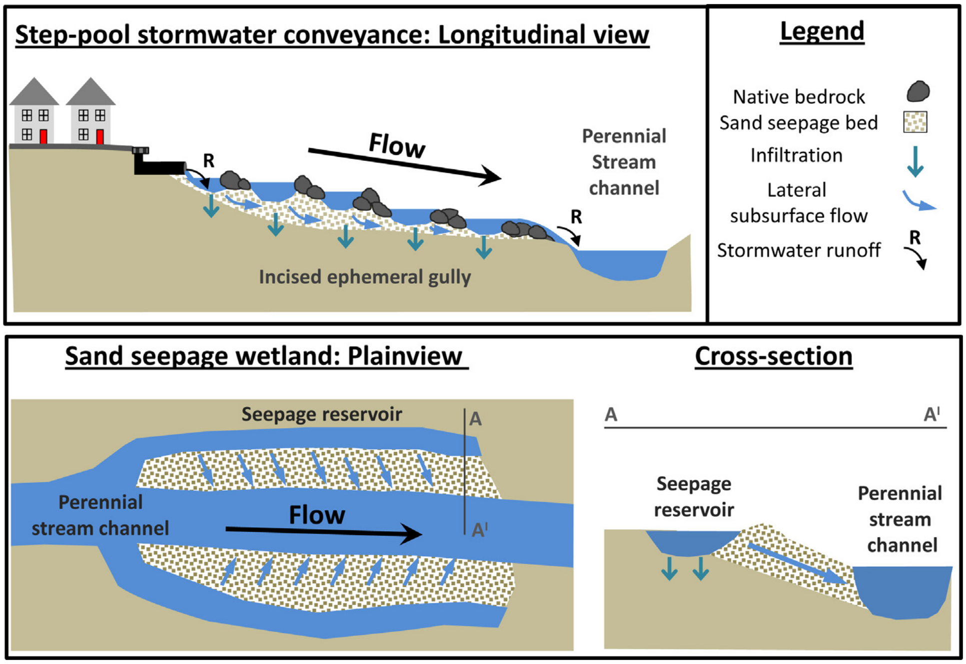

Fig. 1. Schematic diagram of the approaches used to transform streams to engineered systems designed to reduce stormwater impacts to urban waters. These stormwater "ecosystems" follow two general design configurations and may be referred to under different names. *Step-pool stormwater conveyances* are designed for incised ephemeral, intermittent, and perennial sites. They contain a thick sand-seepage bed and step-pool sequences. The sand elevates the original channel bed and ties it to the adjacent valley sides, and the step-pool sequences provide extra energy dissipation in sloped topographic conditions. The structures also armor the eroding banks to reduce further erosion of channels. *Wetland seepage systems* are designed for moderately entrenched, relatively low-gradient perennial streams. A series of moats ("seepage reservoirs") and riffle-pool wetlands are used to store stormwater runoff; side channels are constructed and are underlined with a sand-seepage bed that connects them to the main, perennial channel.

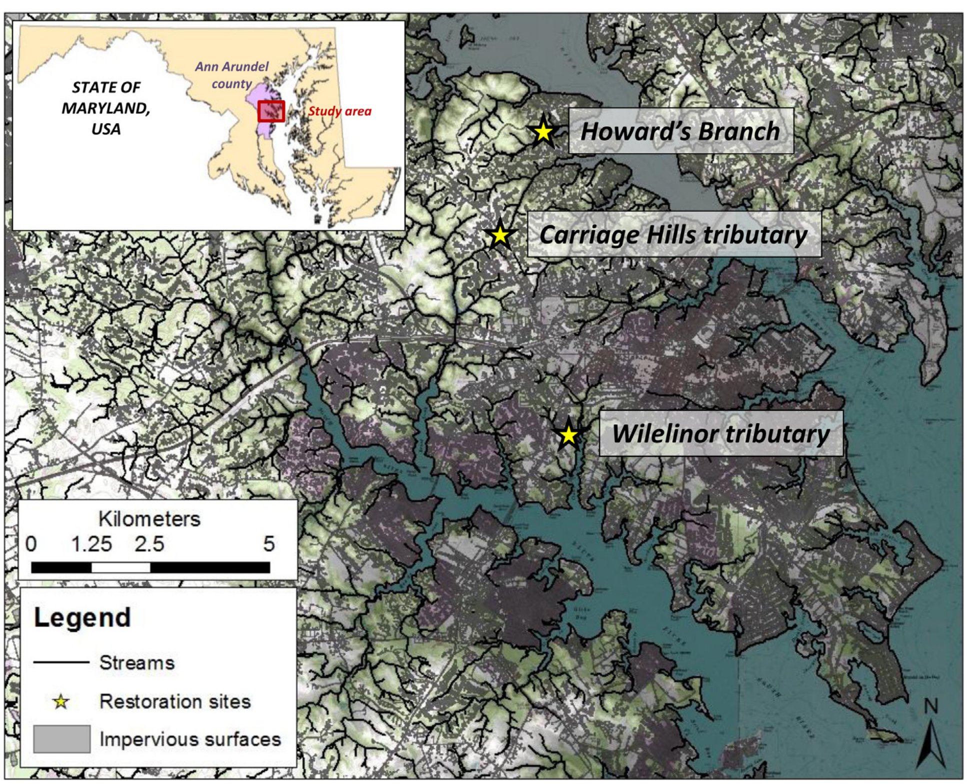

Fig. 2. Locations of the three restoration projects presented in this paper; all are located in the Coastal Plain physiographic province in Ann Arundel County, Maryland, U.S. Wilelinor and Howard's Branch were placed in perennial stream channels, while the Carriage Hills project was placed in an ephemeral gully.

spanned a narrow band of Coastal Plain region along the entire eastern coast of North America (Laderman, 1989). The third project, Carriage Hills, was on an incised ephemeral channel that had been deeply eroded by poor stormwater management. It has been reconfigured as a step-pool stormwater conveyance system. The results evaluated include several years of data collected for the first two projects but only one year of data from the Carriage Hills project.

3.2. Monitoring and evaluation methods

The projects were monitored to determine if they produced the desired ecosystem services (e.g., water purification and consequent reduction in N and loads of total suspended solids (TSS) exported downstream). The two seepage wetland projects were assessed using a mass balance approach where the annual loads of N and TSS were quantified by very frequent measurements of discharge and concentrations of N and TSS over a wide range of hydrological conditions above and below the implemented projects (Filoso and Palmer, 2011).

The third project (step-pool stormwater conveyance) was monitored for discharge, TSS and N concentrations during a series of storm events at a site immediately downstream of the stream reach where the conveyance system was implemented. Matching data were collected in an adjacent, degraded headwater stream with similar drainage area, topography, and land use for comparison (i.e., a negative control). The discharge data collected from each stream (engineered and control) was coupled with a full year of precipitation data to determine if the step-pool design modified the frequency of stream runoff responses. This allowed us to determine if the design reduced the frequency of surface runoff flowing from the channel outlet. For storm events that produced flow from the outlet, we can compare the flow volumes and peaks from the reconfigured and control channels.

3.3. Results

The designs altered the hydrology of all three stream reaches, especially during storm flow conditions. In the two seepage wetland systems, the peak flow rate decreased downstream of the restored reaches, and lengthened the storm recession limbs (Fig. 3). The total load of N exported downstream during storm events decreased on some dates, but not consistently. When N loads were reduced, it was often due to the retention of N in particulate form during high flows rather than being due to increased N uptake or reductions in dissolved N (Filoso and Palmer, 2011).

In the Carriage Hills Tributary, the frequency of runoff responses (binned by storm size) in the degraded control stream was higher than in the engineered stream below the constructed step-pool structure (47 runoff responses vs. 22 in the unrestored tributary; Fig. 4). Further analysis showed that the design mitigated surface runoff delivery to the stream reach but only for small- to intermediate-sized events (up to ~1 in. in magnitude; Fig. 4). Frequent sampling during several storms events just above 1 in. showed that as rain fell and discharge increased, retention of TSS declined i.e., flux downstream increased (Fig. 5). While, the design potentially reduced the loads of TSS exported downstream during small rainfall events, reduction of total dissolved N (TDN) is less certain (Fig. 5). For storms larger than 1.0 in., the frequency of runoff responses in the two streams was identical suggesting that a 1-in. storm size exceeds the storage capacity of the restoration structure.

3.4. Ecological effectiveness in perspective

It is not a matter of debate whether streams in most highly urbanized watersheds are degraded and that some sort of remedial action is necessary. The management questions are in regard to the choices available for addressing this problem and the trade-offs of various methods, some of which are highly invasive and result in the complete transformation of ecosystems. Although stream restoration is a very young watershed management practice and it is appropriate to experiment with new methods coupled with rigorous, scientific assessments, the projects that we describe are more akin to structural fabrication than restoration, as their "stormwater conveyance structures" or "sand-seepage wetland" labels suggest. They are an attempt to use a few short eroded gullies and streams at the base of watersheds to address an environmental problem created up in the watershed (compromised infiltration capacity). In short, the projects attempt to enhance stream

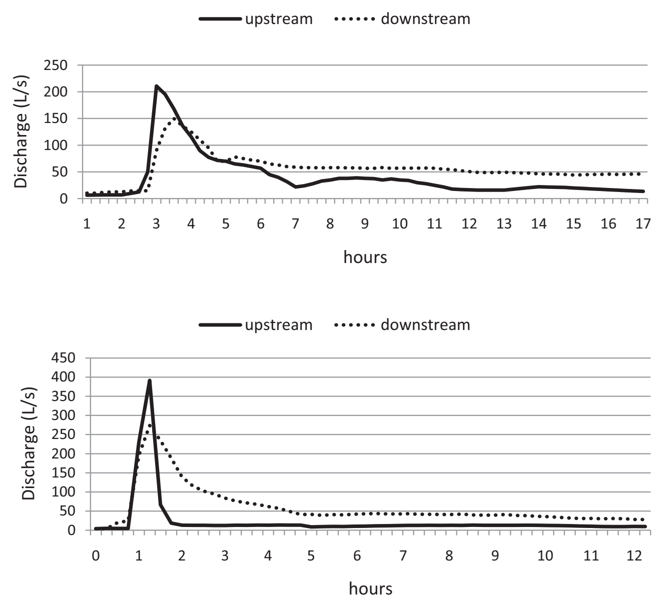

Fig. 3. Hydrographs from the two sand-seepage projects (Howard's Branch, upper panel; Wilelinor tributary, lower panel) illustrating peak discharges and recession times measured during storm flow conditions at the upstream and downstream segments of the constructed reaches.

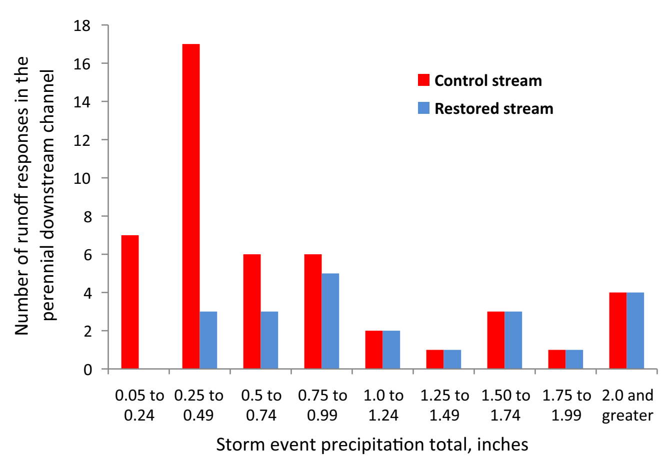

Fig. 4. Histogram of runoff responses in a degraded stream and in a nearby step-pool transformed stream (carriage hills) for different sized storms during the period September 2011 to September 2012. For example, for rainfall depths ranging from 0.05 to 0.24 in., the unmodified stream draining the urban degraded watershed experienced 7 runoff responses, while the stream draining the modified urban watershed did not experience any runoff in response to the storms at the tributary outlet. For larger rainfall events (> 1 in.), there was no difference in the number of runoff responses at the restored vs. unrestored control.

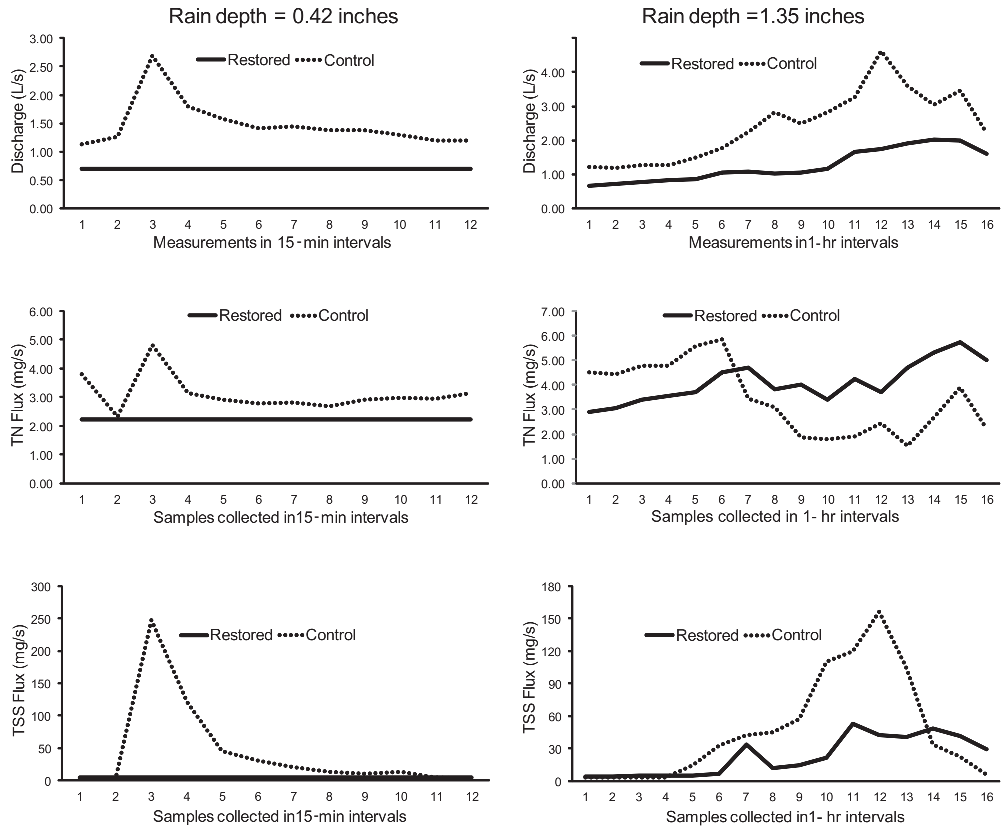

Fig. 5. Instantaneous discharge (top panels), loads of total suspended solids (TSS; mid panels) and total dissolved nitrogen (TDN; bottom panels) during two storm events at the step-pool project stream (carriage hills) and the control, impaired streams. The panels on the left contain data from a 0.42-in. rain event that lasted for <2 h; the right panels data from a 1.35 in. rain event that lasted ~13 h. Samples were collected frequently from the beginning of stream stage rise until the return to pre-storm conditions.

functions beyond what they would naturally do. Given this backdrop, it is appropriate to evaluate effectiveness of these projects in a watershed context. We use N retention as an illustration because excess N is a leading cause of water quality degradation in urban streams.

Stream channel design projects like the Wilelinor project that result in a significant increase in floodplain hydraulic connectivity have the potential to enhance infiltration capacity and remove or store N. But because such streams are so low in the watershed (i.e., at the outlet), infiltration can be offset by competing processes like groundwater discharge of N-laden groundwater. Thus, net annual removal of N was insignificant in the Wilelinor project despite a long restored reach and an extensive floodplain (Filoso and Palmer, 2011). In the Carriage Hills step pool stormwater conveyance system, it is too early to determine if significant N removal will occur but given the small drainage area of the project, it is unlikely to be significant at the watershed scale.

The best-case scenario for reducing N was found in the Howard's Branch sand-seepage project which also has an extensive floodplain. Because stormflow accounts for up to 70% of the annual discharge in these small urbanized streams, load reduction during stormflow conditions is essential to the effectiveness of the system (Filoso and Palmer, 2011). Results from three years of monitoring for this project show a reduction in the export of N during only select stormflow events (Fig. 6). High variability in N retention rates associated with storm sizes suggest that the system is dynamic and not effective at reducing N loads during larger storms (>0.75 in.) (Fig. 6). It is important to recognize that even though these larger storms typically account for less than 15% of the rain events in the study region, they contribute most of the annual discharge because of the volume of runoff that they generate. Thus, for the project to be effective at reducing the net downstream flux of N on an annual or longer basis, retention of N during these larger rain events would be needed.

These and other examples emphasize that the effectiveness of these projects in removing N may not be effective compared to other options. Even with additional benefits from other ecosystem services, a recent economic analysis showed that the costs of urban stream projects are greater than the least expensive alternatives for management of N loads (Kenney et al., 2012).

4. Restoration as design: implications

We began this paper discussing factors that are contributing to shifting frameworks that guide ecosystem restoration. The move from an ecosystem restoration perspective in which efforts are made to restore historical wildland or least-impacted communities may be giving way to efforts to restore specific ecosystem services. This shift may be associated with a focus on restoring, recovering, or engineering ecosystems to maximize a subset of biophysical processes or ecosystem attributes that underlie these services. However, the foundations on which the science and practice of ecological restoration were built are explicitly linked to restoring the full suite of processes and attributes that are characteristic of comparable but intact "reference" ecosystems; these may be nearby existing sites or conditions that occurred at the degraded site historically. In the case of streams, local and regional jurisdictions in the U.S. and many regions beyond (e.g., Canada, the European Union, Australia), define reference systems as those that support specific stream biota, namely sensitive aquatic insects

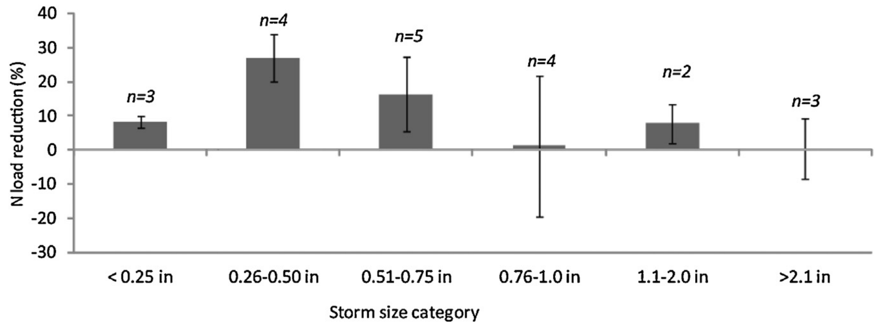

Fig. 6. Percent reduction in the export of nitrogen (N) along the restored reach of Howard's branch during stormflow conditions. The data summarize loads from 21 different storm events, where discrete samples were collected in 10–15-min intervals for the duration of the event. The 21 events were divided into 5 categories according to the storm depth (in inches). The categories range from storms smaller than 0.25 in. (<0.25 in.) to larger than 2.1 in. The number of storms (*n*) included in each category is indicated above each bar.

characteristic of running-water ecosystems in the region (Dallas, 2012; EPA, 2013). These organisms spend months or years in the water before emerging as flying adults and are considered effective indicators of overall and integrated water quality and stream health (Rosenberg and Resh, 1993). Recovery of these organisms are not however necessary for many of the services rivers can provide humans, e.g., N or sediment storage or removal, abundant water for irrigation. The question that needs to be addressed is: are there yet unrealized consequences of decisions not to restore the streams and rivers sufficiently to support the full suite of species?

In the stream examples we discuss, an ideal restoration-based approach would be to restore the infiltration capacity of the watershed that has led to stormwater problems. Removing impervious cover and re-vegetating is of course unrealistic in many urban regions, so ecological engineering principles are increasingly being used to implement a combination of practices such as disconnecting downspouts from roofs, constructing swales and rain gardens around storm drains, and strategically locating wetlands to increase overall infiltration capacity in the watershed (Walsh et al., 2005). All of these approaches are attempts to address the problem of uncontrolled stormwater at the problem's source – the terrestrial landscapes up in the watershed.

What we have highlighted in this paper, however, is a step that goes beyond ecological engineering to transforming ecosystems into something quite different from their existing or historical state. Impaired Coastal Plain streams are transformed into stream-wetland stormwater conveyances or steep, rock-lined step-pool conveyances. The aquatic flora and fauna characteristic of stream ecosystems are replaced by terrestrial and wetland species. In cases where gullies are converted to stormwater conveyance systems, the wooded hill slopes adjacent to the gullies may become part of the stormwater structure sometimes with loss of healthy trees. It is not clear at this point if these highly designed stream–wetland systems will require significant maintenance over time. A basic tenet of ecological engineering is that projects should be energy neutral and self-sustaining (Bergen et al., 2001) yet these built conveyance structures are unlikely to conform to this principle. They may be more akin to environmentally engineered structures designed for a fixed purpose (e.g., stabilizing eroding streams or reducing N flux) rather than a dynamic system that is expected to change form and potentially change function in response to

Fig. 7. Photograph of Wilelinor during the early stages of the project showing bags of fertilizer to be used to promote early growth of young plantings.

Fig. 8. Photograph of a Coastal Plain stream a few days after the complete removal of trees and tree roots from the stream banks to implement a Maryland stream restoration project in 2012.

changing environmental conditions (Allen et al., 2003). While research to determine the longevity of the stormwater conveyances is ongoing, it is clear that projects like Wilelinor and Howard's Branch will have a finite lifespan–as they trap sediments, the pools will eventually fill up and the sand-seepage wetlands may become clogged, which will reduce future potential for N removal and additional sediment storage. The only way to remedy this limitation without allowing the trapped sediment to be exported downstream is to manually remove the sediment from pools and replace the sand-seepage layer. Such practices certainly violate the principle of self-sustainability and are costly.

The net environmental costs of implementing stream restoration and ecological engineering projects such as these conveyances have not been evaluated. Whether fertilizer is applied to promote vegetative growth (Fig. 7) or excessive amounts of sediment are released during construction, such impacts should be included in calculations of environmental costs to determine effectiveness. Manipulative projects in streams or in their riparian corridors are simply high risk projects because stream flow conveys the impacts of disturbances, often unintended, downstream. Disturbance is particularly severe when project implementation includes the complete removal of trees and tree roots (Fig. 8).

5. Conclusions

There may be no way to avoid the dramatic urbanization trend occurring worldwide and therefore impacts to natural systems are inevitable. However, there are ways to limit those impacts and even reverse some using principles from restoration science and ecological engineering. Both of these disciplines emphasize identification of the underlying cause of impacts and then determining how lost or impaired biophysical processes can be sustainably recovered or replaced to reverse impacts. Moving to a framework focused on enhancing a subset of biophysical processes to maximize the delivery of specific services of ecosystems runs the risk of shifting the focus from whole systems, species assemblages and suites of tightly linked biophysical processes toward a focus on a few processes or system features. It also shifts the focus away from solving the underlying problem to treating symptoms, a shift that rarely leads to sustainable outcomes. Regardless of the approach, all projects should be assessed in the context of the relative environmental benefits and the economic and social costs of alternatives.

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