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Impediments and Solutions to Sustainable, Watershed-Scale Urban Stormwater Management: Lessons from Australia and the United States

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Abstract In urban and suburban areas, stormwater runoff is a primary stressor on surface waters. Conventional urban stormwater drainage systems often route runoff directly to streams and rivers, thus exacerbating pollutant inputs and hydrologic disturbance, and resulting in the degradation of ecosystem structure and function. Decentralized stormwater management tools, such as low impact development (LID) or water sensitive urban design (WSUD), may offer a more sustainable solution to stormwater management if implemented at a watershed scale. These tools are designed to pond, infiltrate, and harvest water at the source, encouraging evaporation, evapotranspiration, groundwater recharge, and re-use of stormwater. While there are numerous demonstrations of WSUD practices, there are few examples of widespread implementation at a watershed scale with the explicit objective of protecting or restoring a receiving stream. This article identifies seven major impediments to sustainable urban stormwater management: (1) uncertainties in performance and cost, (2) insufficient engineering standards and guidelines, (3) fragmented responsibilities, (4) lack of institutional capacity, (5) lack of legislative mandate, (6) lack of funding and effective market incentives, and (7) resistance to change. By comparing experiences from Australia and the United States, two developed countries with existing conventional stormwater infrastructure and escalating stream ecosystem degradation, we highlight challenges facing sustainable urban stormwater management and offer several examples of successful, regional WSUD implementation. We conclude by identifying solutions to each of the seven impediments that, when employed separately or in combination, should encourage widespread implementation of WSUD with watershed-based goals to protect human health and safety, and stream ecosystems.

Keywords Stormwater runoff · Water resource management · Watershed protection · Policy · Restoration · Sustainability

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Introduction

Stormwater runoff from impervious surfaces is a key contributor to the collapse of healthy freshwater ecosystems in urban environments in both the United States (US) and Australia (Paul and Meyer 2001; Konrad and Booth 2005; Ladson and others 2006). This is the result of stormwater management policies that emphasize expedient removal of stormwater from communities for the protection of human health and property, but place a low priority on ecosystem preservation. This problem has been recognized for many years (e.g., Arnold and Gibbons 1996; Booth and Jackson 1997) and has inspired the development of novel stormwater management approaches designed to minimize impervious cover and maximize infiltration of rainfall. These approaches — called low impact development (LID) in the US and water sensitive urban design (WSUD) in Australia — have been embraced by several cities, implemented as demonstration projects, and endorsed by several state and federal agencies. However, in most locations source control tools have not been widely implemented, and the vast majority of new stormwater management in the US and Australia remains in the form of conventional storm sewers with, perhaps, limited treatment by detention or retention basins.

In this article we pose the question: how can we as a society create a system of sustainable urban stormwater management where we protect not only human health and property, but also preserve natural, functioning aquatic ecosystems? We offer three premises that we believe are fundamental to achieving sustainable stormwater management and frame our analysis of the challenges facing such management.

Premise 1: Sustainable urban stormwater management maintains the natural ecological structure and function of receiving water bodies. For lotic ecosystems (the focus of this article), ecosystem structure and function are fundamentally influenced by their flow regimes. Stream geomorphology, temperature, water chemistry, habitat diversity, nutrient cycling, and other ecosystem processes are closely tied to discharge, and stream biota are adapted to the inter- and intra-annual changes inherent in natural flow regimes (Resh and others 1988; Poff and others 1997). Thus, any change in the landscape that alters components of the hydrologic cycle (e.g., infiltration, runoff, evapotranspiration), in turn, alters stream and river ecosystems (Allan 2004; Konrad and Booth 2005). For example, stormwater runoff from impervious surfaces serves as both a physical impact to streams and a transport vector of pollutants from the landscape. Because hydrology is a "master" variable, with direct and indirect impacts on most components of stream ecosystems (Konrad and Booth 2005), protection and restoration of natural hydrologic regimes is a necessary and critical component of sustainable management in urban landscapes. We do not presume that hydrologic restoration will *necessarily* restore urban streams; rather, we suggest that ecosystem sustainability cannot occur *without* hydrologic restoration.

Premise 2: Technologies already exist that are capable of mimicking the natural water cycle and reducing downstream transport of stormwater pollutants. LID and WSUD techniques (hereafter WSUD) are designed to capture and temporarily retain stormwater (e.g., rain barrels), infiltrate stormwater (e.g., biofiltration swales, pervious pavement,), and promote evapotranspiration (e.g., green roofs, rain gardens) (US EPA 2000). By capturing stormwater at or near the source of runoff, WSUD should reduce flood frequency, which risks human health and safety and infrastructure damage. Additionally, implementation of WSUD should serve to restore the critical components of natural flow regimes of lotic ecosystems, including the magnitude, duration, timing, rate of change, and frequency of low and high flow conditions (Poff and others 1997). Equally important, the use of infiltration practices provides filtration of pollutants. Thus, WSUD has the potential to remediate both water quantity and water quality issues in streams (Hatt and others 2004). These technologies have been implemented in various climates and settings around the world, and have proven effective at reducing runoff and pollutant loads at the individual site scale (i.e., single property, street, and subdivision) (e.g., Horner and others 2002; Phillips and others 2003; Villareal and others 2004). Walsh and others (2005) suggested that these approaches could be used to protect streams whose catchments include as much as 50% imperviousness. However, we acknowledge potential practical limitations to the ability of WSUD techniques to maintain healthy streams where (1) there is limited space for storing and infiltrating stormwater, (2) contaminants may overwhelm these technologies, and/or (3) the system has surpassed recovery thresholds. In these cases, sustainability may not be feasible, although this remains untested.

Premise 3: Sustainable urban stormwater management must be planned and implemented at the watershed scale. For the purpose of this article we use the term "watershed" to include drainages of various sizes that can have one or multiple jurisdictions responsible for management. By "watershed-scale implementation," we mean widespread installation of stormwater management with the explicit objective of protecting stream ecosystems, human health and safety, and private and public property. Because stream ecosystem effects have been linked to the proportion of untreated impervious area in the upstream watershed (Walsh and others 2005), watershed-wide application seems to be a prerequisite for sustaining ecosystem health. Accordingly, whether localized mitigation of stormwater runoff will result in downstream improvements will depend on the amount of untreated stormwater runoff remaining in the watershed.

These three premises suggest that sustainable urban stormwater management is attainable with existing technology; however, streams remain impaired because WSUD projects are presently implemented as small-scale demonstrations scattered amid a matrix of conventional stormwater drainage. In this article we (1) provide a brief, historical overview of stormwater management in the US and Australia, (2) identify the major impediments to widespread implementation of WSUD, and (3) provide examples of successful regional implementation of WSUD. The carefully refined list of impediments was developed from a synthesis of the literature and compilation of the authors' ideas, based on our own experiences and those of colleagues and practitioners in our respective countries. We focus on the US and Australia because both countries have explored WSUD techniques and have a recent history of interest in watershed management strategies (Margerum 2001; Brown 2005; Brown 2008). At the same time, the differences in institutional and legal underpinnings between the two nations offer an opportunity to explore different impediments and solutions. Based on perspectives and examples from both countries, we recommend avenues for advancing from small-scale demonstrations to widespread implementation of sustainable urban stormwater management.

The Evolution of Stormwater Management

United States

For most of the 20th century, stormwater runoff from impervious surfaces was managed with the goal of rapid conveyance and discharge into streams and rivers. In many large cities in the US, storm sewers were combined with sanitary sewers and conveyed to wastewater treatment plants, which provided treatment of runoff during small storm events. However, large rain events would overwhelm these combined systems and result in an overflow, which allowed discharge of not just stormwater runoff, but also untreated sewage into streams and rivers. In contrast, in smaller communities in the US, stormwater was discharged directly into nearby streams. Where regulations existed, they took the form of controls on peak flow rates with the goal of reducing downstream flooding, rather than addressing concerns of stream ecosystem degradation.

The Clean Water Act (CWA) of 1972 marked a major shift in management of US waters, providing regulatory requirements to address water quality problems. Specifically, it gave the US Environmental Protection Agency (US EPA) the authority to regulate effluent by requiring permits for point source discharges through the National Pollution Discharge Elimination System (NPDES) program. The CWA also required the development of water quality standards to bring water bodies into compliance with their designated use. Most of the permitting, enforcement, and monitoring has been passed from the federal government to the states, although the US EPA still develops policies, administers programs, and distributes funds under the CWA.

While the CWA motivated large-scale reductions in point source pollution, it did not provide a system for direct regulation of stormwater (Prahalad and others 2007). This changed in 1987 when the US EPA initiated the NPDES Stormwater program under the CWA, which required large municipal separate storm sewer systems located in incorporated areas with populations of 100,000 or more to obtain NPDES permits for stormwater discharges (US EPA 1996b). In 1999, Phase II of the NPDES Stormwater Program extended this regulatory oversight to smaller municipalities and required permit-holders to implement post-construction stormwater management programs mandating the use of stormwater best management practices (BMPs) in new development and redevelopment (US EPA 2005; note that the term stormwater BMP is used in the US to refer to any tool or practice for managing stormwater runoff, not only the "best" ones). Many ordinances implemented by local governments in compliance with NPDES Phase II included requirements for contaminant reduction and measures to reduce hydrologic alteration.

Concurrent with the evolution of federal water protection legislation, researchers were drawing attention to the benefits of controlling runoff at its source by reducing impervious cover and employing infiltration (e.g., Schueler 1994). This marked the emergence of WSUD in the US. These techniques were embraced in some communities, such as Prince Georges County, Maryland, and were the focus of various case studies elsewhere (US EPA 2000). Despite the promise of WSUD in reducing both contaminants and hydrologic alteration, the preferred approach to these problems in most communities remained conveyance of runoff to streams or stormwater detention ponds. Originally these ponds were designed for short-term storage to prevent flooding, but in some jurisdictions ponds are now designed for longer-term storage intended to reduce hydrologic alteration and provide some removal of contaminants via settling. However, conveyance and detention ponds remain less effective than WSUD at protecting downstream ecosystems.

Australia

As with the US, stormwater runoff in Australia was traditionally treated as a nuisance, and the solution was rapid conveyance directly to streams. Increased recognition of ecosystem degradation linked to stormwater runoff in the 1960s resulted in the some of the first moves toward more holistic management of stormwater, when stormwater management was incorporated into greenspace areas that were also available for recreational use (Fig. 1). Awareness greatly increased in the 1990s with interactions between government and scientists under the umbrella of the Cooperative Research Centre program (Brown and Clarke 2007). By this stage, investigations of the impacts of stormwater on the environment were being commissioned by government (e.g., O'Loughlin and others 1992).

Building on the new research undertaken in the early 1990s, various states of Australia began to act. For example, Western Australia released the first guidelines on WSUD in 1994 (Whelans and others 1994). Also around this time the Victorian Stormwater Initiative was formed, releasing guidelines on the best practice environmental management of urban stormwater (Victoria Stormwater Committee 1999). These guidelines were developed in consultation with another Australian state (New South Wales), and similar documents were released by Queensland (Brisbane City Council 1999). Throughout this period it was the states and territories that took the initiative in the area of stormwater quality management, not relying on national government leadership. The first major national attempt to provide guidance on stormwater management came in 2000 (ARMCANZ and ANZECC 2000), but by this stage most states had developed their own policies.

Currently, the water management agenda is influenced by the most severe drought since European settlement. Consequently, the perception of stormwater runoff has changed from strictly a liability to having a value as a water resource, and management of stormwater has shifted accordingly. Debate is also increasingly centered on how to achieve improved ecosystem health outcomes through stormwater management (Walsh 2004; Walsh and others

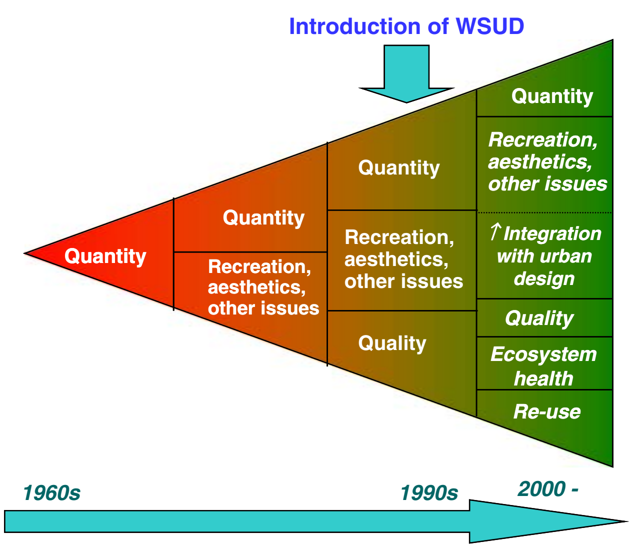


Fig. 1 In the 1960s, management of stormwater quantity for flood prevention was the only imperative, but in subsequent decades objectives for stormwater management have diversified (adapted from Whelans and others 1994)

2004). The management of stormwater quality and quantity is now considered a topic of national importance.

Impediments to Sustainable Urban Stormwater Management

In both the US and Australia, various factors have impeded the transition from conventional stormwater management to widespread implementation of WSUD. Several papers have been written on impediments to the adoption of WSUD, especially with respect to institutional capacity in Australia (Lloyd and others 2001b; Lloyd and others 2002; Brown 2005; Brown and others 2006b; Brown 2008). However, our present discussion is focused specifically on impediments to *watershed-scale* implementation. The distinction is important, because there is a need for consistent institutional, legislative, economic, and social arrangements to apply across an entire watershed if implementation is to be effective. Here, we present seven barriers that we believe must be overcome to achieve sustainable urban stormwater management (Table 1).

1. *Uncertainties in the Performance and Cost*

One of the most fundamental barriers to WSUD implementation is the dearth of adequate data related to the performance of WSUD tools in various settings. While many WSUD practices have been well studied and implemented under a range of soil and climatic conditions, many planners and engineers remain skeptical of results from different regions with similar climate and soil conditions. These practitioners require demonstrations of successful implementation in their own communities before they are willing to incorporate WSUD into design guidelines (Ewing and others 2000). Furthermore, there have been no studies that have demonstrated that watershed-wide implementation of WSUD achieves its goal of aquatic ecosystem protection. Without such demonstrations, it is difficult to ensure that WSUD is implemented at a scale, and with appropriate design, to result in downstream improvements.

The lack of defensible WSUD cost data has also impeded implementation. While there is evidence that using WSUD techniques can be cheaper than constructing traditional, large stormwater infrastructure (Thurston and others 2003; US EPA 2007), on the scale of individual stormwater management practices, cost data are mixed. Brown and Schueler (1997) found that conventional stormwater ponds are less expensive than many WSUD practices such as bioretention areas in the Mid-Atlantic region of the US. Conversely, Wossink and Hunt (2003) found that under at least some circumstances, bioretention and wetlands are more cost effective than stormwater

Table 1 Major impediments and solutions to sustainable stormwater management

No.	Impediment	Solution
1	Uncertainties in performance and cost	Conduct research on costs and watershed-scale performance
2	Insufficient engineering standards and guidelines	Create a model ordinance and promote guidance documents
3	Fragmented responsibilities	Integrate management across levels of government and the water cycle
4	Lack of institutional capacity	Develop targeted workshops to educate professionals
5	Lack of legislative mandate	Use grassroots efforts to garner support for ordinances and regulations
6	Lack of funding and effective market incentives	Address hurdles in market approaches to provide funding mechanisms
7	Resistance to change	Educate and engage the community through demonstrations

ponds in North Carolina. If WSUD practices can be used to eliminate the conveyance network, cost savings can be substantial, but it is not clear the extent to which this is feasible under a range of real-world conditions. More cost analyses are needed to provide convincing evidence for decision makers.

2. *Insufficient Engineering Standards and Guidelines*

A second, critical impediment to WSUD implementation is the lack of sufficient performance standards and guidelines. Performance standards allow developers and engineer consultants to select stormwater management techniques from a menu of tools and specifications in guidance documents; however, they arguably have impeded WSUD rather than encouraged it. Traditionally, these standards required safe conveyance and maintenance of peak flows at pre-development levels, and more recently require pollutant removal and slow release of accumulated stormwater in order to reduce scouring and erosion caused by large pulses of stormwater runoff. Although WSUD techniques are generally a permissible way to meet such rules, in practice most developers construct detention ponds which drain commercial lots and subdivisions, and are often not effective at protecting naturally-functioning aquatic systems (Maxted and Shaver 1997). While detention ponds are capable of removing considerable amounts of pollutants (e.g., mean 65% removal of total suspended solids; Wossink and Hunt 2003), WSUD which can provide nearly complete removal of many contaminants from small runoff events (Lloyd and others 2001a, 2002). In some cases, standards actually *prevent* developers from using source-control WSUD tools. For example, even if pervious pavements are used, codes often require installation of curb and gutter systems along roads in new developments. In other cases where bioinfiltration swales are used to infiltrate runoff, stormwater detention basins often must still be built and sized to accommodate runoff from the entire subdivision.

Even where appropriate standards exist, the engineering guides for practitioners often do not support the achievement of policy goals. For example, objectives for stormwater drainage in the Plumbing Code of Australia solely relate to the conveyance and disposal of water to off site drainage systems; water quality objectives are not explicitly recognized nor is there any mention of stormwater or roof runoff as a resource (National Plumbing Regulators Forum 2004). The current Australian Standard (AS/NZS 3500 Plumbing and Drainage), which is the guide plumbers and engineers use to size and install stormwater conveyances within subdivisions and on individual lots, is similarly deficient. Although on-site stormwater detention (OSD) is mentioned, and the advantage of using OSD devices to reduce peak flow is acknowledged, no guidance is currently provided on their design or installation because "sufficient data are not available." Similarly, the possibility of managing stormwater through on-site infiltration is acknowledged but a plumber (equivalent to stormwater engineer in US) looking for assistance on installing this WSUD tool is left unsupported because design is "subject to research and when available will be considered for adoption in the standard." Therefore, any situation leading to even temporary ponding of water is discouraged and WSUD techniques, such as rain gardens, would generally not be consistent with the standard.

3. *Fragmented Responsibilities*

Another significant impediment to watershed-scale management of stormwater runoff is that multiple entities are often responsible for management of a single watershed. In addition to spatial fragmentation that occurs when a watershed is shared among multiple governing jurisdictions, various components of the urban water cycle (municipal water, stormwater, surface water) may be managed separately, leading to limited integration of water resources management (Niemczynowicz 1999). Responsibilities may also be fragmented across different levels of government. For example, in Melbourne, jurisdictional authority for watersheds of greater than 60 ha rest with a state-level authority (Melbourne Water), while local governments govern smaller watersheds.

Consequently, Melbourne Water is deterred from investing in works to improve small watersheds, even though they affect the condition of the larger watersheds into which they drain. For watersheds of large rivers, difficulties arise in achieving a coordinated approach across an entire watershed that may involve 15 municipalities, each of which may have different priorities, policies, and capacity. Where management is coordinated, the objectives driving improvements in stormwater management are often not appropriately aligned with achieving watershed-scale protection. For example, in Australia, until recently, management has focused largely around the protection of downstream estuaries and bays, due to concerns about nutrient loads and sediment loads affecting bay ecology (Murray and Parslow 1999; Abal and others 2001). While it may seem that this would encourage a watershed-scale approach, it has favored end-of-pipe strategies, diminishing the attention paid to values of waterways throughout the watershed.

In the US, similar issues with fragmented responsibility across levels of government and urban water management have arisen. There is a general lack of coordination among federal, state, and local authorities in terms of water resource management (Caruso 2000), which can be attributed to three factors. First, there are several local authorities (e.g., county and city-level health and engineering departments, environmental quality bureaus, soil and water conservation districts, etc.) that all have a hand in land and water resource management. There is great variation at the local level in the existence and nature of these entities, as their funding is a function of local priorities and tax structure, among other economic factors. Second, regulation and enforcement of policies are in the hands of both state (e.g., NPDES discharge permits) and the local (e.g., land use regulations) government. Finally, because these institutions are based on political and geographic boundaries, rather than watershed boundaries, water resources management remains governed at scales inappropriate for integrated watershed protection. Combined, these factors lead to incomplete, and thus, ineffective, regional management.

4. *Lack of Institutional Capacity*

Many institutions lack the capacity — in terms of funding, personnel, guidelines, and other resources — necessary to support a program which will regulate and enforce widespread implementation of WSUD. Most engineers, architects, and landscapers lack the training to integrate WSUD within engineering specifications and design guidelines. There is a need to better educate professionals (e.g., engineers and planners) and policy makers on: (1) the uses and limitations of WSUD technologies, (2) strategies for identifying the primary sources of stormwater runoff within watersheds (e.g., impervious surfaces directly connected to stormwater pipes), and (3) the importance of consistent application throughout watersheds to achieve downstream improvements. Finally, most governments lack the capacity for enforcing widespread implementation of WSUD, which is necessary to ensure downstream protection.

5. *Lack of Legislative Mandate*

As mentioned previously, there is no national, legal mandate to control or treat stormwater runoff in the US or Australia. In the US stormwater runoff is primarily regulated at the local level of cities and counties, while in Australia regulatory authority primarily rests with the states and local government areas. The result is inconsistent management policies across jurisdictions, leading to ineffective protection of human health and safety, and freshwater resources. While the US CWA's NPDES Stormwater program requires permits for stormwater discharges, this only pertains to new development and redevelopment, leaving watersheds with mixed regulatory oversight. Comprehensive stormwater ordinances have been employed by proactive local governmental authorities; however, there is considerable variability in requirements within ordinances and presence of such requirements nationwide. While we do not believe regulatory mandates are necessary to achieve widespread implementation of WSUD, the lack of strict requirements limits the ability to promote consistent use of WSUD throughout watersheds.

6. *Lack of Sufficient Funding and Effective Market Incentives*

While WSUD may be cheaper or cost-neutral compared to traditional stormwater control methods (see above; US EPA 2007), additional costs not included in construction costs may prevent implementation. Maintenance costs and opportunity costs (the portion of the property taken out of its next best use) pose an additional burden to stormwater managers or private landowners. In already-developed areas, costs of removing or replacing existing infrastructure may be incurred. Finally, in communities where there is limited experience with WSUD technologies, professional training, education, and design costs will initially be high.

There are several incentive-based policies for stormwater runoff control that could be used to offset the costs of WSUD implementation, and otherwise encourage source-control stormwater management. The idea behind these approaches is to provide financial incentives (e.g., offering subsidies or reducing stormwater fees) for individuals and companies employing WSUD tools, and these costs are redistributed to the public. This mechanism internalizes environmental costs to all citizens, since the benefits serve the public good (e.g., via clean drinking water, healthy streams). While theoretically effective, the most common market-based tools (fee and rebate, tradable allowances) face challenges, as discussed below.

A fee and rebate approach uses stormwater fees in combination with rebates on stormwater runoff abatement strategies (e.g., WSUD, disconnection of impervious surfaces) to encourage homeowners to manage stormwater runoff on their properties (Fullerton and Wolverton 1999). If the rebate is high enough to encourage stormwater abatement behavior, a stormwater runoff reduction goal can be met at a relatively low cost to the utility and at a low per-unit cost to the average property owner. This type of policy is already in place in many municipalities in the US (Doll and others 1998; Doll and Lindsey 1999); however, it is usually a flat rate, not tied to differing quantities of stormwater runoff, and too low to encourage implementation of WSUD. For example, monthly residential stormwater fees in Columbus, Ohio, St. Louis, Missouri, and Indianapolis, Indiana are about \$2.70, \$0.24, and \$1.25, respectively. Thurston (2006) estimates that rebates, and therefore fees, would have to be of the order of \$500 to \$1500 to cause the appropriate abating behavior.

An alternative approach is tradable allowance (i.e., cap-and-trade) programs, whereby land developers who find it relatively expensive to implement the required level of stormwater quality management within their own development can purchase a stormwater quality offset, which will fund management in other locations. Such a system could be used to encourage WSUD to be prioritized in the areas with the greatest environmental (or other) values to be protected. However, tradable allowance programs have not been widely employed because there are legal and political issues that make it difficult to set a “cap” on watershed level runoff or impervious surfaces (Colby 2000). For example, for local governmental authorities to impose new restrictions on existing development, it must be seen as a legitimate exercise of police power for protecting human health and welfare, and subject to community vote (Parikh and others 2005). Even if legal constraints are overcome, these programs can fail if they allow end-of-pipe alternatives to on-site treatment, thus ineffectively protecting downstream waters.

7. *Resistance to Change*

There are multiple layers of risk and risk aversion that may cause resistance to WSUD by both practitioners and the general public. At an institutional level, risks pertain to developers (risk of cost penalty), engineers (risk of loss of functionality), municipalities (risk of failure and requirements for maintenance), public health bureaus (risk of disease), water supply agencies (risk of losing revenue), and plumbers (risks associated with doing work not authorized by a standard) (Argue 1995). Community resistance — especially to parcel-scale stormwater harvesting — has also hampered the ability to implement WSUD at a local scale. Some have argued that WSUD, particularly if it is poorly maintained, may have a “messy” appearance that is not appreciated by the community (Gardiner 2006). Due to the relative novelty of WSUD tools, proponents struggle with counteracting common perceptions that it is unattractive or ineffective. Another part of the problem is that the public understanding of the role of WSUD systems is often limited or inaccurate (Eadie 2002; Mongard 2002). Despite numerous publications, reports and demonstration projects, in most locations WSUD tools have not penetrated the public consciousness.

Examples of Regional Stormwater Management: Achievements and Challenges

While there are many impediments to sustainable stormwater management, there are an increasing number of cases in both Australia and the US where WSUD is being integrated into local stormwater policies and implemented within communities. Although most of these efforts are not aimed at improving stream ecosystems per se, the impetus behind them is to address downstream water quality and quantity issues, which necessarily requires widespread implementation of WSUD. Figures 2 and 3 describe two leading sustainable stormwater management programs in the US and Australia, respectively. The Etowah Basin stormwater management program (Fig. 2) is one of the largest programs to require stormwater infiltration, and represents one of the best examples to date in terms of scaling from demonstration projects to a whole-watershed approach. Its development was driven by the need to balance urban growth with protection of multiple, federally-listed fish species, so it may not be an example that is readily applicable to areas without imperiled aquatic species. Nevertheless, over time it is expected to provide a large-scale example of the feasibility of sustainable stormwater management. There is already considerable interest from neighboring jurisdictions, who will watch it closely for signs of success or failure.

Melbourne, Australia (Fig. 3) has made great advances in engaging a range of organizations and the community in the pursuit of WSUD. The State has developed and trialed new technologies, and has forged partnerships between state government agencies and municipalities, to enable a coordinated approach between regional and local planning and implementation. More recently, WSUD appears to be becoming more integrated into everyday practice.

Background

The Etowah River Basin, on the northern edge of the Atlanta Metropolitan Area in Georgia, USA, is a major tributary of the Coosa River system in the Mobile River Basin. It is characterized by a diverse aquatic assemblage, with 76 extant native species of fish (Burkhead 1997), including three that are listed under the U.S. Endangered Species Act (ESA) and six others that are state-listed. A paramount threat to the species is stormwater runoff from impervious surfaces, due in part to the rapid suburbanization in the watershed in recent years (Wenger and Freeman 2006). Researchers estimate that at least one of the federally listed species is likely to be extirpated at low levels (<10%) of total impervious cover in a 1.5 km radius (Wenger and others 2008). They recommend that species protection requires limiting effective impervious area by encouraging infiltration of stormwater runoff through a volume-based stormwater performance standard, which addresses both water quantity and water quality concerns.

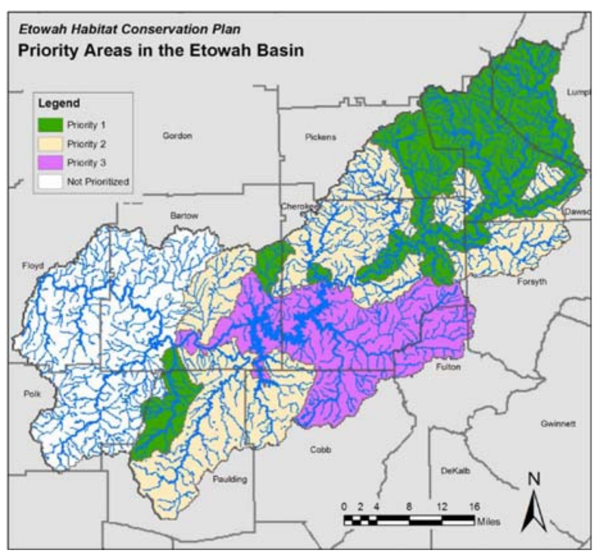
Runoff Limits Program

Under the Runoff Limits Program, the basin is divided into "Priority Areas" based on the distributions of the protected fish species (Wenger and others 2006). The habitat for the most sensitive species is designated as Priority 1; within these watersheds the volume of stormwater runoff in the 2-year storm is limited to what would occur if the site were in a forested condition, given the soils present. Watersheds supporting less sensitive species or that are downstream of Priority 1 areas are designated Priority 2; in these locations, a slightly less strict version of the performance standard applies. This Priority 2 standard allows for an increase in runoff over forested condition equivalent to the addition of 5% impervious cover. The program also allows for designated development nodes, where a much less strict standard applies. The locations of development nodes are established by local governments but limited in size and location such that they will not result in extirpation of the protected fish species, based on forecasting from a model that links future effective impervious area (EIA) to fish occurrence and abundance.

The performance standard applies to all new development and redevelopment that adds at least 5000 square feet of impervious area (certain exemptions apply and variances are available if strict criteria are met). To meet the standard, developers must use WSUD tools to return runoff to the soil close to where it is generated. They can also use site design techniques to minimize impervious cover and maximize forest cover, thus reducing the need for structural solutions.

Current Status

The standard is designed to be implemented by local governments through stormwater management ordinances as part of the "Etowah Aquatic Habitat Conservation Plan" or HCP. At the time of writing, the HCP has not yet been approved and the ordinances have not been adopted. However, the US Fish and Wildlife Service, which has responsibility for enforcing the ESA in this case, has required most large development projects to meet the performance standard since 2006. Other developers have voluntarily offered to meet the standard in order to promote their developments as environmentally friendly. Once the HCP is approved and adopted, WSUD practices are expected to become the norm within the Etowah basin.



Locations of priority areas for determining stormwater regulations based on distributions of protected fish species in the Etowah River Basin (Georgia, USA). Figure reproduced with permission (Wenger and others 2006).

Fig. 2 Watershed-scale stormwater management in Etowah River Basin, Georgia, USA

Historical Development Of WSUD

Melbourne has been acknowledged as a leader in the development of WSUD in Australia. Brown and Clarke (2007) identified several phases in the transition towards WSUD. Starting in the late 1960s, social activism began to place pressure on governments to improve the community and environmental values of waterways, particularly the Yarra River. Between 1990 and 1995, new partnerships between government agencies (e.g., Melbourne Water, municipalities, EPA), community groups, and research institutions were developed. In this phase, new technologies were formed, based on collaborative research initiatives.

The Port Phillip Bay Environmental Study (Harris and others 1996) was a primary motivator for the implementation of WSUD in Melbourne. The study identified a need to reduce the annual load of nitrogen entering the bay by 1000 kg, of which 500 kg was identified to come from reductions in stormwater loads. Guidelines were set for reductions in mean annual loads of TSS, TP, TN, and gross pollutants by 80, 45, 45 and 70%, respectively (Victoria Stormwater Committee 1999). Melbourne Water (a state-owned authority) was given responsibility for meeting these pollution reduction targets, and has played a leading role in driving the WSUD agenda ever since. Because subcatchments of less than 60 Ha are the responsibility of local government, Melbourne Water has worked in partnership with the EPA and the Municipal Association of Victoria to develop the Victorian Stormwater Initiative in 1996. In 2000, the first statewide stormwater program, the Victorian Stormwater Action Program, was formed with $22.5 million from the State Government. Also in this period, performance targets for stormwater quality were developed for the first time, and published in guidelines. Community concern related to waterways, in combination with space constraints on downstream end-of-pipe solutions, has driven a recent move towards at-source treatment, consistent also with the national guidelines for stormwater management (ARMCANZ and ANZECC 2000).

(a) Incorporation of a rain-garden, as part of a road reconstruction (photo courtesy of Melbourne Water); and (b) guidelines for WSUD in Melbourne.

Current Programs And Directions

Having achieved significant gains in community awareness of the need for WSUD, and in the development of suitable technologies, the current focus in Melbourne is centered on trying to incorporate WSUD into everyday practice, so that it becomes institutionalized (Brown and Clarke 2007). For example, the Clearwater Program (currently run by Melbourne Water, but previously coordinated by the Municipal Association of Victoria) provides information on stormwater management and sustainable urban water management more generally, specifically tailored to the needs of LGAs (see http://www.clearwater.asn.au/). Clearwater uses a very participatory approach, running training workshops on everything from construction practices, stormwater modeling tools, to negotiation skills. Melbourne Water's main focus is also on capacity-building within local government. Much of their resources are spent on supporting municipalities to incorporate WSUD into the typical retrofit or renewal projects, such as the reconstruction of roads, or the renewal of commercial areas. This initiative has also been underpinned by the development of guidelines on the selection, design, construction and maintenance of WSUD technologies (Melbourne Water 2005).

Lloyd and others (2001b) identified the gap between regional planning and local statutory planning as an impediment to the implementation of WSUD. To overcome this, the Victorian Government recently introduced a new clause (Clause 56) under the Sustainable Neighborhoods Code of the Victorian Planning Provisions (DSE 2006). Amongst other things, this legally required that the pollutant load reductions of TSS, TP, TN and gross pollutants be provided as part of any residential subdivisions. Clause 56 also requires flows to be maintained at their pre-development levels, based on the 1.5 and 100 year average recurrence interval flood events. Software tools are available that allow developers to predict the loads generated from their proposed development, with and without proposed treatment measures, in order to demonstrate compliance. Clause 56 also provides for the purchase of an "offset", where a developer cannot (for example, due to site constraints) meet the required targets on-site. In this case, the developer would pay Melbourne Water an offset calculated according to the cost required to deliver the required additional treatment as part of regional treatment measures.

Fig. 3 Regional stormwater management in Melbourne, Australia

Table 2 Examples of regional-scale stormwater management programs in Australia and the US

No.	Title/Description	Location	Impetus	Primary players	Incentives	Impediments	References
1	Etowah HCP Stormwater Management policy	Georgia, US	US Endangered Species Act	1. University of Georgia 2. US Fish & Wildlife Service 3. LGAs	1. Impacts of runoff on endangered species 2. Developer delays in creating individual HCPs	1. Fragmented responsibilities among LGAs (#3) 2. Costs of limiting development (#6) 3. No legal requirement for existing development (#5)	Wenger and others 2006
2	Portland's Downspout Disconnection program	Oregon, US	CSOs into the Willamette River	1. Portland Bureau of Environmental Services 2. Portland Office of Neighborhood Involvement	1. NPDES requirements to reduce CSOs 2. Money to community organizations who perform disconnections ($13/ downspout) 3. Free to homeowner	1. No legal requirement to force compliance (#5)	
3	Nine Mile Run Rain Barrel Initiative	Pennsylvania, US	Non-point source pollution problems	1. Nine Mile Run Watershed Association 2. Three Rivers Wet Weather	1. Free rain barrel, installation, & technical support (to targetted neighborhoods)	1. Low public awareness 2. Costs/time to do door-to-door canvassing (#6)	
4	KC's 10,000 Rain Gardens Initiative	Missouri, US	KC Water Services Department interviews; concerns about flooding & runoff	1. Elected officials 2. Stakeholders	1. Education campaign	1. Lack of institutional capacity (#4) 2. No legal requirement to force compliance (#5) 3. Cost to homeowners (#6)	
5	Victorian Stormwater Initiative (and Clause 56, etc)	Melbourne, Australia	Port Phillip Bay Study	1. Melbourne Water 2. Victorian EPA 3. CRCFE/CH 4. Municipal Association of Victoria	1. Over-arching influence of MW, EPA 2. Good partnership between industry & research 3. "Pragmatic, practical" targets for industry 4. Software model for assessment	1. Lack of capacity within councils (#4) 2. No dedicated long-term fund source (until recently) (#6) 3. Uncertainties in performance/ links to ecological outcomes (#1)	Harris and others1996 Victoria Stormwater Committee 1999
6	Healthy Waterways Partnership	SE Queensland, Australia	Moreton Bay study	1. Brisbane City Council 2. Queensland EPA 3. Healthy Waterways Partnership	1. Perception of strong science, but with community focus 2. Widespread power/influence of Brisbane City Council	1. Lack of capacity within councils and development industry (#4) 2. No legal requirement transecting all scales (#5) 3. Extremely rapid rate of development placing pressure on infrastructure and planning processes 4. Differing priorities between States and LGAs (#3	Brisbane City Council 1999 Abal and others 2001

Numbers after impediments correspond to major impediments (see Table 1)

HCP, Habitat Conservation Plan; US, United States; LGAs, local government authorities; CSOs, combined sewer overflows; NPDES, National Pollution Discharge Elimination System; KC, Kansas City; MW, Melbourne Water; EPA, Environmental Protection Agency; CRCFE/CH, Cooperative Research Centre for Freshwater Ecology/ Catchment Hydrology; SE, Southeast; WSUD, water sensitive urban design

However, some important challenges remain, particularly if WSUD is to be implemented at a whole-of-watershed scale (i.e., not just at outlets of catchments), and is to produce improvements in the ecological health of waterways (Lloyd and others 2001a, b). Currently, targets for WSUD in Melbourne are based on pollutant load reductions, for the protection of Port Phillip Bay. While State environmental protection policies specify maximum pollutant concentrations, minimum values of metrics based on macroinvertebrate assemblage composition, and presence of five fish species in waterways (e.g., Government of Victoria 1999), there is currently no clear connection between these ecological indicators and the targets that are applied to WSUD. A more integrated suite of performance targets is thus needed, which is based on the desired ecological outcomes for both waterways and bays (Walsh 2004). Such a set of targets would address both water quality and flows in an integrated manner, requiring WSUD to achieve a replication of the predevelopment hydrology and water quality, at least for frequent storm events (e.g., up to the 3 month average recurrence interval; Walsh and others 2004).

There are several other examples of regional-scale stormwater management programs in the US and Australia (Table 2). These specific examples have been highlighted because WSUD and stormwater management strategies are being employed across entire cities and counties, with the objective of reducing stormwater problems in the larger watershed. While there are many stormwater management efforts throughout the US, they are typically at small scales (site, subdivision) and are not expected to result in ecosystem improvement for the larger watershed. In Australia, both the Victorian Stormwater Initiative and the Healthy Waterways Partnership are large, regional efforts that have arisen from a gradual building of knowledge and concern for downstream waters, culminating in government-level efforts to address stormwater issues.

Interestingly, the impetus behind all of the examples presented in Table 2 is the concern for downstream water quality. This suggests that regional or watershed-scale management may be easier to implement when potential or actual downstream ecosystem impairment has been identified and targeted for improvement. This is distinctly different from most stormwater management projects that have been implemented opportunistically, scattered across expansive urban areas (Brown and others 2006a; Wong 2006). In these cases, there are specific concerns or interests in runoff from the site; however, the cumulative effects of other stormwater contributors into the watershed prevent any objective or potential for watershed-scale improvements.

Several of the major impediments to WSUD that were highlighted earlier were considered impediments in the case studies (Table 2). In particular, fragmented responsibilities, lack of capacity, lack of a legal mandate, and costs of WSUD were repeatedly cited as problems, although these ultimately did not halt the programs. Notably, insufficient engineering standards were not highlighted as a major impediment, presumably because these locations addressed this hurdle before implementing programs to encourage WSUD. There was also no mention of public resistance to change, although low public awareness could result in resistance if not properly addressed. Together, these examples underscore the issues that must be addressed or overcome by incentives to allow for widespread implementation of WSUD.

Lastly, these examples highlight the importance of *both* "top-down" (regulatory) and "bottom-up" (incentive/assistance) approaches to encouraging sustainable stormwater management. The Etowah case study is an example of watershed-scale stormwater management driven by a very strong federal regulation, the Endangered Species Act. However, this top-down approach to stormwater management was only possible because scientists and policy analysts worked closely with regulators, county and city officials, and other stakeholders to garner input into program development and identify potential problems and barriers in advance. Similarly, the CWA, through NPDES Phase I and II permit violations, has provided a regulatory driver to force municipalities to develop solutions to stormwater runoff and combined sewer overflows. However, WSUD is not the only solution to violations, and source-control approaches have only been implemented where there is substantial grassroots support (e.g., Portland, Oregon, Table 2). Other examples such as the Nine Mile Run Barrel Initiative and the 10,000 Rain Gardens program were initiated by watershed groups, county officials, and other stakeholders; yet, it is likely these grassroots efforts will ultimately lead to ordinances that enforce WSUD implementation. In Australia, a combination of bottom-up and top-down approaches has also been employed to get stormwater management at the forefront of state interests. In both Victoria and Queensland, research has played an important role in demonstrating the downstream impacts of stormwater runoff, testing various WSUD technologies, and developing institutional capacity. From there, EPA Victoria and other governmental groups have played a primary role in educating the community and putting funds into sustainable stormwater projects. The coordination among scientists, community groups, state and local government agencies, and municipalities has been a key component of the success in integrating WSUD into standard development practices.

Recommended Actions for Encouraging WSUD

Our analysis of the major impediments to sustainable urban stormwater management and the case studies of regionallysuccessful implementation of WSUD provide several insights that point the way toward practically achieving widespread implementation. We conclude with seven recommended actions that address each of the seven major impediments to sustainable stormwater management (Table 2). The first two actions include fundamental research and development of guidelines which should lay a foundation for the other actions. While not all steps are essential, when used alone or in combination they should move from conventional management toward sustainable, watershed-scale stormwater management.

1. Conduct Research on Costs and Watershed-Scale Performance

Research is particularly needed in the area of costs and benefits of WSUD; we need more on-the-ground data comparing WSUD to conventional approaches. In addition, engineering specifications need to be better linked to ecological objectives, with procedures for incorporating new research results on the effectiveness of WSUD technologies as they become available. We need comprehensive sources of information to compare tools (for different soil types, climatic condition, population densities, etc.) and help guide appropriate local and regional implementation of WSUD. Performance data on WSUD tools should be incorporated into watershed plans using an iterative process, adaptively managing watersheds based on the most up-to-date information. We also need proof-of-concept that WSUD technologies distributed throughout watersheds (in both new development and retrofit contexts) will be sustainable and improve downstream ecosystem quality. To date, there have been no examples of watershed-scale retrofit of stormwater infrastructure, replacing conventional stormwater drainage with WSUD tools (but see Roy and others 2006). While opportunistic implementation may be necessary in the short-term, the effects of scattered WSUD across a large urban area are likely to be undetectable in the receiving water for many years (Walsh and Fletcher 2006). Greater efficiency and learning is likely to be achieved through projects that comprehensively treat subcatchments and can be more easily monitored.

2. Create a Model Ordinance and Promote Guidance Documents

Most existing stormwater regulations mandate performance standards designed to prevent flooding, although more recently developed codes seek to reduce contaminants and slow the release of stormwater as well. A more sustainable alternative is to set a standard that requires maintenance of natural or near-natural hydrologic conditions — for example, by requiring no net increase in runoff volumes or no increase in the frequency of runoff events. Meeting this standard will generally require the use of WSUD approaches, but the standard gives developers and engineers the flexibility to use whatever methods are most suitable to a given site. In fact, such a standard is general enough to be applied virtually anywhere, because it is based on the maintenance of local hydrologic patterns. In the US, this type of performance standard could be incorporated into the model ordinance provided through the NPDES permitting program. These ordinances must be supported by comprehensive engineering guidance manuals and specifications. Best practice guidance documents and information about WSUD tools, which are becoming more widely available, have addressed some of the essential components missing from previous engineering manuals. In Australia, national guidelines have been prepared (ARMCANZ and ANZECC 2000; Engineers Australia 2006) and there is guidance for municipal engineers and others through the recent design manuals (Argue 2004; Melbourne Water 2005). This handbook includes information on design of biofiltration systems, rain gardens, infiltration systems and storage and reuse of stormwater. Similarly in the US, the EPA has been involved with creating multiple resources intended to distribute knowledge of WSUD tools, such as the International Stormwater BMP Database, a literature review about WSUD (US EPA 2000), and a collection of model state stormwater ordinances.

3. Integrate Management Across Levels of Government and the Entire Water Cycle

There are examples where institutions have successfully overcome this fragmented responsibility with at least partial success. In the Etowah Basin in Georgia, a number of counties and municipalities have joined together to develop a watershed-scale management plan focused around stormwater control as part of a program to balance development with protection of endangered species (see Fig. 2). In Melbourne, despite the above-mentioned multi-tiered responsibility for urban stormwater, there are quite strong incentives for collaboration between agencies. For example, Melbourne Water uses funds to help build the capacity of municipalities to deliver improved stormwater management outcomes (Edwards and others 2006). In addition to integration across levels of government, a greater level of communication and integration between stormwater managers, urban designers, stream managers and water supply managers is necessary to integrate management of the entire water cycle. Brisbane City Council nominally has complete control over both stormwater and stream management, and is responsible for both strategic and statutory planning (Lloyd and others 2001b).

It can theoretically use this combined power to provide more efficient and effective management of urban water resources by requiring developers to implement stormwater management works aimed at improved environmental outcomes. While these theoretical advantages do not ensure that strategic directions will always be clear and pursued in a consistent manner, they offer a potential avenue within governments toward achieving sustainability. Integrated management also has greater potential to consider stormwater runoff as a valued resource, not merely a nuisance. Widespread adoption of stormwater harvesting systems (e.g., rainwater tanks, domestic and commercial greywater reuse), in combination with filtering and extended detention (e.g., Pezzaniti and others 2002), has the potential to address a variety of urban water issues (e.g., water supply, flood protection, and stream water quality and quantity).

4. Develop Targeted Workshops to Educate Professionals

As mentioned previously, research on the impacts of and solutions to stormwater management has been essential for creating institutional capacity in Australia. To ensure proper and efficient dissemination of information, workshops led by scientists and engineers should be used to train engineers, planners, and policy makers about the importance of a watershed-scale approach to stormwater management. Such training should include how to prioritize stormwater management within watersheds, the importance of consistent application throughout watersheds, and tools to incentivize runoff mitigation behavior. Then, institutions will be armed with tools to develop policies, guidelines, and programs that will encourage sustainable practices. Educated professionals and appropriate guidelines will form the foundation to generate more funds and personnel to support widespread implementation of WSUD.

5. Use Grassroots Efforts to Garner Support for Ordinances and Regulations

Given existing legal structures, especially private property rights issues, any new legal mandate for stormwater runoff abatement must have wide, public support if it is to succeed. With necessary grassroots support for WSUD, there are several avenues to use regulations to encourage implementation. For example, in the US the federal government could require adoption of a stormwater ordinance that compels the use of WSUD for the approval of local or state-level NPDES stormwater programs under the CWA. Watershed groups and other stakeholders could also encourage local governmental agencies governing a single watershed to adopt consistent ordinances. The Australian government has recently established an inter-governmental committee for "Water Sensitive Cities" to provide strategic guidance on how to best advance WSUD practices, which may bring about some federal oversight. At the state level, there is good potential for future regulatory oversight in Australia. For example, recent regulatory reforms in Victoria mandate all new developments to meet best practices WSUD techniques to conserve, reuse, and recycle water and manage the quality of stormwater runoff (DSE 2006). Such reforms are unprecedented, and largely brought on by recent drought conditions and the public support (or lack of resistance) generated by concerns over water supply.

6. Address Hurdles in Market Approaches to Provide Funding Mechanisms

If fee and rebate approaches are to be successful, the rebate amount must be high enough to encourage runoff-mitigating behavior, and the fee has to be high enough to permit such rebates. Further, the fee (and therefore rebate) should be tied explicitly with the runoff volume from a property. While it has been cost-prohibitive to do this in the past, recent improvements in GIS capability and hydrologic modeling have made it possible for municipalities to determine parcel level runoff and deal with a more complex fee structure. As an alternative to fee and rebate, stormwater trading may prove a successful market mechanism if management can be considered at a watershed scale, and if there is legal precedent for setting a watershed-level cap on runoff. The US EPA's *Draft Framework for Watershed-Based Trading* (1996a) provides guidance for tradable allowance programs for reducing concentrations of nutrients or toxics, and may invoke watershed-scale stormwater trading programs. In Australia, Melbourne Water has also recently introduced a stormwater offsets program (RossRakesh and others 2006).

Lastly, an approach which has recently been promoted due to the lack of legal hurdles is a voluntary auction (Parikh and others 2005). Auctions are designed to compensate residents for adopting WSUD on their property. Participants who wish to adopt WSUD tools submit bids that consist of the size and type of the WSUD and the minimum compensation that they require. Bids are then ranked according to cost and potential environmental benefit, and the most cost effective are selected for funding until the funds are exhausted or the reserve price is reached. This is the market mechanism employed in the Shepherd Creek Pilot project (Roy and others 2006). The US Department of Agriculture in its Conservation Reserve Program, the World Resources Institute in the Conestoga project (Greenhalgh and others 2007), and the Onkaparinga Catchment's "Catchment Care" (Bryan and others 2005), while not exclusively focused on stormwater, also employ a reverse auction and provide precedence for this market mechanism.

7. Educate and Engage the Community Through Demonstrations

While there is widespread skepticism surrounding new technologies, progressive US cities such as Portland, Seattle, and Milwaukee have demonstrated that pubic engagement and awareness can lead to widespread support for WSUD. In Australia, the drought in recent years and growing concerns for the security of water supplies as a result of climate change (Pittock 2003) has increased public awareness and acceptability of WSUD. Other mutual benefits for communities, such as the potential for substantially improved social amenity and land value through the integration of WSUD technologies within the urban landscape, may increase public acceptance. Lloyd and others (2002) report on a survey of 300 householders and prospective buyers at one of the first, large-scale WSUD demonstrations (Lynbrook Estate in Melbourne). They showed that in excess of 90% of respondents were supportive of the incorporation of at-source treatment systems (such as biofiltration systems) into the streetscape. Most (>66%) found them to be attractive. Other studies have also showed significant landscape amenity benefits through the incorporation of WSUD (Eadie 2002; Mongard 2002). Major land developers have also reported that the incorporation of WSUD can increase the market value of developments (Lloyd and others 2002; Brown and Clarke 2007). We need to use demonstrations and the media to increase public awareness and reduce any skepticism or resistance to WSUD.

It is important to emphasize the interactions among the solutions, such that overcoming one impediment can actually encourage WSUD implementation in a variety of ways. For example, implementation of market incentives can reduce public resistance to WSUD, and also provide funding to increase institutional capacity. Research and appropriate guidance documents can generate increased support from managers and push legal mandates. Community support and engagement, in turn, can feed a sustainability vision and inspire local champions to push for watershed-scale management (Brown and others 2006b). For example, in Melbourne, the activism of community groups in attempting to protect and restore the Yarra River has provided an impetus to which the government and its agencies began to respond (Brown and Clarke 2007). Finally, as more WSUD are implemented, costs of WSUD will go down, and institutions and the public will likely be more receptive to sustainable, stormwater management.

Conclusion

To protect both human health and infrastructure and natural ecosystems in this urbanizing world, we need to make drastic changes in how we manage stormwater, emphasizing source-control stormwater management technologies distributed throughout watersheds. We acknowledge that every location is different, and source-control approaches may take different pathways depending on local guidelines, concerns, stakeholders, and champions. We emphasize that a legal framework is not necessary, but overcoming institutional discrepancies and formulating an integrated approach to water management are essential for laying the foundation for watershed-scale management. Furthermore, we strongly believe that experimental manipulation at the watershed scale, where the relative effectiveness of different WSUD approaches are compared in adjacent small watersheds, coupled with adaptive management, is critical to advance research and develop appropriate guidelines for stream restoration and protection. So far, in Australia, management agencies have been reluctant to focus funds on priority catchments, and the short timeframes of research projects preclude whole-of-catchment approaches (Brown 2005). Securing sufficient funding to ensure tangible ecological outcomes in a single watershed will help not only to demonstrate the benefits of WSUD, but also to gain community and political support for widespread implementation. Fortunately, we already have many of the technologies to address the problem of stormwater runoff; it is now time to use this knowledge to move toward environmental sustainability.

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