Principles for urban stormwater management to protect stream ecosystems

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Abstract: Urban stormwater runoff is a critical source of degradation to stream ecosystems globally. Despite broad appreciation by stream ecologists of negative effects of stormwater runoff, stormwater management objectives still typically center on flood and pollution mitigation without an explicit focus on altered hydrology. Resulting management approaches are unlikely to protect the ecological structure and function of streams adequately. We present critical elements of stormwater management necessary for protecting stream ecosystems through 5 principles intended to be broadly applicable to all urban landscapes that drain to a receiving stream: 1) the ecosystems to be protected and a target ecological state should be explicitly identified; 2) the postdevelopment balance of evapotranspiration, stream flow, and infiltration should mimic the predevelopment balance, which typically requires keeping significant runoff volume from reaching the stream; 3) stormwater control measures (SCMs) should deliver flow regimes that mimic the predevelopment regime in quality and quantity; 4) SCMs should have capacity to store rain events for all storms that would not have produced widespread surface runoff in a predevelopment state, thereby avoiding increased frequency of disturbance to biota; and 5) SCMs should be applied to all impervious surfaces in the catchment of the target stream. These principles present a range of technical and social challenges. Existing infrastructural, institutional, or governance contexts often prevent application of the principles to the degree necessary to achieve effective protection or restoration, but significant potential exists for multiple co-benefits from SCM technologies (e.g., water supply and climate-change adaptation) that may remove barriers to implementation. Our set of ideal principles for stream protection is intended as a guide for innovators who seek to develop new approaches to stormwater management rather than accept seemingly insurmountable historical constraints, which guarantee future, ongoing degradation.
Key words: urban hydrology, management, stream protection, stream restoration

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DOI: 10.1086/685284. Received 3 March 2015; Accepted 28 August 2015; Published online 5 January 2016.
Freshwater Science. 2016. 35(1):398–411.

Urban water management in many cities is evolving from a sole focus on primary services that ensure public health (through provision of water, disposal of wastewater, and flood mitigation) toward a more integrated use of urban water flows. Integrated water management (of water supply, wastewater, and stormwater) serves to meet multiple objectives, such as social amenity, protection of receiving waters, reduced consumption of external water and other resources, and improved urban microclimate (Brown et al. 2009b). The management of urban drainage is central to achieving this broader range of sustainability objectives, and the evolution of urban drainage management in cities around the world has resulted in a divergence of terminology and management approaches for reducing the negative environmental effects of urban drainage (Fletcher et al. 2015).

The earliest attempts to recast urban drainage management for environmental protection included a focus on the protection of the ecological and physical integrity of streams, either explicitly (Schueler 1987, King County 1990, Whelans et al. 1994, Prince George's County Maryland Department of Environmental Resources 1999) or implicitly, through pollution abatement objectives (Martin et al. 2000). In the 1990s and 2000s, however, stormwater management for environmental protection tacitly became less explicit in describing the ecosystems to be protected or restored. (We primarily refer to protection in this paper, but our arguments also apply to requirements for restoration.) The lack of focus on streams as receiving waters to be protected has resulted in many instances of replacement of stream ecosystems by constructed stormwater wetlands (e.g., Taylor et al. 2005) or re-engineering of streams as stormwater treatment measures themselves to meet narrow management objectives, such as the reduction of N export to coastal waters. Following such modification these streams have little functional resemblance to their former state (Palmer et al. 2014).

Typically, minor or no improvement in ecological indicators has been observed downstream following implementation of such stormwater control measures (SCMs). In some instances, insufficient implementation across catchments or variability in design and effectiveness of SCMs may be to blame (Horner et al. 2001, May and Horner 2002). Elsewhere, limited and sometimes contradictory effects of SCMs have been reported. Greenway (2010) found an increase in macroinvertebrate species richness downstream of 2 stormwater treatment wetlands constructed on the stream channel. In contrast, Walsh (2004) noted shifts in macroinvertebrate assemblage composition downstream of on-line stormwater treatment wetlands, which suggested that stormwater wetlands were nutrient sources rather than sinks during dry weather. The scant evidence for the efficacy of SCMs in protecting stream ecosystems suggests a need to re-evaluate SCM design objectives for stream protection.

More recently, authors of low-impact design manuals and stormwater regulations (e.g., Perrin et al. 2009, Toronto and Region Conservation Authority and Credit Valley Conservation Authority 2010, California Central Coast Regional Water Quality Control Board 2013) have re-established the original intent of low-impact design to protect stream ecosystems through replication of pre-urban hydrologic processes, with an emphasis on replicating the volume balance of runoff, infiltration, and evapotranspiration in urban catchments. The primary focus of such objectives is hydrologic, but control of water quality is implicit because of the dominant contribution of subsurface flows in most nonurban catchments (e.g., Tanaka et al. 1988). Such subsurface flows tend to be of high quality because of filtration and assimilation by soils, subsoils, and aquifers (Jarvis 2007).

In proposing design objectives for stream protection, Perrin et al. (2009; p. 2-1) posited that "if the predevelopment volumes of runoff are mimicked, then other water quantity goals such as stream stability outflows and 1-year, 24-hour storm peak mitigation are assumed to be met". By this reasoning, reducing flow volumes (i.e., preventing water from reaching streams) to approach those of the predevelopment state is likely to be a prerequisite to achieving the flow and water-quality regimes required for stream protection and restoration.

However, current design standards for SCMs generally fail to protect streams (Burns et al. 2012), in part, because stormwater management approaches traditionally have not been focused on restoring or maintaining the hydrologic balance. In fact, strategies for mitigating urban runoff vary across countries, regions, cities, and municipalities as a result of differences in political context, physiography, and existing infrastructure (Booth et al. 2016, Hale et al. 2016, Parr et al. 2016). For instance, in regions and cities situated on coastal embayments with potential for eutrophication, reducing pollution loads to bays is a primary management objective (Victoria Stormwater Committee 1999, National Research Council 2009). In older cities with combined sewerage systems the focus is on flood and pollution mitigation to limit the environmental and human health problems associated with combined sewer overflows (Woods-Ballard et al. 2007). Despite this diversity of objectives, the increasing recognition that protection of stream ecosystems requires different stormwater management approaches (Burns et al. 2012, Walsh et al. 2012) suggests a clear need for stream ecologists, working with hydrologists, geomorphologists, and engineers, to better inform the design of SCMs. Such an interdisciplinary approach is necessary to identify the critical stressors to stream ecosystems delivered by urban stormwater runoff that need to be redressed.

The goal of our paper is to articulate 5 critical principles of stormwater control that are necessary for protection of stream ecosystems in urban landscapes. We identified the

5 principles collectively during the 2014 Symposium on Urbanization and Stream Ecology and in subsequent discussions, and they are based on the literature and our collective experiences from around the globe. Our primary focus is on the principles underpinning the management of stormwater runoff, but we acknowledge the importance of limiting the generation of stormwater runoff by minimizing the creation of impervious areas wherever possible.

The principles outlined are intentionally idealistic—our hope is that by articulating the hydrologic goals necessary to protect and restore streams fully, we also offer insights into situations where ecosystems cannot be fully restored. After describing the principles we explore their application in contrasting contexts around the globe. These examples highlight technical and sociopolitical challenges given physiographic and institutional differences among cities. Thus, these principles may be difficult to accomplish fully in many existing urban settings without institutional change. In the final section, we describe co-benefits that could be provided by adopting the technologies. These co-benefits may provide the critical motivation for changes in institutions and governance structures that are needed to protect streams effectively.

THE PRINCIPLES

The overarching hypothesis guiding the principles is that ecologically successful protection of stream ecosystems in urbanizing catchments, or restoration of stream ecosystems that are already degraded by urban stormwater runoff, requires catchment-scale management of stormwater drainage to replicate predevelopment hydrologic processes (Table 1). Such an outcome might seem difficult to achieve and examples of ecologically successful restoration of urban streams do not yet exist, but prevention of degradation by negative effects of stormwater has been demonstrated (Walsh et al. 2012). We draw from such examples to propose principles that require testing in restoration contexts.

Two of the principles (3 and 4) directly address the manifold stressors to stream ecosystems resulting from urban stormwater runoff. The other 3 principles set out practical steps that are required to apply the core principles adequately to achieve stream protection.

In many urban areas, the immediate receiving water is a large river, or a lentic or marine environment, typically with a large buffering capacity that makes longer-term loads of pollutants more important than alterations to flow regime. In contrast, small- to medium-sized stream ecosystems are strongly influenced by the flow regime as a primary driver of the ecological structure and function (Poff et al. 1997): shorter-term changes in water and pollutant delivery from the catchment are likely to have a greater effect on such ecosystems. Therefore, protecting stream ecosystems requires objectives for stormwater control different from those that might be suitable for large rivers and lentic and marine environments. We restrict our principles to consideration of objectives for protection or restoration of stream ecosystems but note that the following objectives for volume reduction and replication of predevelopment flow and water-quality regimes also are likely to protect larger downstream waters adequately.

Principle 1. The stream ecosystems to be protected or restored should be identified, and a target for their ecological state should be set

Our definition of urban stormwater management for stream protection assumes that stormwater is managed with the aim of maintaining the ecological structure and function of receiving streams in a functioning, dynamic state similar to a defined reference condition or 'guiding image'. This definition follows the guidance of Palmer et al. (2005; p. 210) that restoration projects should move river ecosystems "to the least degraded and most ecologically dynamic state possible, given the regional context". In protecting stream ecosystems from the effects of urban stormwater runoff, an appropriate target could be the condition of the stream before the urban development of its catchment or of analogous rural streams in the same region. We are not suggesting that all streams must be restored to such a level (that is a decision left for managers; Smith et al. 2016), but if attempting to restore streams, the stream scale and ecological target should be identified first.

The point at which a stream begins is a vexed question (Doyle and Bernhardt 2011) that potentially makes identification of the smallest streams requiring protection a challenge. By virtue of the increased interaction between water and sediments in small streams and their abundance in nonurban landscapes, they are recognized as hotspots for retention and transformation of contaminants (McClain et al. 2003) and, therefore, should be protected. However, many small streams in cities are commonly buried and converted to stormwater drains (Graf 1977, Meyer and Wallace 2001, Elmore and Kaushal 2008). These hydraulically efficient, modified drainage courses are a primary driver of stream degradation (Walsh et al. 2005). Smaller flow paths with accumulation areas often too small to initiate channel formation are even more common in the landscape than are small streams and, thus, are more frequently converted into stormwater pipes.

In existing urban areas, where such a transformation has already occurred, SCMs should be designed to prevent stormwater from flowing into these pipes except in rare large storm events that present a risk of urban flooding. However, even small streams and unchannelled flow

Table 1. Summary of principles for urban stormwater management to protect stream ecosystems. The primary considerations and challenges for each principle are presented; benefits associated with the principles are also listed, but many do not map simply to a single principle. WQ = water quality, ET = evapotranspiration, SCMs = stormwater control measures.

Principles	Considerations	Challenges	Benefits
1. Identify ecosystems to be protected and set targets	If system is a stream or river, the principles apply; set target for stream condition, water balance, and flow and WQ regimes	Finding appropriate reference condition can be difficult (Smith et al. 2016)	Healthy streams and associated ecosystem services
	If deep seepage flows to a river, marine/lentic system, confined aquifer, set target for acceptable loss to deep seepage	Identifying quantity and destination of deep seepage; without information, assume it is small	
2. Mimic predevelopment water balance	Volume prevented from reaching the stream (through harvesting for irrigation [ET loss] or loss to sewer/another catchment) should ideally equal predevelopment ET loss	Finding sufficient demand	Water supply, flood mitigation
	Streamflow volume should be delivered through infiltration systems		
	Deep infiltration delivered through infiltration systems, determined by probable receiving ecosystem		
3. Implement SCMs that deliver filtered flows	Filtration and infiltration systems to meet flow and WQ targets	Designing systems to deliver quick flow; management of mobile contaminants; maintenance	Urban agriculture, urban cooling through ET, shading, climate change resilience, human well-being
4. Implement SCMs with capacity to store rain events that would produce disturbance to stream biota	Appropriate balance of storage volume/demand/loss through ET or infiltration	Space, cost, demand	Increased demand reduces space requirements, reduces costs by reducing potable demand
5. Apply SCMs to all impervious surface in the catchment	Catchment-scale planning required	Space, social acceptance	A greener, cooler landscape

paths should be recognized as ecosystems worth protecting in and of themselves at the first stages of planning new urban areas. Ideally, they should be reserved as linear green spaces that could retain their retentive function while providing valuable open space. Such ideas are consistent with early conceptions of low-impact design that have been expressed in a few small-scale developments (Karvonen 2011).

An important corollary of this principle is that stream protection requires SCMs to intercept runoff *before* it enters the stream rather than allowing water to flow into the stream and then further altering the stream ecosystem by constructing an in-stream treatment system. Such interception necessitates the location of SCMs near sources (e.g., intercepting road or roof runoff) or on flow paths upstream of where they first discharge to defined channels.

The importance of sediment–water interactions in the ecological function and structure of streams also points to the need to consider the riparian zone and floodplain of streams as an integral part of the stream ecosystem to be protected (Vietz et al. 2012). These areas are part of the dynamic flow regime of streams and are critical for ecological functions, such as organic matter inputs and retention, nutrient cycling, and temperature modification (e.g., Pusey and Arthington 2003, Jackson et al. 2014). The hydrologic isolation of riparian ecosystems that commonly results from incision of urbanized streams (Groffman et al. 2003) is likely to constrain ecological restoration even if the catchment-scale hydrologic effects of stormwater runoff can be mitigated adequately because the interaction between channel and floodplain will be reduced.

Principle 2. The postdevelopment water balance should mimic the predevelopment water balance. Specifically, the volumes of runoff and infiltrated water from an impervious area with SCMs should be similar to those of the predevelopment state. This requires that the volume of water lost (such as via sanitary sewers or evapotranspiration) approximate the volume of water that would have been lost through evapotranspiration in the predevelopment state

A primary determinant of successful protection is the receiving stream's flow regime and most fundamentally its streamflow coefficient: the proportion of catchment rainfall that, on average, becomes stream flow. The proportion of rainfall that is lost to the air through evapotranspiration or to deep seepage is the complement of the streamflow coefficient. In their global analysis, Zhang et al. (2001) assumed that net long-term losses to deep seepage are typically small, and they estimated evapotranspiration to be the functional complement of stream flow. (In referring to lost water in this paper, we mean water that does not become stream flow.) They found that mean annual evapotranspiration loss from undeveloped catchments of the world typically ranged from 40 to 60% of rainfall in wet regions (depending on the extent of catchment forest cover) to almost 100% in arid regions.

In contrast, the evaporation losses from impervious surfaces are much smaller and less variable, ranging from <10% in wet regions to ~25% in warm arid areas (Walsh et al. 2012). Where loss of forest accompanies urbanization, reductions in evapotranspiration from remaining pervious areas may explain an increase in perennial flow (Roy et al. 2009). Thus, in urban areas, a primary challenge in achieving a predevelopment flow regime is losing the additional runoff from impervious surfaces (and possibly increased subsurface flows from pervious areas) that would not have reached the stream in its predevelopment state.

North American stormwater managers commonly estimate that a large proportion of rainfall is 'lost' to deep seepage (e.g., Perrin et al. 2009), with the effect that infiltrated water also is assumed to be lost from the study catchment's overall water balance. However, the hydrology and ecological function of the receiving aquifer should be considered before infiltrating or injecting urban stormwater runoff into it. The increased runoff volume from impervious surfaces means that stormwater infiltration systems may increase flows into unconfined aquifers, with potential negative effects on downstream waters (Roy and Bickerton 2012). If the receiving aquifer is depleted (e.g., by abstractions), then addition of urban stormwater could aid its recharge. However, if abstractions and replenishment are from the same urban area, aquifer demand could instead be reduced directly by harvesting urban stormwater at the rainfall source rather than continuing to extract at the same rate from the aquifer and attempting to compensate by infiltrating stormwater.

Therefore, maintaining near-natural flow volumes in streams and aquifers requires careful consideration of the water balance and of the state of the groundwater table and baseflow regime (Bhaskar and Welty 2012), reinforcing the importance of minimizing the creation of directly connected impervious areas as a 'first-resort' strategy wherever possible. Infiltration to provide an appropriate baseflow regime is important, but given the excess volume from impervious areas, SCMs also will need to promote losses of water, either through evapotranspiration (e.g., rain gardens, stormwater harvesting for irrigation or cooling processes) or through harvesting for other uses where it is exported to sanitary sewers (e.g., use for toilet flushing and hot water).

The long-term increase in runoff volume addressed by this principle is not a direct stressor driving ecological degradation in streams. However, we posit that removing the excess runoff volume and preventing it from reaching the stream is necessary to mitigate the critical stressors that do result and that are addressed in the following 2 principles.

Principle 3. SCMs should be designed to deliver flows in a quality and flow regime that mimic, as much as possible, the dominant predevelopment hydrologic processes

Consistent with the natural flow regime concept proposed by Poff et al. (1997), we posit that the best chance of protecting or restoring stream ecosystem health (sensu Karr 1999) is through flow and water-quality regimes that are as similar as possible to the natural or predevelopment regime.

Delivery of near-natural low-flow regimes may be complicated by the number and complexity (and thus, relative uncertainty) of factors influencing baseflow pathways (Price 2011, Hamel et al. 2013, Bhaskar et al. 2016). (We follow the distinction made by Hamel et al. 2013, whereby the term 'low flow' refers to flow magnitude, whereas 'base flow' refers to the [subsurface] pathways by which flows make it to the stream.) Factors other than urban stormwater runoff, such as changes to catchment vegetation and leaking water-supply and wastewater infrastructure, may increase base flows in many urban catchments (Smakhtin 2001, Price 2011, Bhaskar et al. 2016), but the contribution of rainfall that falls on conventionally drained impervious surfaces to base flow is certainly reduced or eliminated altogether by prevention of infiltration by impervious surfaces and drainage (Walsh et al. 2012). These interacting factors can produce variable outcomes in different urban areas (Konrad and Booth 2005, Brown et al. 2009a).

Once the frequency of untreated runoff has been limited to near predevelopment levels (see principle 4), SCMs should be designed to deliver the volume and temporal pattern of flows that mimic what would formerly have been delivered as base flow from the land now covered by impervious surfaces. The most obvious approach to achieve this goal is to promote infiltration of a similar amount of water as would have been infiltrated in the predeveloped state (principle 2), acknowledging the uncertainty over the pathways and losses of infiltrated flows as they move into groundwater and to the receiving stream (Hamel et al. 2013). An alternative approach is to use carefully engineered systems that aim to mimic natural baseflow regimes by means of controlled discharge (Hatt et al. 2009). For example, DeBusk et al. (2011) suggest that lined bioretention systems have the potential to achieve near-natural baseflow regimes.

Water quality must be considered in parallel with the delivery of suitable flow regimes. Doing so requires consideration of the nature of the receiving waters. For instance, do they have a large buffering capacity (and, thus, are primarily affected by long-term loads) or are they sensitive to short-term variations in concentration? Of the range of SCMs available, bioretention systems perhaps show the greatest promise for delivering water quality that meets the needs of sensitive receiving waters (Hatt et al. 2009, Hunt et al. 2011). Other infiltration-based techniques also can deliver very high levels of treatment because of the long filtration pathways. Optimal management of water quality probably will involve a combination of source controls and appropriate treatment by well-designed SCMs.

Principle 4. SCMs should be designed to prevent untreated flows to streams in all but rare, large storms. They should have capacity to store rain from events up to the size of a storm that probably would have produced widespread surface runoff and disturbed stream biota in the predevelopment state

In natural catchments, rainfall up to the size necessary to generate measurable runoff (typically, a substantial majority of rainfall events) is unlikely to cause any significant disturbance through increased stream discharges. Only large or intense storms will be sufficient to exceed the 'initial loss' (the amount of rainfall necessary to generate surface runoff) from large portions of catchments, and even then, overland flow from uplands is likely to be reabsorbed into patches of greater soil porosity downslope before reaching the stream (Tanaka et al. 1988). Such infrequent storms are likely to represent an important natural disturbance to stream and riparian ecosystems.

In contrast, connected impervious surfaces typically deliver high flows carrying a range of pollutants under almost any amount of measurable precipitation (with initial loss typically <1 mm) and at least an order of magnitude more frequently than in the natural state (Booth 1991). This increased disturbance frequency is the cause of many of the stressors driving urban stream degradation.

Thus, retaining runoff from impervious surfaces for rainfalls smaller than those that would have generated widespread overland flow in the predeveloped catchment is key to maintaining near-natural frequency and intensity of disturbance (both hydraulic and water quality) in streams. The rainfall necessary to produce runoff varies across a natural catchment and with season and antecedent soil moisture, but analysis of stream hydrographs in natural catchments can identify typical rainfall depths required to generate widespread runoff. For example, in forested catchments in southeastern Australia, Hill et al. (1996) frequently observed initial loss of ~25 mm. Similar hillslope initial losses were reported from a forest in New Zealand (Graham et al. 2010). Regional estimates could be derived from analysis of streamflow records in natural catchments, as proposed by Burns et al. (2013).

Principle 5. SCMs should be applied to all impervious surfaces in the catchment of the target stream

The negative effects of urban stormwater runoff on streams are discernible even at very low levels of connected imperviousness (Walsh and Kunapo 2009, King and Baker 2011, Walsh and Webb 2016). Many governmental agencies have sought to distribute SCMs opportunistically (driven, e.g., by urban renewal or maintenance activities) throughout their jurisdiction, with the aims of minimizing costs and ensuring geographic equity among landowners and communities (e.g., Prosser et al. 2015). However, an inevitable result of such strategies is the continuing dominance of conventional stormwater drainage in most catchments, with SCMs treating runoff from only a portion of impervious surfaces. The incomplete treatment may, in part, explain the lack of ecological response observed in studies designed to test the ecological efficacy of SCMs (Horner et al. 2001, May and Horner 2002, Roy et al. 2014).

SCMs should be designed and placed such that runoff from all impervious areas of the catchment is managed in a manner consistent with the above principles. Principle 5 highlights the importance of scale in protecting streams from urban stormwater effects. From one perspective, this principle might appear implicit in the preceding principles, which are designed to achieve a flow and water-quality regime in the receiving stream similar to that of the predevelopment stream. However, principles 2 to 4 provide guidance on design objectives for SCMs that could be constructed at a range of scales. We argue here that effective implementation of these principles requires catchment-wide application upslope of the receiving stream. Thus in almost all catchments, multiple SCMs will be required to retain and treat runoff from all impervious surfaces adequately.

CHALLENGES FOR APPLYING THE PRINCIPLES

We propose these principles as necessary to maximize the chance of protecting or restoring the ecological structure and function of streams in urbanizing catchments (Paul and Meyer 2001, Walsh et al. 2005). Our principles are intended to articulate ideal management of urban stormwater for full protection of stream ecosystems, recognizing that challenges to implementation must be overcome (Roy et al. 2008). Such a statement of ideal principles is aimed at encouraging innovation rather than accepting existing impediments and proposing suboptimal objectives that increase the risk of ecological degradation.

In this section, we identify a number of technical, social, institutional, and governance challenges to the implementation of our principles (Table 1). We discuss probable stream ecosystem responses if certain elements of the principles are not achievable and address how these responses are likely to differ with physiographic context.

Insufficient opportunities for volume reduction

Arguably the greatest challenge to applying our principles for stream protection is finding ways to lose (i.e., prevent from becoming stream flow) the excess volume of water generated by reduced evapotranspiration. For instance, in Melbourne, Australia, the excess volume of urban stormwater runoff equates to between 57% of the total demand per person in the driest part of the city (400 mm/y rainfall) to 147% in the wettest part (1200 mm/y) (Walsh et al. 2012). Thus, finding sufficient demand for the excess urban stormwater in the context of existing water supplies is challenging from the outset. Other cities of the world with rainfall in a similar range are likely to produce similar volumes of excess runoff. However, perhaps counterintuitively, finding demand may prove easier in more densely populated cities, where the impervious area to person ratio is smaller.

Some stormwater runoff can be lost to evapotranspiration by irrigating vegetation with stormwater or through vegetated infiltration systems. However, the area required to lose the entire excess volume through evapotranspiration is likely to be prohibitive in most urban settings (Hamel et al. 2011, 2012). Water loss solutions require storage of the water, whether it be in the soil, in infiltration systems, or in tanks. However, if sufficient demand (that does not vary seasonally) can be found, then these storage volumes, and the required land-take for them, can be small (Mitchell et al. 2008, Walsh et al. 2014).

Technologies for harvesting stormwater are well-developed and applied in many parts of the world (Fletcher et al. 2008). However, the problem of finding sufficient demand remains and is amplified by the widespread disinterest or resistance of water authorities to using urban stormwater as a water source. Such barriers to finding demand make principle 2 difficult to achieve under current institutional and governance frameworks because of insufficient opportunities to reduce volumes of runoff reaching the stream.

Challenges to using infiltration and filtration technologies to address water quality and quantity

Infiltration and filtration tools (e.g., biofiltration swales, infiltration trenches, rain gardens) are commonly used to address stormwater quantity and quality issues simultaneously (e.g., Perrin et al. 2009, California Central Coast Regional Water Quality Control Board 2013). Even if inflow volumes into such systems can be adequately reduced, design challenges remain for delivery of appropriate flow regimes. Bioretention systems with controlled discharge show potential (DeBusk et al. 2011), but practical difficulties exist in providing enough storage to mimic the long detention times of natural baseflow processes while also mimicking the quicker throughflow that occurs in the upper soil horizon (Hamel et al. 2013). One possible strategy to help overcome these challenges is to preserve upland flow paths, which could, in the urban context, act to receive, convey, and buffer contributions from upstream SCMs.

Infiltration and filtration systems are effective at removing many pollutants, but current infiltration technologies do not adequately treat several mobile contaminants, such as Cl^- and certain classes of pesticides, which are not removed by settling or soil attenuation. Inadequate pollutant removal can result in contamination of surface waters and even shallow groundwater (Weiss et al. 2008, Foulquier et al. 2009). Road salt, a commonly used de-icing agent in cold climates, can increase the mobility of metals (Environment Canada and Health Canada 2001) in SCMs. Moreover, road salt can impair pollutant removal in SCMs by decreasing the functioning of vegetation and soil microbes (Environment Canada and Health Canada 2001).

Simple design solutions, such as using salt-tolerant plant species, situating SCMs to avoid hotspots (Toronto and Region Conservation Authority and Credit Valley Conservation Authority 2010), and sizing SCMs to meet performance objectives that take account of seasonal variations in climate and performance (Roseen et al. 2009), can be implemented to maintain much of the functionality of SCMs. However, these strategies do not address mobile urban contaminants, for which source control (i.e., restricted availability and use) or, less desirably, specialized filtration is necessary.

Extreme variations in water quality and quantity also can pose difficulties when designing SCMs. Extreme flow events are critical for certain channel-forming processes, but contaminants associated with high flows in urban areas are an important source of stream impairment. The treatment of snowmelt is particularly difficult, given that the amount of snow and timing of spring melt is temporally and spatially unpredictable. Spring melt is associated with elevated levels of contaminants, such as metals and road salt, that have been stored in snow packs. Rapid release of accumulated contaminants in the snow pack during melting creates stresses to streams that may not otherwise be present in nonurban environments.

In cases where stormwater volume cannot be adequately reduced, infiltration-based SCMs may result in elevated water tables (Hamel et al. 2013, Liu et al. 2013), which may, in some cases, mobilize legacy pollutants already in the ground water, transporting them toward receiving surface waters (Roy and Bickerton 2012). Increased infiltration flows, particularly when compounded with other water sources (such as water imports and leaky infrastructure) or forest loss and associated reduced evapotranspiration, may result in increased base flows (Price 2011, Hamel et al. 2013, Bhaskar et al. 2016). This increase in base flows can result in naturally intermittent and ephemeral streams becoming perennial (Roy et al. 2009), which, in turn, can increase species richness (Chadwick et al. 2012). However, any such alteration of biotic communities in previously intermittent streams is likely to have deleterious effects on regional native biodiversity, particularly in arid regions with intermittent rivers harboring assemblages specifically adapted to frequent drying (Cooper et al. 2012, Steward et al. 2012).

Thus, infiltration SCMs have the potential to reduce effects of urbanization on receiving waters, but their design must consider the local physiographic context and climate, and they must be used in conjunction with other SCMs and pollution-mitigating tools to provide the water quality and flow regimes necessary for protection of streams and their native biota.

Social, economic, institutional, and governance constraints

Some technical challenges to the achievement of our principles remain, but the dominant impediments to adoption of the principles are social and institutional (Brown and Farrelly 2009). Urban stormwater governance can be difficult for a variety of reasons, including resistance to change, limited funding, outdated or nonexistent policy, lack of political leadership, and limited regulatory incentives (Brown 2005, Roy et al. 2008). Design and implementation approaches become entrenched in organizations because of their known feasibility and costs. This limits opportunities for innovative technologies to be used, particularly if organizations are risk averse (Burns et al. 2015b). Legislative requirements often define what stormwater solutions are permitted and, therefore, can constrain innovation. For example, lack of national guidance in the USA on at-source harvesting has resulted in some locally restrictive codes that discourage indoor use of harvested water (Findlay 2008).

The development process in most cities is a complex web of transportation, drainage, environmental, and building codes that all have entrenched means and methods frequently at odds with each other. All stakeholders in the process are in competition for space and money, so establishing stormwater practices that increase cost or space requirements are unlikely to succeed without strong public support for the protection of stream ecosystems or strong regulatory mandates. Perceptions of the ecological values and services provided by neighborhood streams can be variable, but acceptance and appreciation can be improved through engagement and education programs (Wagner 2008, Bos and Brown 2015). Perceptions of SCMs as human-health risks, either through exposure to contaminated water or as attractants for pests, such as mosquitoes, are driven largely by the way SCMs and their risks are framed cognitively (Mankad et al. 2012). Our principles potentially reframe SCMs by de-emphasizing large, end-of-pipe systems, such as constructed wetlands, which do present certain risks (Jackson et al. 2009), and placing greater emphasis on smaller-scale infiltration and harvesting systems. These small-scale systems also present risks—e.g., exposure to contaminants through use of stormwater directly or for agriculture—but they are likely to be low and easily managed (e.g., Heyworth et al. 2006, Tom et al. 2013).

The required widespread, strategic implementation of SCMs across catchments as outlined in principle 5 brings with it specific challenges. Such implementation will require collaboration and a shared commitment across multiple levels of government (Morison and Brown 2010, Bos and Brown 2012), widespread community engagement (including active participation of property owners in implementation of SCMs on their property; Bos and Brown 2015), the combination of retrofit activities and proactive planning to ensure future development effects are mitigated (Prosser et al. 2015), and a commitment to long-term programs because the level of implementation necessary to see tangible ecological responses probably will take several years.

From institutional and governance perspectives, perceptions that stormwater management for stream protection will lead to increased costs (of construction and maintenance) and increased taking of land (National Research Council 2009, Burns et al. 2015b) are primary barriers to reform. Stormwater management approaches suggested in the principles are potentially costly if considered in isolation from the benefits they provide (e.g., provision of alternate water supplies, flood mitigation, avoidance of channel restoration works), and the potential cost can lead to major opposition. However, any debate over the costs of such approaches should recognize and, where possible, quantify the environmental costs (through the lack of environmental services and the cost of rehabilitation works) of not implementing effective stormwater management. Our principles potentially inform such a discussion. First, land-take for harvesting systems is reduced with increasing demand, and volume reduction, in turn, reduces the size required for infiltration systems (Walsh et al. 2014). Second, dispersed SCMs designed to meet our principles can provide a range of co-benefits (discussed below), which mean that cost of and space for SCMs that protect streams can be shared with other benefits.

OPPORTUNITIES FOR CO-BENEFITS WHEN APPLYING THE PRINCIPLES

Many approaches to managing urban stormwater runoff can protect streams while providing co-benefits to the human community (Walsh et al. 2012), and a number of investigators have considered the multiple benefits of integrated urban water management (e.g., Jayasooriya and Ng 2014). However, by shifting the focus of SCMs to smaller scales (at or near source) and increasing the emphasis on harvesting, our principles provide co-benefits that have arguably been underemphasized in cost–benefit analyses to date (Table 1). Full consideration of such co-benefits could shift the economic balance and favor stormwater management approaches that protect streams.

Water supply

Eighty percent of the global population lives in countries where water security is threatened (Vörösmarty et al. 2010). Urban stormwater has great potential to reduce these threats through augmentation of urban water supplies. This potential should grow in concert with world population, as new impervious surfaces produce additional excess stormwater runoff that should be captured and used. Urban stormwater already is widely used for irrigation of gardens and open spaces and for nonpotable uses, such as laundry and toilet flushing (Mitchell et al. 2008). Such approaches are capable of substantially reducing potable demand in cities, but larger demands are typically required to reduce volumes for stream protection adequately (Walsh et al. 2014). Such demands could be achieved, and potable demand reduced even more substantially in many urban contexts, if harvested stormwater could be treated to a potable standard and incorporated into the potable water supply (Wong et al. 2012). In short, urban stormwater runoff presents a hitherto undervalued water supply opportunity that could simultaneously provide a service to the human population and to receiving water ecosystems (Walsh et al. 2012).

Flood mitigation

Stormwater-related flooding can be a major problem in urban catchments. In conventional stormwater management approaches, such flooding is commonly alleviated (and potentially mitigated) by increasing the size of stormwater infrastructure, such as detention basins, where runoff is temporarily stored and released at rates that approximate the capacity of downstream stormwater pipes. These flow rates often exceed channel erosion thresholds (McCuen 1979) and, thereby, aggravate negative effects of urban stormwater on streams. Recent research suggests that the small-scale application of SCMs is a viable, alternative flood management approach. Indeed, Burns et al. (2015a) predicted that the extensive application of rainwater tanks and infiltration trenches in a small urban catchment could mitigate stormwater-related flooding even for relatively infrequent storms (20-y annual recurrence interval). At small spatial scales (e.g., <1 ha), these events tend to be short in duration and depth and could be retained by SCMs that meet our principles for stream protection. For example in Melbourne, Australia, most rain falls in discrete events (separated by dry periods) where the depth of rainfall is less than 25 mm (Bureau of Meteorology 2015), similar in size to storms considered in principle 3. Future work is required to test the effects of SCMs on large-scale floods, but their potential for mitigating localized flood hazards is clear. SCMs that reduce flood risk also may reduce erosion and maintain downstream channels, promoting connectivity between stream riparian zones and floodplains (important processes for stream protection, as per principle 1) (Hawley and Vietz 2016).

Terrestrial biodiversity

In addition to their utility for flow management and urban stream restoration, SCMs can increase terrestrial biodiversity in urban environments. SCMs affect biodiversity directly by mimicking lost habitat and providing refugia for rare species (Kadas 2006, Dearborn and Kark 2010, Madre et al. 2014) or indirectly by serving as biological 'stepping stones' that increase connectivity between fragmented regions of natural habitat (Goddard et al. 2009, Braaker et al. 2014, Briers 2014). Green roofs, which can be useful stormwater control measures, particularly when coupled with harvesting and infiltration technologies (e.g., Hilten et al. 2008), provide some of the best evidence for biodiversity co-benefits of SCMs. High insect diversity has been reported on green roofs (Oberndorfer et al. 2007). Green roofs may also be particularly useful for reestablishing shallow soil habitat, such as rock pavements, scree slopes, and cliff faces, in temperate climates. These habitats are: 1) hotspots of plant diversity and endemism, and 2) likely to persist well in harsh rooftop conditions, which include high winds, extreme temperatures, intense solar radiation, and moisture stress (Oberndorfer et al. 2007). Given the utility of native gardens and streetscapes for promoting connectivity (particularly of birds; White et al. 2005), distributed, vegetated SCM measures, such as rain gardens and green spaces that are well irrigated by harvested stormwater, are likely to confer similar benefits in urban environs.

Urban cooling

Mimicking predevelopment flows requires loss of large volumes of stormwater from the catchment (see principle 2). Some of this excess could be used to irrigate parks, gardens, and street trees, thereby enhancing green spaces of cities. Infiltration systems also have the potential to serve as well-irrigated gardens themselves. Collectively, these actions can lower summer temperatures and improve thermal comfort through replenishment of soil moisture and maintenance of tree health, resulting in increased evapotranspiration, provision of shade, and surface cooling (Coutts et al. 2013). The potential human health outcomes associated with urban cooling are substantial (M. Loughnan et al. 2010, M. E. Loughnan et al. 2010).

Resilience to climate change

Climate change is likely to reduce precipitation, and therefore runoff, in many parts of the world (Arnell 1999). Reductions in runoff volumes from pervious catchments will be greater than reductions in volumes of runoff from impervious surfaces. Thus, urban stormwater runoff should be a more reliable source of water in response to long-term changes in rainfall patterns. Furthermore, the diverse, deeper rooted perennial plant communities that are possible with well-irrigated urban green spaces may also exhibit increased resistance, as they are buffered from the vagaries of our ever harsher climate.

Urban agriculture

Well-irrigated gardens planted with native and ornamental species may attract more pollinators, potentially improving productivity of small-scale urban agriculture. Rain gardens themselves have the potential of being productive sources of agriculture, in addition to their function as SCMs (Tom et al. 2013).

Human well-being

In addition to green spaces providing direct health benefits (van den Berg et al. 2010), the increased biodiversity afforded by retaining more water in the urban landscape (for irrigation and in SCMs) may also be important psychologically for city dwellers. Plant and bird biodiversity is positively correlated with measures of human well-being, such as reflection (ability to think and gain perspective), attachment (emotional ties to a greenspace), and distinct identity (feeling unique because of association with a greenspace) (Fuller et al. 2007). This evidence suggests that the biodiversity benefits of green stormwater infrastructure have the potential to be far reaching and to enhance urban quality of life as well as local species preservation, habitat connectivity, and ecosystem services.

CONCLUSION

Our primary purpose in this paper is to articulate how urban land and water should be managed to maximize the chances of providing cities and their inhabitants with healthy streams that supporting ecological structure and function and provide ecosystem services that are otherwise degraded by conventional urban stormwater drainage. Our interest in outcomes is focused on the stream, but almost all of our principles focus on the catchment because that is where the problem is generated and, thus, where its solutions must lie. The manifold stressors arising from urban stormwater runoff originate on every roof, road, and car park of our cities, and the most effective way to mitigate them is through appropriately designed SCMs situated near those sources.

Technical challenges remain that require innovative solutions, particularly with regard to infiltration systems that can adequately mimic the water quality and hydrologic processes of predevelopment catchments. Secondary challenges (and opportunities) are presented by design innovations that maximize multiple societal benefits, including stream protection. Unfortunately SCMs increasingly are being implemented primarily for those other benefits, such as the reduction in energy demand provided by green roofs, without a primary concern on their effect on downstream waters (e.g., Glasgow's sustainable construction strategy, discussed by Jones and Macdonald 2007). We argue that SCMs should not be implemented for co-benefits without coincident evaluation of their probable effects on downstream waters. Thus, our principles are presented with the aim of refocusing the design and implementation of SCMs on stream protection, while acknowledging that co-benefits may help overcome implementation barriers.

However, the largest challenges in achieving such an outcome are social and political. Thus, the greatest need for innovation lies in the realms of governance, economics, and social engagement. Such innovation requires clear articulation of the values of healthy stream ecosystems and the management actions that will be required to achieve them. We propose our stormwater management principles in such a spirit.

ACKNOWLEDGEMENTS

This paper arose from a discussion session at the 3rd Symposium on Urbanization and Stream Ecology in Portland, Oregon, in May 2014, which was funded in part by the US National Science Foundation (NSF) award DEB 1427007. The authors acknowledge financial support from the NSF Partnerships for International Research and Education (OISE-1243543, MAR); NSF grant EPSCoR IIA 1208732 (RLH); the UK Engineering and Physical Sciences Research Council Grant EP/K013661/1 (LNH); Melbourne Water, through the Melbourne Waterway Research-Practice Partnership (CJW, MJB, TDF); and Australian Research Council Future Fellowship (FT10010044, TDF). Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US Government.

LITERATURE CITED

Arnell, N. W. 1999. Climate change and global water resources. Global Environmental Change 9:S31–S49.

Bhaskar, A. S., L. Beesley, M. J. Burns, T. D. Fletcher, P. Hamel, C. E. Oldham, and A. H. Roy. 2016. Will it rise or will it fall? Managing the complex effects of urbanization on base flow. Freshwater Science 35:293–310.

Bhaskar, A. S., and C. Welty. 2012. Water balances along an urban-to-rural gradient of metropolitan Baltimore, 2001–2009. Environmental and Engineering Geoscience 18:37–50.

Booth, D. B. 1991. Urbanization and the natural drainage system—impacts, solutions and prognoses. Northwest Environmental Journal 7:93–118.

Booth, D. B., A. H. Roy, B. Smith, and K. A. Capps. 2016. Global perspectives on the urban stream syndrome. Freshwater Science 35:412–420.

Bos, D. G., and H. L. Brown. 2015. Overcoming barriers to community participation in a catchment-scale experiment: building trust and changing behavior. Freshwater Science 34:1169–1175.

Bos, J. J., and R. R. Brown. 2012. Governance experimentation and factors of success in socio-technical transitions in the urban water sector. Technological Forecasting and Social Change 79:1340–1353.

Braaker, S., J. Ghazoul, M. Obrist, and M. Moretti. 2014. Habitat connectivity shapes urban arthropod communities: the key role of green roofs. Ecology 95:1010–1021.

Briers, R. A. 2014. Invertebrate communities and environmental conditions in a series of urban drainage ponds in eastern Scotland: implications for biodiversity and conservation value of SUDS. Clean – Soil, Air, Water 42:193–200.

Brown, L. R., T. F. Cuffney, J. F. Coles, F. Fitzpatrick, G. McMahon, J. Steuer, A. H. Bell, and J. T. May. 2009a. Urban streams across the Untied States: lessons learned from studies in 9 metropolitan areas. Journal of the North American Benthological Society 28:1051–1069.

Brown, R. R. 2005. Impediments to integrated urban stormwater management: the need for institutional reform. Environmental Management 36:455–468.

Brown, R. R., and M. A. Farrelly. 2009. Delivering sustainable urban water management: a review of the hurdles we face. Water Science and Technology 59(5):839–846.

Brown, R. R., N. Keath, and T. H. F. Wong. 2009b. Urban water management in cities: historical, current and future regimes. Water Science and Technology 59(5):847–855.

Bureau of Meteorology. 2015. Rainfall intensity frequency duration data system. Bureau of Meteorology, Melbourne, Australia. (Available from: http://www.bom.gov.au/water/designRainfalls/revised-ifd/?)

Burns, M. J., T. D. Fletcher, C. J. Walsh, A. R. Ladson, and B. Hatt. 2013. Setting objectives for hydrologic restoration: from site-scale to catchment-scale (Objectifs de restauration hydrologique : de l'échelle de la parcelle à celle du bassin versant). On disk *in* J.-L. Bertrand-Krajewski and T. Fletcher (editors). NOVATECH 2013. GRAIE, Lyon, France.

Burns, M. J., T. D. Fletcher, C. J. Walsh, A. R. Ladson, and B. E. Hatt. 2012. Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform. Landscape and Urban Planning 105:230–240.

Burns, M. J., J. E. Schubert, T. D. Fletcher, and B. F. Sanders. 2015a. Testing the impact of at-source stormwater management on urban flooding through a coupling of network and channel propagation models. Wiley Interdisciplinary Reviews: Water 2:291–300.

Burns, M. J., E. Wallis, and V. Matic. 2015b. Building capacity in low-impact drainage management through research collaboration. Freshwater Science 34:1176–1185.

California Central Coast Regional Water Quality Control Board. 2013. Resolution No. R3-2013-0032, approving post-construction stormwater management requirements, for development projects in the Central Coast Region. California Regional Water Quality Control Board, San Luis Obispo, California. (Available from: http://www.waterboards.ca.gov/centralcoast/water_issues/programs/stormwater/docs/lid/hydromod_lid_docs/2013_0032resolution_signed.pdf)

Chadwick, M. A., J. E. Thiele, A. D. Huryn, A. C. Benke, and D. R. Dobberfuhl. 2012. Effects of urbanization on macroinvertebrates in tributaries of the St. Johns River, Florida, USA. Urban Ecosystems 15:347–365.

Cooper, S. D., P. S. Lake, S. Sabater, J. M. Melack, and J. L. Sabo. 2012. The effects of land use changes on streams and rivers in mediterranean climates. Hydrobiologia 719:383–425.

Coutts, A. M., N. J. Tapper, J. Beringer, M. Loughnan, and M. Demuzere. 2013. Watering our cities: the capacity for water sensitive urban design to support urban cooling and improve human thermal comfort in the Australian context. Progress in Physical Geography 37:2–28.

Dearborn, D. C., and S. Kark. 2010. Motivations for conserving urban biodiversity. Conservation Biology 24:432–440.

DeBusk, K. M., W. F. Hunt, and D. E. Line. 2011. Bioretention outflow: does it mimic nonurban watershed shallow interflow? Journal of Hydrologic Engineering 16:274–279.

Doyle, M. W., and E. S. Bernhardt. 2011. What is a stream? Environmental Science and Technology 45:354–359.

Elmore, A. J., and S. S. Kaushal. 2008. Disappearing headwaters: patterns of stream burial due to urbanization. Frontiers in Ecology and the Environment 6:308–312.

Environment Canada and Health Canada. 2001. Canadian Environmental Protection Act, 1999—Priority Substances List Assessment Report—Road Salts. Gatineau, Quebec, Canada. (Available from: http://www.hc-sc.gc.ca/ewh-semt/pubs/contaminants/psl2-lsp2/road_salt_sels_voirie/index-eng.php)

Findlay, D. 2008. Rainwater collection, water law, and climate change: a flood of problems waiting to happen. North Carolina Journal of Law and Technology 10:74–95.

Fletcher, T. D., A. Deletic, V. G. Mitchell, and B. E. Hatt. 2008. Reuse of urban runoff in Australia: a review of recent advances and remaining challenges. Journal of Environmental Quality 37:S116–S127.

Fletcher, T. D., W. Shuster, W. F. Hunt, R. Ashley, D. Butler, S. Arthur, S. Trowsdale, S. Barraud, A. Semádeni-Davies, and J.-L. Bertrand-Krajewski. 2015. SUDS, LID, BMPs, WSUD and more—the evolution and application of terminology surround ing urban drainage. Urban Water Journal 12:525–542.

Foulquier, A., F. Malard, S. Barraud, and J. Gibert. 2009. Thermal influence of urban groundwater recharge from stormwater infiltration basins. Hydrological Processes 23:1701–1713.

Fuller, R. A., K. N. Irvine, P. Devine-Wright, P. H. Warren, and K. J. Gaston. 2007. Psychological benefits of greenspace increase with biodiversity. Biology Letters 3:390–394.

Goddard, M. A., A. J. Dougill, and T. G. Benton. 2009. Scaling up from gardens: biodiversity conservation in urban environments. Trends in Ecology and Evolution 25:90–98.

Graf, W. L. 1977. Network characteristics in suburbanizing streams. Water Resources Research 13:459–463.

Graham, C. B., R. A. Woods, and J. J. McDonnell. 2010. Hillslope threshold response to rainfall: (1) a field based forensic approach. Journal of Hydrology 393:65–76.

Greenway, M. 2010. Wetlands and ponds for stormwater treatment in subtropical Australia: their effectiveness in enhancing biodiversity and improving water quality? Journal of Contemporary Water Research and Education 146:22–38.

Groffman, P. M., D. J. Bain, L. E. Band, K. T. Belt, G. S. Brush, J. M. Grove, R. V. Pouyat, I. C. Yesilonis, and W. C. Zipperer. 2003. Down by the riverside: urban riparian ecology. Frontiers in Ecology and the Environment 1:315–321.

Hale, R. L., M. Scoggins, N. J. Smucker, and A. Suchy. 2016. Effects of climate on the expression of the urban stream syndrome. Freshwater Science 35:421–428.

Hamel, P., E. Daly, and T. D. Fletcher. 2013. Source-control stormwater management for mitigating the impacts of urbanisation on baseflow: a review. Journal of Hydrology 485:201–211.

Hamel, P., T. D. Fletcher, E. Daly, and J. Beringer. 2012. Water retention by raingardens: implications for local-scale soil moisture and water fluxes. Pages 137–144 *in* WSUD 2012: Water Sensitive Urban Design; Building the Water Sensitive Community; 7th International Conference on Water Sensitive Urban Design. Engineers Australia, Barton, Australian Capital Territory, Australia.

Hamel, P., T. D. Fletcher, C. J. Walsh, J. Beringer, and E. Plessis. 2011. Water balance of infiltration systems in relation to their operating environment. 12th International Conference on Urban Drainage (ICUD), Porto Alegre, Brazil. International Water Association, London, UK.

Hatt, B. E., T. D. Fletcher, and A. Deletic. 2009. Pollutant removal performance of field-scale stormwater biofiltration systems. Water Science and Technology 59.8:1567–1576.

Hawley, R. J., and G. J. Vietz. 2016. Addressing the urban stream disturbance regime. Freshwater Science 35:278–292.

Heyworth, J. S., G. Glonek, E. Maynard, P. Baghurst, and J. Finlay-Jones. 2006. Consumption of untreated tank rainwater and gastroenteritis among young children in South Australia. International Journal of Epidemiology 35:1051–1058.

Hill, P. I., U. Maheepala, and R. G. Mein. 1996. Empirical analysis of data to derive losses for flood estimation in south-eastern Australia. Report 96/5. Cooperative Research Centre for Catchment Hydrology, Melbourne, Australia. (Available from: http://www.ewater.com.au/archive/crcch/archive/pubs/pdfs/technical199605.pdf)

Hilten, R. N., T. M. Lawrence, and E. W. Tollner. 2008. Modeling stormwater runoff from green roofs with HYDRUS-1D. Journal of Hydrology 358:288–293.

Horner, R., C. W. May, E. Livingston, D. Blaha, M. Scoggins, J. Tims, and J. Maxted. 2001. Structural and non-structural BMPs for protecting streams. Pages 60–77 *in* B. Urbonas (editor). Linking stormwater BMP designs and performance to receiving water impact mitigation. Engineering Research Foundation Conference. American Society of Civil Engineers, Snowmass, Colorado.

Hunt, W. F., A. P. Davis, and R. G. Traver. 2011. Meeting hydrologic and water quality goals through targeted bioretention design. Journal of Environmental Engineering 138:698–707.

Jackson, C. R., D. S. Leigh, S. L. Scarbrough, and J. F. Chamblee. 2014. Herbaceous versus forested riparian vegetation: narrow and simple versus wide, woody and diverse stream habitat. River Research and Applications. doi:10.1002/rra.2783

Jackson, M. J., J. L. Gow, M. J. Evelyn, N. E. Meikleham, T. J. S. McMahon, E. Koga, T. J. Howay, L. Wang, and E. Yan. 2009. *Culex* mosquitoes, West Nile virus, and the application of innovative management in the design and management of stormwater retention ponds in Canada. Water Quality Research Journal of Canada 44:103–110.

Jarvis, N. 2007. A review of non-equilibrium water flow and solute transport in soil macropores: principles, controlling factors and consequences for water quality. European Journal of Soil Science 58:523–546.

Jayasooriya, V., and A. Ng. 2014. Tools for modeling of stormwater management and economics of green infrastructure practices: a review. Water, Air, and Soil Pollution 225:1–20.

Jones, P., and N. Macdonald. 2007. Making space for unruly water: sustainable drainage systems and the disciplining of surface runoff. Geoforum 38:534–544.

Kadas, G. 2006. Rare invertebrates colonizing green roofs in London. Urban Habitats 4:66–86.

Karr, J. R. 1999. Defining and measuring river health. Freshwater Biology 41:221–234.

Karvonen, A. 2011. Politics of urban runoff: nature, technology, and the sustainable city. MIT Press, Cambridge, Massachusetts.

King County. 1990. Surface water design manual. King County Department of Public Works, Surface Water Management Division, Seattle, Washington. (Available from: http://your.kingcounty.gov/dnrp/library/water-and-land/stormwater/1990_SWDM.pdf)

King, R. S., and M. E. Baker. 2011. An alternative view of ecological community thresholds and appropriate analyses for their detection: comment. Ecological Applications 21:2833–2839.

Konrad, C. P., and D. B. Booth. 2005. Hydrologic changes in urban streams and their ecological significance. American Fisheries Society Symposium 47:157–177.

Liu, G., F. W. Schwartz, and Y. Kim. 2013. Complex baseflow in urban streams: an example from central Ohio, USA. Environmental Earth Sciences 70:3005–3014.

Loughnan, M., N. Nicholls, and N. Tapper. 2010. Mortality–temperature thresholds for ten major population centres in rural Victoria, Australia. Health and Place 16:1287–1290.

Loughnan, M. E., N. Nicholls, and N. J. Tapper. 2010. The effects of summer temperature, age and socioeconomic circumstance on acute myocardial infarction admissions in Melbourne, Australia. International Journal of Health Geographics 9:41.

Madre, F., A. Vergnes, N. Machon, and P. Clergeau. 2014. Green roofs as habitats for wild plant species in urban landscapes: first insights from a large-scale sampling. Landscape and Urban Planning 122:100–107.

Mankad, A. 2012. Decentralised water systems: emotional influences on resource decision making. Environment International 44:128–140.

Martin, P., B. Turner, K. Waddington, C. Pratt, N. Campbell, J. Payne, and B. Reed. 2000. Sustainable urban drainage systems: design manual for Scotland and Northern Ireland. C521. CIRIA, London, UK.

May, C. W., and R. R. Horner. 2002. The limitations of mitigation-based stormwater management in the Pacific Northwest and the potential of a conservation strategy based on low-impact development principles. Pages 1–16 *in* E. W. Strecker and W. C. Huber (editors). 9th International Conference on Urban Drainage, Global Solutions for Urban Drainage, Portland, Oregon. American Society of Civil Engineers, Reston, Virginia.

McClain, M. E., E. W. Boyer, C. L. Dent, S. E. Gergel, N. B. Grimm, P. M. Groffman, S. C. Hart, J. W. Harvey, C. A. Johnston, E. Mayorga, W. H. McDowell, and G. Pinay. 2003. Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems. Ecosystems 6:301–312.

McCuen, R. H. 1979. Downstream effects of stormwater management basins. Journal of the Hydraulics Division. Proceedings of the American Society of Civil Engineers 105:1343–1356.

Meyer, J. L., and J. B. Wallace. 2001. Lost linkages and lotic ecology: rediscovering small streams. Pages 295–317 *in* M. C. Press, N. J. Huntly, and S. Levin (editors). Ecology: achievement and challenge. Blackwell Science, London, UK.

Mitchell, V. G., D. McCarthy, A. Deletic, and T. D. Fletcher. 2008. Sensitivity of urban stormwater harvesting storage capacity–reliability–yield relationships to behaviour analysis method selection. Environmental Modelling and Software 23:782–793.

Morison, P. J., and R. R. Brown. 2010. Avoiding the presumptive policy errors of intergovernmental environmental planning programmes: a case analysis of urban stormwater management planning. Journal of Environmental Planning and Management 53:197–217.

National Research Council. 2009. Urban stormwater management in the United States. The National Academies Press, Washington, DC.

Oberndorfer, E., J. Lundholm, B. Bass, R. R. Coffman, H. Doshi, N. Dunnett, S. Gaffin, M. Köhler, K. K. Liu, and B. Rowe. 2007. Green roofs as urban ecosystems: ecological structures, functions, and services. BioScience 57:823–833.

Palmer, M. A., E. S. Bernhardt, J. D. Allan, P. S. Lake, G. Alexander, S. Brooks, J. Carr, S. Clayton, C. N. Dahm, J. Follstad-Shah, D. L. Galat, S. G. Loss, P. Goodwin, D. D. Hart, B. Hassett, R. Jenkinson, G. M. Kondolf, R. Lave, J. L. Meyer, T. K. O'Donnell, L. Pagano, and E. Sudduth. 2005. Standards for ecologically successful river restoration. Journal of Applied Ecology 42:208–217.

Palmer, M. A., S. Filoso, and R. M. Fanelli. 2014. From ecosystems to ecosystem services: stream restoration as ecological engineering. Ecological Engineering 65:62–70.

Parr, T. B., N. J. Smucker, C. N. Bentsen, and M. W. Neale. 2016. Potential roles of past, present, and future urbanization characteristics in producing varied stream responses. Freshwater Science 35:436–443.

Paul, M. J., and J. L. Meyer. 2001. Streams in the urban landscape. Annual Review of Ecology and Systematics 32:333–365.

Perrin, C., L. Milburn, L. Szpir, W. Hunt, S. Bruce, R. McLendon, S. Job, D. Line, D. Lindbo, S. Smutko, H. Fisher, R. Tucker, J. Calabria, K. Debusk, K. C. Cone, M. Smith-Gordon, J. Spooner, T. Blue, N. Deal, J. Lynn, D. Rashash, R. Rubin, M. Senior, N. White, D. Jones, and W. Eaker. 2009. Low impact development: a guidebook for North Carolina. AG-716. North Carolina Cooperative Extension Service, North Carolina State University, Raleigh North Carolina. (Available from: http://www.ncsu.edu/WECO/LID)

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. 1997. The natural flow regime. BioScience 47:769–784.

Price, K. 2011. Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: a review. Progress in Physical Geography 35:465–492.

Prince George's County Maryland Department of Environmental Resources. 1999. Low-impact development design strategies: an integrated design approach. Department of Environmental Resources, Prince George's County, Largo, Maryland. (Available from: http://water.epa.gov/polwaste/green/upload/lidnatl.pdf)

Prosser, T., P. J. Morison, and R. A. Coleman. 2015. Integrating stormwater management to restore a stream: perspectives from a waterway management authority. Freshwater Science 34:1186–1194.

Pusey, B. J., and A. H. Arthington. 2003. Importance of the riparian zone to the conservation and management of freshwater fish: a review. Marine and Freshwater Research 54:1–16.

Roseen, R. M., T. P. Ballestero, J. J. Houle, P. Avellaneda, J. Briggs, G. Fowler, and R. Wildey. 2009. Seasonal performance variations for storm-water management systems in cold climate conditions. Journal of Environmental Engineering 135:128–137.

Roy, A. H., A. L. Dybas, K. M. Fritz, and H. R. Lubbers. 2009. Urbanization affects the extent and hydrologic permanence of headwater streams in a midwestern US metropolitan area. Journal of the North American Benthological Society 28:911–928.

Roy, A. H., L. K. Rhea, A. L. Mayer, W. D. Shuster, J. J. Beaulieu, M. E. Hopton, M. A. Morrison, and A. S. Amand. 2014. How much is enough? Minimal responses of water quality and stream biota to partial retrofit stormwater management in a suburban neighborhood. PLoS ONE 9:e85011.

Roy, A. H., S. J. Wenger, T. D. Fletcher, C. J. Walsh, A. R. Ladson, W. D. Shuster, H. W. Thurston, and R. R. Brown. 2008. Impediments and solutions to sustainable, watershed-scale urban stormwater management: lessons from Australia and the United States. Environmental Management 42:344–359.

Roy, J. W., and G. Bickerton. 2012. Toxic groundwater contaminants: an overlooked contributor to urban stream syndrome? Environmental Science and Technology 46:729–736.

Schueler, T. R. 1987. Controlling urban runoff: a practical manual for planning and designing urban BMPs. Metropolitan Washington Council of Governments, Washington, DC.
Smakhtin, V. 2001. Low flow hydrology: a review. Journal of Hydrology 240:147–186.
Smith, R. F., R. J. Hawley, M. W. Neale, G. J. Vietz, E. Diaz-Pascacio, J. Herrmann, A. C. Lovell, C. Prescott, B. Rios-Touma, B. Smith, and R. M. Utz. 2016. Urban stream renovation: incorporating societal objectives to achieve ecological improvements. Freshwater Science 35:364–379.
Steward, A. L., D. von Schiller, K. Tockner, J. C. Marshall, and S. E. Bunn. 2012. When the river runs dry: human and ecological values of dry riverbeds. Frontiers in Ecology and the Environment 10:202–209.
Tanaka, T., M. Yasuhara, H. Sakai, and A. Marui. 1988. The Hachioji Experimental Basin Study—storm runoff processes and the mechanism of its generation. Journal of Hydrology 102:139–164.
Taylor, G. D., T. D. Fletcher, T. H. F. Wong, P. F. Breen, and H. P. Duncan. 2005. Nitrogen composition in urban runoff—implications for stormwater management. Water Research 39: 1982–1989.
Tom, M., P. J. Richards, D. T. McCarthy, T. D. Fletcher, C. Farrell, N. S. Williams, and K. Milenkovic. 2013. Turning (storm) water into food; the benefits and risks of vegetable raingardens. 8th International Conference on Sustainable Techniques and Strategies in Urban Water Management. NOVATECH 2013. GRAIE, Lyon, France.
Toronto and Region Conservation Authority and Credit Valley Conservation Authority. 2010. Low impact development stormwater management planning and design guide. Toronto, Ontario, Canada. (Available from: http://sustainabletechnologies.ca/wp/publications/publications-low-impact-development)
van den Berg, A. E., J. Maas, R. A. Verheij, and P. P. Groenewegen. 2010. Green space as a buffer between stressful life events and health. Social Science and Medicine 70:1203–1210.
Victoria Stormwater Committee. 1999. Urban stormwater: best practice environmental management guidelines. CSIRO, Melbourne, Australia.
Vietz, G., M. Stewardson, C. J. Walsh, and T. D. Fletcher. 2012. Another reason urban streams are stuffed: geomorphic history, challenges and opportunities. Pages 110–115 *in* J. R. Grove and I. D. Rutherford (editors). Proceedings of the 6th Australian Stream Management Conference, Managing for Extremes. River Basin Management Society, Canberra, Australia.
Vörösmarty, C. J., P. Green, P. B. McIntyre, M. O. Gessner, D. Dudgeon, A. Prusevich, P. Green, S. Glidden, S. E. Bunn, C. A. Sullivan, C. R. Liermann, and P. M. Davies. 2010. Global threats to human water security and river biodiversity. Nature 467:555–561.
Wagner, M. M. 2008. Acceptance by knowing? The social context of urban riparian buffers as a stormwater best management practice. Society and Natural Resources 21:908–920.
Walsh, C. J. 2004. Impacts of stormwater treatment wetlands on stream macroinvertebrates: a study of four wetlands constructed by Melbourne Water on streams in eastern Melbourne. Water Studies Centre, Monash University, Melbourne, Australia. (Available from: http://www.urbanstreams.unimelb.edu.au/cwalsh/docs/NHT_wetland_bugs_Final_report.pdf)
Walsh, C. J., R. L. Eddy, T. D. Fletcher, and M. Potter. 2014. Feasibility and cost of stormwater management for stream protection at property, street and precinct scales. Melbourne Waterway Research Practice Partnership Technical Report 14-1. The University of Melbourne, Melbourne, Australia. (Available from: http://www.urbanstreams.unimelb.edu.au/MWRPPDocs/14.1 Scaled stormwater management - Summary.pdf)
Walsh, C. J., T. D. Fletcher, and M. J. Burns. 2012. Urban stormwater runoff: a new class of environmental flow problem. PLoS ONE 7:e45814.
Walsh, C. J., and J. Kunapo. 2009. The importance of upland flow paths in determining urban effects on stream ecosystems. Journal of the North American Benthological Society 28:977–990.
Walsh, C. J., A. H. Roy, J. W. Feminella, P. D. Cottingham, P. M. Groffman, and R. P. Morgan. 2005. The urban stream syndrome: current knowledge and the search for a cure. Journal of the North American Benthological Society 24:706–723.
Walsh, C. J., and J. A. Webb. 2016. Interactive effects of urban stormwater drainage, land clearance, and flow regime on stream macroinvertebrate assemblages across a large metropolitan region. Freshwater Science 35:324–339.
Weiss, P. T., G. LeFevre, and J. S. Gulliver. 2008. Contamination of soil and groundwater due to stormwater infiltration practices: a literature review. University of Minnesota Stormwater Assessment Project, Minneapolis, Minnesota. (Available from: http://conservancy.umn.edu/bitstream/handle/11299/115341/pr515.pdf?sequence=1&isAllowed=y)
Whelans, C., H. G. Maunsell, and P. Thompson. 1994. Planning and management guidelines for water sensitive urban (residential) design. Department of Planning and Urban Development of Western Australia, Perth, Australia.
White, J. G., M. J. Antos, J. A. Fitzsimons, and G. C. Palmer. 2005. Non-uniform bird assemblages in urban environments: the influence of streetscape vegetation. Landscape and Urban Planning 71:123–135.
Wong, T. H. F., R. Allen, J. Beringer, R. R. Brown, A. Deletic, T. D. Fletcher, L. Gangadharan, W. Gernjak, C. Jakob, T. O'Loan, M. Reeder, N. Tapper, and C. J. Walsh. 2012. Blueprint2012—stormwater management in a water sensitive city. Centre for Water Sensitive Cities, Monash University, Melbourne, Australia.
Woods-Ballard, B., R. Kellagher, P. Martin, C. Jefferies, R. Bray, and P. Shaffer. 2007. The SUDS manual. CIRIA, London, UK.
Zhang, L., W. R. Dawes, and G. R. Walker. 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resources Research 37:701–708.