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Restoring streams in an urbanizing world

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SUMMARY

1. The world's population is increasingly urban, and streams and rivers, as the low lying points of the landscape, are especially sensitive to and profoundly impacted by the changes associated with urbanization and suburbanization of catchments.
2. River restoration is an increasingly popular management strategy for improving the physical and ecological conditions of degraded urban streams. In urban catchments, management activities as diverse as stormwater management, bank stabilisation, channel reconfiguration and riparian replanting may be described as river restoration projects.
3. Restoration in urban streams is both more expensive and more difficult than restoration in less densely populated catchments. High property values and finely subdivided land and dense human infrastructure (e.g. roads, sewer lines) limit the spatial extent of urban river restoration options, while stormwaters and the associated sediment and pollutant loads may limit the potential for restoration projects to reverse degradation.
4. To be effective, urban stream restoration efforts must be integrated within broader catchment management strategies. A key scientific and management challenge is to establish criteria for determining when the design options for urban river restoration are so constrained that a return towards reference or pre-urbanization conditions is not realistic or feasible and when river restoration presents a viable and effective strategy for improving the ecological condition of these degraded ecosystems.

Keywords: catchment management, river restoration, urbanization

Introduction

Over the next 30 years, virtually all of the world's human population growth is expected to occur in urban areas with over 60% of the people in urban areas by 2030 (UNPD, 2003). Urban areas are variously defined based on population density. The US census bureau, for example, defines an urban area as having a core with a population density of at least 386 people per square kilometre and all surrounding areas that have an overall density of at least 193 people per square kilometre. The UNPD (2003) predicts that urban areas will experience growth rates nearly double the worldwide population growth rate because of rural to urban migration and the transformation of rural areas to cities. Already, 75% of the people in the developed world live in or near cities, yet even in these areas, substantial growth in population size is expected (UNPD, 2003). For example, in both Europe and North America, the percent of the population living in urban areas should reach 85% by 2030 (UNPD, 2003). The increase of urban populations is expected to be even more rapid throughout the developing world (UNPD, 2003).

The ecological impacts of this growth and population re-distribution are profound. The loss of forests and agricultural lands to urbanization influences local climate and air quality, alters energy and nutrient flows and leads to decreased native biodiversity (Vitousek *et al.*, 1997; Grimm *et al.*, 2000; Alberti *et al.*, 2003; Dudgeon *et al.*, 2006). As running waters occupy the lowest-lying areas on the landscape, they integrate the effects of land-use change and thus are very sensitive to urbanization. As land is cleared of

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vegetation and replaced with a large amount of impervious surface such as asphalt, concrete and rooftops, the amount of run-off entering streams increases; the hydrology and geomorphology of receiving streams are fundamentally altered; and the consequences for ecological changes can be severe and complex (Wolman, 1967; Walsh, 2000; Paul & Meyer, 2001). Urbanization simultaneously increases the loading of water and nutrients while simplifying receiving stream channels, turning the urban river from a functioning ecosystem to an efficient gutter.

Concerns over the impacts that land-use changes may have on the ability of river systems to provide the ecological and social services upon which human life depends (Postel & Richter, 2003) have resulted in the initiation of major investments in urban river restoration. Further, investments have been driven by a recognition that since ca. 17% of all urban land in the United States is located in the 100-year flood zone, restoration of riverine floodplains and wetlands in urban areas could reduce deaths and property loss from floods (Palmer, Allan & Meyer, 2007). Indeed, river and stream restoration has become a worldwide phenomenon as well as a booming enterprise (e.g. NRC, 1999; Henry, Amoros & Roset, 2002; Carpenter *et al*., 2004; Bernhardt *et al*., 2005). The goal of urban river restoration should be to restore the essence of the ecological structure and function characterising non-urban streams, and to reestablish the natural temporal and spatial variation in these ecological attributes rather than stable conditions (e.g. Palmer *et al*., 2005). In some cases, urban river restoration efforts attempt to reverse decades of physical degradation through reshaping the channel, manipulating habitat heterogeneity and replanting riparian vegetation in order to return the stream ecosystem towards non-urban 'reference' conditions. However, in many urban settings management activities that are called 'river restoration' focus almost exclusively on stabilising streambanks in order to protect infrastructure such as sewer pipes and buildings.

In this paper we (i) briefly summarise the impacts of urbanization on streams; (ii) examine what can and is being done currently to restore urban streams; and (iii) consider whether and when urban stream restoration should be attempted given the multitude of factors that constrain restoration options in urban settings.

The urban stream: complex hydrology, simplified geomorphology and reduced ecological function

Excellent reviews of the rapidly expanding literature on streams draining urban areas have recently been published (Paul & Meyer, 2001; Walsh *et al*., 2005b), therefore we provide only a brief description of the impacts of urbanization here. The most obvious and immediate consequences are an increase in impervious surface area with resultant increased runoff to receiving streams, higher peak discharges, greater water export and higher sediment loads during the construction phase (Dunne & Leopold, 1978; Arnold & Gibbons, 1986; McMahon & Cuffney, 2000; Rose & Peters, 2001; Nelson & Booth, 2002; Walsh, Fletcher & Ladson, 2005a). Over time as the catchment is built out (new construction slows or ceases), the hydrologic alterations remain but sediment delivery to streams decreases dramatically (Trimble, 1997; Wheeler, Angermeier & Rosenberger, 2005), leading to channel erosion and sometimes dramatic increases in channel width and depth (incision) (Booth, 2005; Leopold, Huppman & Miller, 2005). These changes in channel morphology disconnect the stream from its floodplain, decrease sinuosity, and homogenise stream profiles (Hammer, 1972; Douglas, 1974; Roberts, 1989; Booth, 1990). Leopold, Huppman & Miller (2005) described these hydrogeomorphic changes as part of the 'urbanization cycle' in small river basins. These impacts have historically been exacerbated by sealed and piped drainage systems, as well as channelisation, which is often used for reducing lateral channel migration and managing flow to protect urban infrastructure (Dunne & Leopold, 1978).

A number of recent papers have added an ecological perspective to these well established hydrogeomorphic patterns (e.g. Wang *et al*., 2000; Murdock, Roelke & Gelwick, 2004; Grimm *et al*., 2005; Groffman, Dorsey & Mayer, 2005; Harbott & Grace, 2005; Kominkova *et al*., 2005; Meyer, Paul & Taulbee, 2005; Morgan & Cushman, 2005). Analogous to Leopold's 'urbanization cycle', others have referred to the predictable changes as the 'urban stream syndrome' (Meyer *et al*., 2005; Walsh *et al*., 2005b), noting that the physical effects on urban streams are often associated with reduced biotic richness (Arnold & Gibbons, 1986; Makepeace, Smith & Stanley, 1995; Paul & Meyer, 2001; Meyer *et al*., 2005; Walsh *et al*., 2005a). Thus one might use the term 'generic' to describe urban streams, making the point that despite important differences in catchment geology, climate and vegetation, the condition of urban streams is overwhelmingly controlled by the altered timing and volume of water, sediment, nutrients and contaminants resulting from the urbanized catchment.

Urbanization and stream hydrology

An altered hydrograph with high peak flows and reduced baseflows is the most obvious and consistent effect of catchment urbanization on stream hydrology. As a result of increasing impervious cover in developing catchments, evapotranspiration and soil infiltration are reduced. The result is higher peak discharges, flashier stream flows, and reduced groundwater–surface water exchange with potentially an overall reduction in groundwater recharge and hyporheic zone size (e.g. Delleur, 2003; Groffman *et al.*, 2003; Groffman & Crawford, 2003). Since groundwater storage is reduced, many urban streams also experience reduced baseflow. In most cities, urban stormwater drainage systems exacerbate the problem of high peak flows, with piped storm drainage networks efficiently routing stormwater directly into stream channels (Booth & Jackson, 1997; Walsh *et al.*, 2005a). These stormwater/sewer networks effectively bypass the river floodplain (and sewage treatment plants), routing contaminants directly from roads and buildings into surface waters (Paul & Meyer, 2001; CWP, 2003). To illustrate this point, consider the typical view of a stream network (Fig. 1) and how this view changes if one takes into account the direct links between that stream and the underground network of sewer and stormwater pipes that continue to increase in number as the area is built up. With proper sewage treatment facilities and ecologically sound stormwater designs, outflows from these pipes need not further degrade streams (Dreher & Price, 1996; Schueler & Holland, 2000). However, in most cities sewer and stormwater pipes are often in disrepair. Thus, in reality, the urban stream 'network' extends beyond the stream channel into a connected series of manmade pipes and gutters.

Urbanization and stream geomorphology

Engineers and public works managers have historically sought to maintain channels 'unchanging in shape, dimensions and pattern' (Schumm, 1977). This desire for physical channel stability has led to highly simplified urban stream channels – in the most extreme cases urban streams are confined in concrete channels or routed through underground pipes. More commonly the banks of urban streams have been 'hardened' using over-sized boulders or rip-rap to prevent lateral channel migration and bank erosion. Often, these hardened streams are far from physically stable in the traditional sense that there is no progressive adjustment in channel form (Schumm, 1977; Henshaw & Booth, 2000), yet urban stream channels often undergo progressive enlargement and erosion (Hammer, 1972; Leopold *et al.*, 2005). A highly impacted urban stream channel often has little variation in depth or the particle sizes of bed material. Downcutting or channel incision is a common feature of urban stream channels as a result of high volume scouring flows and lateral constraints to channel migration (Wolman, 1967; Henshaw & Booth, 2000).

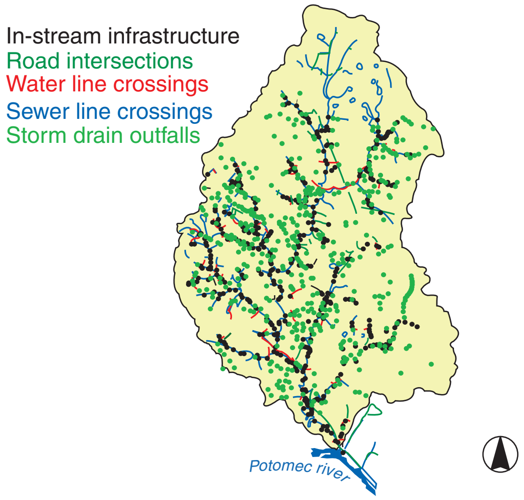

Fig. 1 The stream network overlain with sewer, road and stormwater infrastructure for the Cabin John Creek catchment in suburban Maryland, U.S.A. Shown are 174 road crossings, 415 km of sewer lines, 563 sewer line crossings, 95 water line crossings, 124 km of storm drains, and 549 storm drain outfalls that intersect the 106 km of stream channel in this 66 km^2 watershed. This figure was provided by Cameron Wiegand of the Montgomery Co. Department of Environmental Quality.

Urbanization and stream/riparian ecology

In contrast to the decades of hydrogeomorphic research in urban streams (e.g. Wolman, 1967; Leopold *et al.*, 2005), ecological research has only recently begun to focus on understanding how urbanization affects ecological communities and ecosystem functions. Not surprisingly, given their flashy hydrographs, low habitat heterogeneity and high contaminant loads, this recent research has documented that urban fish and invertebrate assemblages are typically species poor (Wang *et al*., 2000; Freeman & Schorr, 2004; Miltner, White & Yoder, 2004; Walsh, 2004; Moore & Palmer, 2005; Morgan & Cushman, 2005). In Baltimore (MD, U.S.A.) and Washington (DC, U.S.A.) we have found urban streams that are not contaminated with sewage have very low levels of benthic organic matter (E. S. Bernhardt & M. A. Palmer, Fig. 2), a result that corroborates results from Atlanta streams (GA, U.S.A.) by Meyer *et al.* (2005). While this has been suggested as a factor that may limit community metabolism and nutrient retention in urban systems (Grimm *et al*., 2005; Meyer *et al*., 2005; M. A. Palmer, Fig. 3), recent work suggests that urban streams in older cities or near developments with septic systems have high amounts of dissolved organic matter (Kroeger, Cole & Valiela, 2006, S. Kaushal, pers. comm.). Impaired ecosystem functioning can extend out of the channel into the riparian zone, if the water table drops below the rooting zone of riparian plants because of channel incision (Groffman *et al*., 2003). These functionally disconnected riparian zones in urban catchments may have reduced efficiencies of nutrient removal (Groffman *et al*., 2002, 2003). However, uptake rates in urban streams can be quite high and variable (Grimm *et al*., 2005; Meyer *et al*., 2005, Fig. 3). This variability is due in part to large differences among urban sites with respect to geomorphology and water quality, as urban channels vary from concrete beds to earthen channels with some riparian vegetation and water quality varies from slightly to extremely polluted conditions.

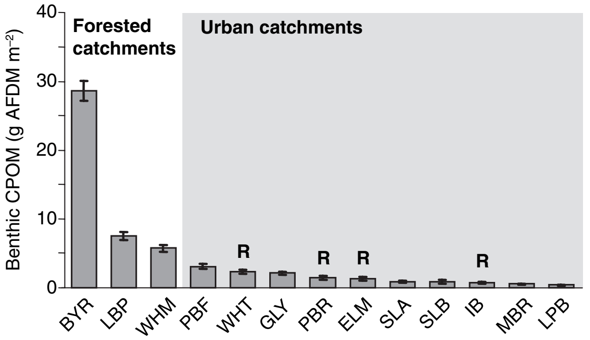

Fig. 2 Benthic coarse-particulate organic matter (CPOM) (mean ± 1 SE) in 13 streams in and around Baltimore, MD and Washington, DC. Ash-free dry mass of CPOM was obtained from 20 stratified random stovepipe core samples collected from each stream study reach. CPOM levels were lower and less variable in all urban streams than in comparable streams draining reference, forested catchments that were minimally impacted, whereas CPOM in restored urban stream reaches (indicated with an R) was not significantly different from amounts in unrestored urban streams.

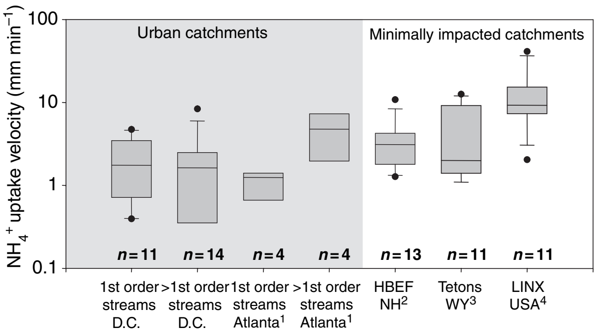

Fig. 3 Uptake velocities for ammonium (NH$_4^+$) compared between urban streams in Washington, DC and Atlanta, GA (U.S.A.) and against a series of widely distributed minimally disturbed streams from throughout the U.S. Except for the data from streams in Washington, DC, uptake velocities were taken from ^{1}Meyer *et al.* (2005), ^{2}Bernhardt, Hall & Likens (2002), ^{3}Hall & Tank (2003) and ^{4}Peterson *et al.* (2001).

What can be done to improve urban stream ecosystems?

While the majority of urban ecological research to date has documented that both biotic communities and biogeochemical function are impaired in urban streams, other recent studies suggest that some simple management strategies can improve these conditions. Moore & Palmer (2005) found that while the invertebrate diversity of headwater streams in suburban Maryland decreased with the proportion of impervious cover in the catchment, there was a positive effect of the extent of intact riparian vegetation on urban stream macroinvertebrate taxa richness (Fig. 4). Sudduth & Meyer (2006) found in both urban and urban restored streams that macroinvertebrate richness and biomass were strongly correlated with the per cent of streambanks covered with roots or wood, indicating that biological structures could improve habitat quality. Yet, localised efforts like riparian conservation or replanting are unlikely to prove effective at improving conditions for mobile taxa such

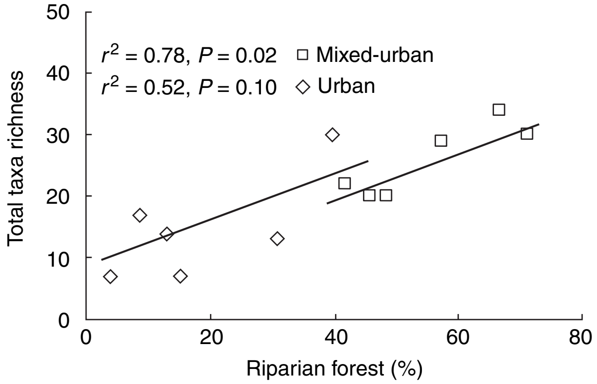

Fig. 4 Relationship between total macroinvertebrate taxa richness and riparian forest cover along Maryland streams surveyed in 2001, demonstrating the relationship within the two land use groups characterised by urban ($n = 6$; imperviousness = 25–58%) and mixed-urban ($n = 6$; imperviousness = 14–27%) sites. Reprinted from Moore & Palmer (2005).

as fish. Several studies have documented lower fish diversity and abundance in catchments with high degrees of imperviousness (Wang *et al.*, 2000; Morgan & Cushman, 2005). Improving conditions for these taxa may require adding new stormwater management structures or retrofitting existing structures to decrease peak flows and prevent contaminants from reaching the receiving streams (Walsh *et al.*, 2005a,b). Improving in-stream habitat conditions may also benefit mobile taxa by providing refugia during high-flow events. There may be other ecological benefits of enhancing in-stream habitat complexity. For example, Groffman *et al.* (2005) found that in some types of habitats within urban streams rates of denitrification were high. They suggested that creating and maintaining debris dams within urban streams would lead to increased denitrification rates and a high capacity for N removal from the water column (Groffman *et al.*, 2005), although they cautioned that maintaining this type of channel form may not be possible in urban streams that experience high peak stormflows. Similarly, restoration efforts for an urban stream in Baltimore (MD, U.S.A.), which involved re-grading the banks (reducing incision) so that more stream water moves through the upper layers of the riparian upper soil, resulted in significant increases in denitrification relative to unrestored reaches (Kaushal, pers. comm.).

Although channel re-configuration, re-grading banks, and manipulation of physical structures within and adjacent to stream channels is an important strategy for improving environmental conditions for stream organisms, many of the structural manipulations that are commonly performed (e.g. creation of debris dams, side pools and diversification of bed materials) can only be maintained successfully in the long run through effective stormwater management (Urbonas, 2001; Walsh, 2004; Walsh *et al.*, 2005a). For this reason, only in catchments where urban stormwater is retained, detained or rerouted to successfully reduce peak flows and improve surface water quality, is it appropriate to consider how to restore structural complexity through active in-channel manipulations. We suggest that the goal of such projects should be to create a variety of habitats within the stream (through alterations of channel form and addition of channel structures), raise the level of the water table in the riparian zone, and achieve inputs of leaf litter and woody debris similar to those from comparable, non-urban streams.

What is being done in the name of restoration in urban streams?

A recent synthesis of river restoration project information for the United States, the National River Restoration Science Synthesis (NRRSS). (Bernhardt *et al.*, 2005), suggests that urban streams receive a disproportionately large share of river restoration monies and effort (Fig. 5). In Maryland, for example, 30% of all river restoration projects over the last decade and about 50% of all reported river restoration funds were spent in the four (of 23) most densely populated counties (Hassett *et al.*, 2005). In part, this concentration of river restoration effort in urban areas may be a response to the more intense degradation in these systems. However, much of the restoration may be motivated by needs to protect streamside infrastructure or by requirements to spend mitigation monies within the same political boundaries as new development. It may also be argued that a large portion of taxpayer money devoted to restoration *should* be spent to improve the immediate environment of cities, where the majority of people live.

From a study of 20 urban stream restorations in Illinois and Washington, DC, U.S.A., Brown (2000) concluded that the most common goals of these projects were to reduce channel erosion and promote channel stability. Our findings from the NRRSS effort

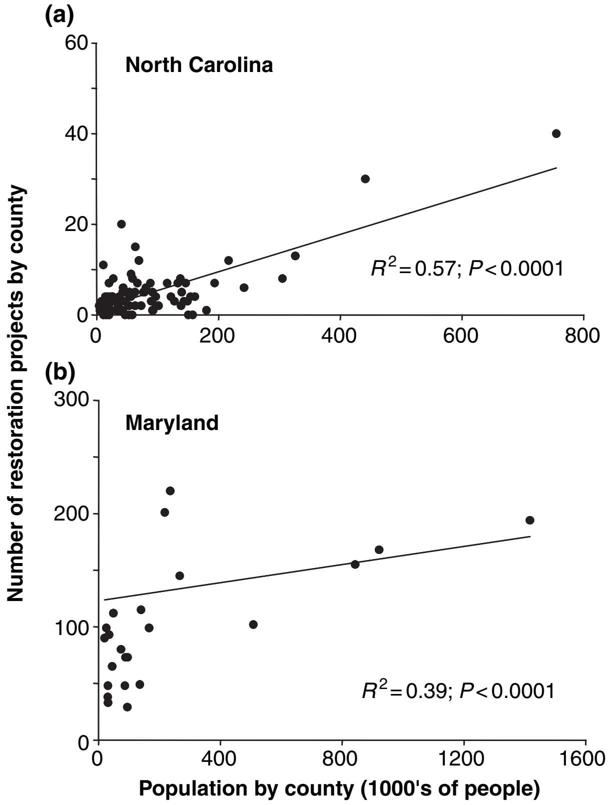

Fig. 5 Relationship between the number of restoration projects per county in the states of NC and MD, U.S.A., expressed as a percentage of all projects in each. The highest numbers are found in the most heavily populated counties. Data are from the National River Restoration Science Synthesis (Bernhardt *et al.*, 2005).

indicate that most urban river restoration projects across seven geographic regions in the United States (http://www.restoringrivers.org) fall into one of four categories. These are not mutually exclusive; often multiple approaches are used within a single restoration project:

Stormwater management

In many urban areas, complex networks of pipes convey run-off from roads, parking lots, and lawns to ponds, wetlands and various flow regulation structures (e.g. Fig. 6c,f). These structures were originally designed to move water rapidly off the landscape and minimise flooding and damage of property. Today the aim is also to reduce peak stream flows and extend flow duration by increasing groundwater recharge. Many site-specific monitoring efforts have been undertaken to examine the effect of stormwater management (SWM) installations on peak flows as well as pollutant loads (e.g. Wanielista & Yousef, 1993; Dreher & Price, 1996; TetraTech, 1997). The general consensus seems to be that SWM structures are effective at moving water rapidly off the landscape and at reducing peak stream flows; however, there is currently little evidence that they actually increase groundwater recharge or significantly improve water quality. New strategies are currently being deployed that involve a mix of low impact development methods, best management practices, and dry stormwater ponds (U.S. EPA, 2005).

The most effective stormwater practices that are currently being tested in various countries involve integrating stormwater systems into the landscape (i.e., minimising alteration of the natural topography) and using local detention devices such as small, vegetated ponds, bio-retention devices, and porous pavement (Lloyd, Wong & Chesterfield, 2002). For areas requiring larger levels of treatment, 'treatment trains' of separate, small ponds and basins have been used within developing catchments rather than a large single stormwater facility. In theory, this approach should mimic a more natural hydrological regime and water quality treatment instead of directing stormwater off-site and downstream into one facility for storage and control. In treatment trains, stormwater passes through a series of structures such as grass swales, sand filters, and constructed wetlands before flowing into a quantity-control structure (usually a dry detention pond to reduce thermal impacts). Treatment in series provides for cumulative improvement in water quality and a dampening of peak flows. Strategies for sediment and erosion control during land development also use a treatment train concept where sediment trap basins are designed as multi-cell basins oversized for the drainage area. All of these designs should minimise impacts to receiving streams and as such enhance the potential for restoration to be successful, yet research is necessary to determine whether these approaches deliver the desired results. Further, comprehensive and controlled scientific studies at the catchment scale that evaluate the broad ecological impacts of stormwater management are needed (Booth & Jackson, 1997). Indeed, an understanding of the influence of stormwater management on the ecological functioning of those ecosystems that are most influenced – namely, urban streams – remains a major research frontier (Urbonas, 2001).

Fig. 6 Examples of common restoration approaches: (a) bank stabilisation of a meander bend with boulders and root wads; (b) bank stabilisation of a meander bend using coir logs; (c) a typical stormwater pond in a new development in a suburban area in MD, U.S.A.; (d) a grade control structure; (e) a channel reconfiguration with reshaped/regraded banks and a meandering channel; (f) a channel reconfiguration and multiple stormwater retention and detention basins along with a large constructed wetland at a severely constrained stream restoration site in Raleigh, NC, U.S.A. (aerial photograph from USGS TerraServer).

Bank stabilisation

Structural materials, bio-engineered products such as coconut fibre rolls, and streambank re-grading are all used to minimise further erosion of urban stream banks (Fig. 6b) (see FISRWG, 1998, for common activities). Rootwads and boulder revetments are also often embedded in the bank in an attempt to minimise channel migration (Fig. 6a). Tightly bound bundles of dormant tree branches – live fascines – are typically anchored to the stream bank by wooden stakes. Mats made of geotextile fabrics may be placed over the repaired stream bank to stabilise banks while vegetation germinates or roots. Prior to planting, re-grading (see below) may be undertaken to alter the angle of the bank and channel geometry. While bank stabilisation projects are fairly successful in rural and agricultural areas, their success rate is often lower in urban areas where they often cannot withstand storm flows, and where high flows and scarcity of transportable sediment create high erosive potential (Wolman, 1967; Ferguson, 1991; Thompson, 2002). Part of this high failure rate may result from the common assumption by restoration practitioners that in order for bank stabilisation methods to be successful, a natural channel design must be restored. Usually the natural channel design approach calls for construction of a single-thread channel with the dimensions, patterns and profiles similar to ones theoretically predicted by various stream classification schemes or similar to unimpacted reference sites. This is typically attempted via channel reconfiguration projects (see below) but in urban settings these are plagued with many constraints due to surrounding infrastructure (Niezgoda & Johnson, 2005) and failures for reasons outlined below.

Channel reconfiguration and grade control

Under this subheading we cluster two somewhat distinct restoration practices because they are often done in tandem and because both involve fairly intrusive manipulation of the landscape. The most cited reasons for use of these practices are to repair heavily incised channels, to improve water conveyance in flood-prone areas, and to improve streambed and bank stability. The channel plan form or longitudinal profile is altered or a covered channel is re-exposed to day-light (e.g. by converting culverts and pipes to open channels) (Pinkham, 2000). Often, in-channel structures are used in an attempt to alter the thalweg of the stream to shunt flow in a desired direction using rock vortex weirs and cross veins (Carpenter *et al*., 2004) (Fig. 6d). Ideally shape of a restored channel should take into account historical and reference conditions as well as empirical data on sediment supply and bedload (Palmer & Bernhardt, 2006). However, in practice the channel shape may be based on what stakeholders consider to be natural or historic conditions or may be based purely on engineering designs to move water with minimal bank erosion and channel meandering (Fig. 6e,f). Use of stream classification schemes, such as those advocated by Rosgen, (1994), to design the channel reconfigurations have become common despite a lack of data on their effectiveness (Kondolf & Micheli, 1995). Re-configuration projects in developed or urbanizing catchments often experience partial or complete structural failures (e.g. the physical structures installed to control stream slope and lateral migration are moved downstream in high flows or stranded as a result of channel migration). In many cases these failures result because reference sites are chosen as a benchmark that are located in catchments with less impervious cover than the restoration target reach (historic or reference reach hydrology has been assumed for the impacted site where flows are highly altered) or because sediment and water flux through the impacted stream were not actually measured but assumed to meet theoretical conditions (Smith & Prestegaard, 2005). Increasingly, restoration practitioners are recognising that selecting a reference condition based purely on geomorphic features (e.g. Rosgen, 1994) must be done with extreme caution and more sophisticated approaches are required that incorporate empirical data on water and sediment flux through the target stream (Kondolf, 1995; Juracek & Fitzpatrick, 2003; Shields *et al*., 2003).

Riparian replanting & management

Through the NRRSS effort we have found replanting of riparian vegetation to be one the most common types of stream restoration throughout the U.S.A., regardless of whether the streams to be restored are urban or rural (Bernhardt *et al*., 2005, 2007). In some areas, exotic species are eradicated prior to the planting; however, ongoing control of exotics is typically required. Most urban riparian restoration efforts involve replanting areas that are damaged by the restoration intervention process or replanting areas immediately adjacent to the channel. More extensive planting is typically limited in urban areas because development or paved sidewalks often extend all the way to the channel edge. However, the presence of riparian vegetation along urban streams is important regardless of the width of the buffer. Not only does it improve bank stability but the generally low aquatic biodiversity in urban streams may be enhanced in reaches where the riparian zone is intact (Moore & Palmer, 2005, but see Walsh, 2004, and Walsh *et al*., 2005a for a discussion of contrasting results).

Challenges to urban stream restoration – constraining restoration options

Because land in urban areas is expensive, urban restoration projects tend to incur greater costs than in rural areas, and it is often difficult to purchase or protect the desired extent of river floodplain habitat. Detailed interviews with project managers of restoration projects throughout the U.S. showed that urban and suburban river restoration projects averaged only 0.6 km in stream length when compared with an average length of 1 km for all stream restoration projects (Bernhardt *et al.*, 2007). Thus, managers must make compromises between the ideal restoration design for achieving management goals and the restoration design that will fit within the available space. The restoration options for urban streams are highly constrained by available land, urban infrastructure, political pressures, and a lack of technical knowledge about how to apply standard restoration techniques in urban settings (Nilsson *et al.*, 2003; Niezgoda & Johnson, 2005).

Site selection

Not only is property more expensive in urban catchments, property ownership is more finely subdivided, thus acquiring the necessary land for large-scale stream restoration requires complex negotiations with multiple landowners. By default, many restoration projects are implemented in lands already owned by the municipal, local or regional government. Interview surveys with practitioners from throughout the United States showed that restoration site selection was much more likely to be driven by available land opportunities in urban catchments than in catchments with other types of land use (Bernhardt *et al.*, 2007). Prioritisation of sites for restoration thus appears to be often driven more by feasibility, than by critical assessment of where restoration efforts are most needed or will be most effective.

Infrastructure

Roads, stormwater drains and sewer pipes run alongside and across urban streams at multiple locations (Fig. 1) setting physical limits on any restoration design. Allowing an urban stream to reestablish natural patterns of channel migration is rarely an option given these boundary conditions. In areas where streams are piped beneath parking lots and buildings, or routed through concrete-lined channels amidst high density business and residential development, restoration to some historic or other reference condition is not a realistic option. This sets limits not only on what can be done locally, but also on the effectiveness of any upstream restoration efforts. Spending large amounts of money on a restoration project along one kilometre of stream while the downstream kilometre remains under pavement, will not restore the ecological conditions of the stream network (Palmer *et al.*, 2005). Infrastructure thus limits site-specific options, but it also reduces connectivity between segments of river networks, with important implications for populations of stream biota dependent on upstream–downstream dispersal.

Chemical pollutants

While urban streamwater throughout the developed world has become progressively cleaner with effective wastewater treatment technologies, there are still significant contaminant problems in urban catchments. Sewer and stormwater pipes often run alongside streams, and many pipes leak directly into streams and riparian zones. During stormwater pulses, many cities have combined sewer stormwater overflows, such that when stormwater inputs are too high, raw sewage combined with surface runoff is allowed to overflow directly into urban streams (Chen *et al.*, 2004). The uncontrolled connection between sewage and surface water leads to high fecal coliform concentrations and nutrient loads in many urban streams (Makepeace *et al.*, 1995; Miltner *et al.*, 2004). Surface runoff brings heavy metals from parking lots and roofs and carries fertilizer nutrients, herbicides and pet wastes from lawns, golf courses and parks (Makepeace *et al.*, 1995; Yuan, Hall & Oldham, 2001; Beasley & Kneale, 2002). In addition, many pharmaceutical compounds persist in urban surface waters despite standard water treatment procedures (e.g. Stackelberg *et al.*, 2004).

Deciding when to restore – triage in urban catchments

Given that urban river restoration projects are expensive and often cannot effectively accomplish ecological success criteria given pre-existing conditions, a critical research and management challenge is to provide guidelines for when restoration is a viable and intelligent management option. In some severely degraded catchments, restoration efforts may be doomed to failure and wise catchment management should first invest in improved water retention, detention and conveyance systems water treatment. In less impacted, or better preserved urbanizing catchments the critical challenge is to decide where restoration projects should be implemented, and what restoration strategies will be effective given existing catchment and riparian constraints. Because monitoring data to understand and evaluate the success of urban stream restoration projects is minimal to non-existent, it is currently impossible to determine whether certain types of restoration are more successful than others at achieving ecological goals (Bernhardt *et al*., 2005; Palmer *et al*., 2005). Results from NRRSS suggest that while river restoration efforts are implemented for ecological reasons, they are often evaluated based on geomorphic or aesthetic attributes (Bernhardt *et al*., 2007).

Restoration and effective catchment management

In many cases, restoration of stream reaches may not be the most effective way to meet management goals. If the primary goal of catchment management is to provide clean drinking water and prevent eutrophication of surface waters, the most successful strategy may be to invest in preserving undisturbed upstream catchments. This has proven to be both an effective and economical approach for New York City, which preserves large areas of the Catskill Mountains as a catchment to supply clean drinking water to city residents (Daily & Ellison, 2002). In the Paint Branch catchment of heavily suburban Montgomery County in Maryland, progressive urban planning has led to purchase and preservation of large areas of riparian forest and used aggressive zoning laws to limit new development in the catchment. This approach has been successful at maintaining high water quality and supporting reproducing populations of trout despite very high impervious cover within the catchment (Montgomery County DEP, 2003). This situation is likely to improve further as a series of strategic stormwater management and stream habitat restoration projects are implemented, as is now sought by Montgomery County. These two examples suggest, thus, that stream channel restoration projects should be most effective when they are integrated in a suite of urban catchment management efforts that may include acquiring or protecting streamside land, preventing or reducing peak stormwater flows, improving and maintaining sewer and stormwater infrastructure, and upgrading sewage treatment facilities.

Conclusions

Urbanization of catchments leads to changes of streams along three axes: (i) geomorphic simplification in that habitat heterogeneity and floodplain connectivity are reduced; (ii) diminished societal value in that stream channels become increasingly unattractive and are avoided for recreational purposes; and (iii) ecological simplification in that stream biodiversity declines and stream ecosystem functioning is impaired, resulting, for example, in a reduced capacity of streams to reduce downstream nutrient losses. Restoration of urban stream channels is highly constrained, thus it is unlikely that an urban stream will ever be restored to its pre-urbanization state. Instead the goal of effective restoration should be to move the stream as far back along the three axes as is possible given existing constraints. Currently, restoration efforts focus on restoring channel form and maintaining channel stability (often artificially), making progress along axes 1 and 2, but not necessarily along the third axis of improving biological communities or ecosystem functioning. A key question for managers, scientists and practitioners to ask is ‘when are the constraints too severe to warrant restoration of urban streams?’ When they are, investment of money and effort towards improving catchment conditions or less impacted streams will be more effective. Site selection and project design in urban settings should be guided by a fundamental understanding of the operating constraints that may preclude success. A great deal more ecological, geomorphic and hydrologic research and evaluation of unrestored and restored urban streams is necessary for guiding the critical decisions about when restoration can have a positive impact on urban stream ecosystems, and when it is merely gardening around urban infrastructure.

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