

# RAINWATER MANAGEMENT TO MITIGATE THE EFFECTS OF DEVELOPMENT ON THE URBAN HYDROLOGIC CYCLE

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## INTRODUCTION

*Traditional stormwater management approaches that rely on rapid conveyance and end-of-pipe detention have not adequately mitigated the effects of urbanization on water resources and the aquatic and human communities that rely upon them. Low-impact development techniques that can support a shift to management of the post-development hydrologic cycle and runoff volumes offer better opportunities to prevent stream erosion and protect groundwater recharge, characteristics of the flow regime and water quality. The application and design of four techniques—porous pavement, bioretention cells, green roofs and rainwater harvesting—in the management of the post-development water balance are presented.*

## BACKGROUND

### Hydrological Effects of Urbanization

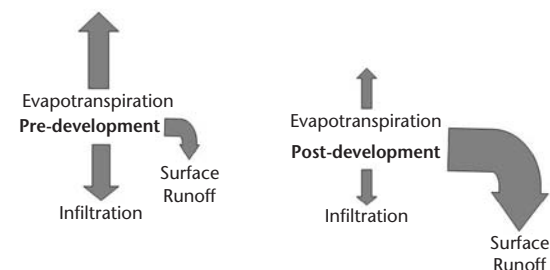
Urban development alters the local hydrologic cycle and has serious consequences for aquatic ecosystems. With site clearing and grading, vegetation that previously intercepted rainfall and the natural depressions that acted as temporary storage are lost and, ultimately, native soils are compacted. The water intercepted by these features is no longer available to be taken up by vegetation and transpired or to infiltrate thereby recharging aquifers and slowly draining to streams. Impervious surfaces such as roads, driveways, parking lots, and roof tops further decrease the amount of rainfall that infiltrates into the ground and increase the volume of stormwater runoff. Impervious surfaces, in conjunction with drainage networks, speed the delivery of runoff to streams.

Figure 1 shows typical changes in the components of the water budget resulting from these alterations to the local hydrologic cycle: decreased evapotranspiration and infiltration, increased surface runoff, and reduced storage capacity. Figure 2 depicts changes in stream response that may be expected after development: a greater volume of runoff, higher peak flows, and an earlier and flashier response. Some of the hydrologic effects are consistent between urban areas, whereas others may vary with climatic and geologic differences as well as variation in urban activities. Streams in arid areas that naturally exhibit rapid rise

and recession of stormflow may not become more “flashy” in response to urbanization (Konrad and Booth 2005). Baseflow, which sustains streamflow between storms, may decrease in response to reduced infiltration and recharge to the groundwater system. However, inputs to the urban water budget besides precipitation, such as leaking water mains and landscape irrigation, can result in increased groundwater recharge and baseflow in some areas.

The increased volume and peak flow of runoff from storm events results in increased flood magnitude and frequency of high flow events. More frequent flows with the capacity to erode stream beds and banks result in unstable stream channels, alterations to the physical habitat of aquatic biota (Figure 3), and loss of hydraulic connection with riparian vegetation. These flows also cause hydraulic distur-

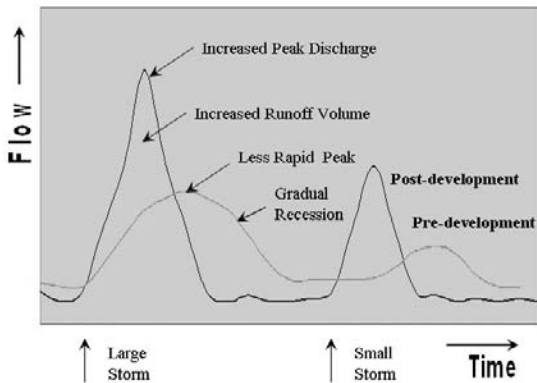
**FIGURE 1.** Changes to components of the water budget resulting from urbanization.



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**FIGURE 2.** Streamflow hydrograph changes resulting from urbanization.



bance to biota and can modify the trophic structure of streams by reducing the retention of nutrients and organic matter (Konrad and Booth 2005). Increased high flow frequency can result in shorter periods between disturbances and affect the reproduction and growth cycles of aquatic organisms that are tied to stable flow periods (Konrad and Booth 2005).

There is a redistribution of runoff from periods of baseflow to periods of stormflow. This results in short periods when hydraulic conditions, nutrient transport, and amount of habitat are favourable and extended periods of time when these conditions are unfavourable (Konrad and Booth 2005). There may be increased daily variation in streamflow, reducing

**FIGURE 3.** Stream erosion and alteration of physical habitat resulting from urbanization. (Photo courtesy of Parish Geomorphic Ltd.)



the time that a particular location has suitable conditions and causing organisms to expend energy in moving to find suitable habitat. Stormflow occurs more frequently; smaller storm events occurring under dry conditions produce runoff more often after urbanization. Runoff events transport contaminants, such as lawn fertilizers, residues from tires, and road salt, which accumulate on impervious surfaces between storms, to receiving streams, impacting their water and sediment quality. Heat also builds up on urban surfaces and is transferred to receiving waters by runoff events (Walsh et al. 2005). Stream temperature increases in the warm season can be exacerbated by reduced baseflow from groundwater discharge.

These changes in hydrology, stream form, temperature regime, and water and sediment quality adversely affect biological communities. There is a consistent decrease in biotic richness and increase in dominance of tolerant species in urban streams (Walsh et al. 2005). It is the challenge of stormwater management to mitigate these effects on aquatic ecosystems, as well as to prevent an increased risk of flooding, loss of property, and damage to infrastructure associated with channel enlargement.

### ***Approaches to Rainwater Management***

Traditional stormwater management, that focuses on rapid conveyance and detention at the end of the pipe, does not achieve the level of watershed management we now realize is necessary to protect hydrologic functions. Wet ponds, for example, are often designed to store runoff and release it slowly enough to prevent post-development peak flows from exceeding those that occurred before development in response to relatively large (infrequent) storm events. This focus on flood control failed to protect biological systems because “single-storm peak discharge is not a hydrologic characteristic of particular significance to biota” (Konrad and Booth 2005).

The approach actually aggravated stream erosion problems because it extended the duration of flows above the critical threshold at which channel materials can be entrained. Advances to pond design have been implemented that account for the susceptibility of channel boundary materials to erosion and that reduce runoff release rates below the critical threshold for entrainment of the mean particle size fraction.

But regardless of increasingly conservative design criteria, end-of-pipe detention ponds have proven inadequate in the control of channel erosion (Aquafor Beech (2006) review of the mechanisms contributing to the unsatisfactory performance of detention ponds and the associated ecological consequences.)

Water detained in ponds can warm up, thereby compounding stream temperature problems. Well-designed ponds can effectively remove a significant proportion of suspended solids, but are less effective in removing soluble contaminants and fine sediments (and the substantial portion of contaminants, which may be associated with this size fraction). End-of-pipe systems like ponds are not effective in replicating the distributed groundwater recharge that is characteristic of many areas under pre-development conditions and do not address the increased frequency of overland flow (Walsh et al. 2005).

A shift is needed to volume-based management (matching post-development components of the water balance to pre-development levels, rather than matching peak flows). More effective management of rainwater at the lot and development site level will help in managing groundwater recharge, characteristics of the flow regime, stream erosion, and water quality. Restoration of the water storage capacity, which was distributed throughout the watershed but lost with urbanization, is needed to address the multitude of ecologically relevant changes in streamflow patterns (Konrad and Booth 2005).

A group of techniques, collectively referred to as Low-Impact Development (LID), aim to protect natural areas for the water quality and quantity functions they provide, use rainwater as a resource, and support the shift to management of the post-development water balance. They include both planning techniques such as alternative development layout, narrower and curbless roads, impervious area disconnection, and engineering techniques such as bioretention and permeable pavement. Distributed LID measures intercept rainfall and facilitate its infiltration, evapotranspiration, and slow release in an effort to reproduce the rates and processes of the pre-development hydrologic regime.

In built-up areas, distributed LID measures can reduce pressure on aging stormwater infrastructure and combined sewer systems, thereby deferring the costs of infrastructure repair and replacement. In

new developments, these measures can reduce the size of stormwater conveyance systems and land-intensive, end-of-pipe facilities, and the costs associated with this infrastructure. The need for costly treatments for residual effects and downstream symptoms, such as stream degradation, should be greatly reduced.

### ***Low-Impact Development Techniques***

LID planning techniques are important tools to reduce both the total and effective impervious area within a watershed. The effective impervious area includes impervious surfaces, which are directly connected to the “rapid” stormwater conveyance system. It may be reduced by disconnecting impervious surfaces, such as rooftops, and directing the runoff to pervious areas. The Centre for Watershed Protection (1999) provides numerous planning techniques to reduce the total impervious cover associated with “car habitat.”

- Avoid excessively wide streets.
- Reduce street length using alternative site layouts, smaller lot sizes, and reduced side yard setbacks.
- Relax front yard setbacks to reduce driveway lengths.
- Minimize use of cul-de-sacs and incorporate landscaped areas in the middle of cul-de-sacs.
- Consider sidewalks on only one side of the street.
- Lower parking ratios and encourage shared parking for adjacent land uses that have peak parking demands at different times of the week.
- Consider structured parking or alternative parking lot design that, for example, includes compact car spaces.

Local ordinance and subdivision codes may not allow for the use of some LID techniques, but many areas are developing alternative development standards to facilitate their implementation.

This paper introduces four engineering techniques for rainwater management that can contribute to the achievement of matching pre-development runoff volumes. Porous pavement, bioretention areas, green roofs, and rainwater harvesting promote storage, infiltration, and/or evapotranspiration. This paper emphasizes the management of relatively clean rainwater near its source. There are additional considerations associated with the management of more contaminated

stormwater runoff, such as that from industrial areas or vehicle maintenance yards, which are not discussed in this paper.

Hydrologic modeling on a subwatershed scale is often undertaken by local authorities to identify stormwater management objectives. A combination of techniques is typically needed to meet the multiple objectives of stormwater management. Porous pavement, bioretention, green roofs, and rainwater harvesting are most effective in managing small storm hydrology. Small events occur more frequently and play an important role in replenishing soil moisture, recharging groundwater, and maintaining baseflow characteristics. They also transport a much greater proportion of the annual load (mass) of contaminants than do large, infrequent events. Hence, the storage and control of runoff volumes from relatively small events can have important long-term hydrologic benefits. The magnitude of a storm event (i.e., rainfall depth), which must be captured to manage a certain proportion of the average annual runoff, can be determined for different geographic areas. For example, Claytor and Schueler (1996) cite the “1 inch rule”; for areas in the Chesapeake Bay Watershed, capture of runoff from all events up to 25.4 mm (1 in.) as well as capture of the first 25.4 mm (1 in.) of larger rainfall events is equivalent to managing about 90% of the average annual runoff.

It will also be necessary to mitigate the effects of large storms. The storage capacities of the low-impact development techniques described here contribute towards reducing the size of end-of-pipe detention facilities. In some cases, it may be possible to increase the storage capacities of low-impact techniques (e.g., use larger tanks in rainwater harvesting system) to manage runoff from large events, but this is often not cost-effective. In the case of other LID techniques, such as bioretention cells, it is preferable to bypass storm volumes in excess of the design volume to avoid damage.

The combination (and extent of implementation) of LID practices needed to achieve water balance objectives will vary from area to area. When considering the objective of matching pre-development water balance, effects of urbanization beyond the site or development scale, such as groundwater abstractions or inputs (e.g., a leaking infrastructure), must be considered. Subwatershed scale hydrologic models are help-

ful in assessing the integrated effects of development and various rainwater management techniques. They can help in the identification of the best combination of LID practices to achieve water balance objectives and assessment of the degree to which these techniques contribute to achievement of other stormwater objectives, such as flood risk management.

## **POROUS PAVEMENT**

### ***Function and Applications***

Porous paving systems include porous asphalt and concrete, which are produced with reduced or eliminated fine material, and pre-cast concrete blocks or plastic grids, which have joints or openings that are filled with permeable materials. They may be applied in driveways, pedestrian walkways, bike trails, parking lots, and residential access roads (with low to moderate traffic loads). Ferguson (2005) describes the advantages, disadvantages, and appropriate applications for various types of porous pavement systems. Appropriate paving materials and configurations can be determined based on the type and frequency of traffic in various areas.

This discussion will focus on permeable interlocking concrete pavement systems (Figure 4). Interlocking concrete pavers provide for infiltration of a large proportion of the precipitation that falls on their surface. An aggregate base functions as a reservoir that temporarily stores water until it infiltrates into the underlying soil or collects in under-drains, which transfer the water to a conveyance system. Therefore, these systems provide detention storage, and, unless design prevents it, infiltration. They are an important low-impact development technique since pavement accounts for about two-thirds of the impervious cover in areas with single-family residential, multi-family residential, and commercial land uses (Ferguson 2005). Porous pavement promotes tree survival by providing water and air to root systems, supporting the benefits that trees provide in maintaining the urban hydrologic cycle. It also provides an environment in which many stormwater pollutants may be filtered and biodegraded. Porous pavement systems manage rainwater at its source, reducing or eliminating symptoms that must be managed downstream.

Permeable paving materials are not recommended for applications where excessive sediment may be de-

**FIGURE 4.** Permeable pavement installation at Seneca College, King Campus, Ontario. (Photo courtesy of Toronto and Region Conservation Authority.)



posited on the surface or transferred from adjacent areas, where there is an elevated risk of chemical spills (Hinman 2005), or where traffic loading is too great. Site conditions that could constrain the use of permeable pavement (or require an impermeable geomembrane that prevents infiltration) also include contaminated soils from which pollutants could be leached (Ferguson 2005) or seasonally high groundwater levels that could prolong saturation within the system. The surface relief associated with interlocking concrete pavements may pose some challenges related to accessibility, particularly for disabled persons (Hinman 2005). High slopes increase surface and subsurface flow velocities and will reduce the storage and infiltration capacity of systems unless extra design features are included. Provisions are needed to ensure regular maintenance and to prevent undesirable activities by property owners. Sand should not be applied for winter maintenance.

### Components

**Paving Blocks.** “Open-jointed” interlocking concrete paving blocks (Figure 5) are those with indented edges, integral spacers, or laying patterns that provide open areas between adjacent blocks, while other parts of the blocks are in contact for structural

interlock (Ferguson 2005). The variety of colours and shapes available allow the pavement’s appearance to be customized for particular sites. Concrete paving blocks conforming to ASTM C 936 “Standard Specification for Solid Concrete Interlocking Paving Units” are strong and durable.

The block shape and dimensional proportions contribute to the degree of interlock. Complex block shapes and narrow joints on many sides provide for interlock in multiple directions (Ferguson 2005). ASTM C 936 restricts the size of a block’s exposed face to no more than  $650 \text{ cm}^2$  ( $100 \text{ in}^2$ ) and the length to no more than 4 times the thickness. Resistance to vertical deformation increases notably with an increase in block thickness from 6 to 8 cm (with little additional resistance produced with further increases in thickness (Ferguson 2005)). As such, 6 cm (2-3/8 in.) and 8 cm (3-1/8 in.) thick blocks are appropriate for pedestrian and moderate vehicular traffic, respectively.

Ferguson (2005) suggests that openings at least 6 mm (1/4 in.) wide are needed to contribute significantly to the porosity and permeability of the pavement. He lists various companies that produce interlocking concrete blocks.

**Joint Fill Material.** Joint fill material must be durable, angular, and for high infiltration capacity, open-graded (Figure 5). It may be the same aggregate used in the bedding layer. ASTM No. 8 (2 to 10 mm, 0.1 to 0.4 in.) is capable of producing high infiltration

**FIGURE 5.** Interlocking concrete paving blocks. (Photo courtesy of Toronto and Region Conservation Authority.)



rates. However, a smaller particle size (e.g., 2/5 mm or 0.08 to 0.2 in. (Ferguson 2005) or ASTM No. 89 (Smith 2006)) may need to be used with blocks that have some narrow joints. Blends of larger and smaller aggregate sizes improve neither structural interlock nor infiltration rate (Ferguson 2005). Although contractors may be accustomed to using concrete sand, kiln dried jointing sand, and other products with a high content of fine particles for tight-jointed pavements, its use is inappropriate for permeable pavement. Care must be taken to ensure that only the specified open-graded aggregate is used to fill joints. It is also absolutely essential to ensure that sediment generated during the construction phase is prevented from entering the pavement surface and base reservoir.

Joint fill material may be subject to clogging as a result of the settling of aggregate and the accumulation of particles generated in-place and transported in by runoff. Regular cleaning (vacuuming of deposited sediment and detritus at least twice a year) to prevent deep clogging is critical. Areas at the upstream end of the drainage area with low traffic may be subject to less clogging. Areas in the middle of the drainage path with intermediate traffic levels may benefit most from occasional restoration of the infiltration rate. This may be accomplished by removing about 13 mm (0.5 in.) of joint fill using a vacuum sweeper and replacing it with new, clean, open-graded aggregate (James and Gerrits 2003). This process may not be effective in areas where drainage accumulates or where there is more traffic and deep clogging has occurred. Blocks may be lifted out and reset with new joint fill as a last resort to restore infiltration rates.

**Bedding Layer.** The bedding layer allows blocks to be placed and leveled. A gradation may be selected relative to the base layer such that a geotextile is not necessary (e.g., ASTM No. 8 over No. 57 (Smith 2006)). On an open-graded base, 25 mm (1 in.) of the bedding material is commonly compacted into the base's large voids and another 25 mm is spread, without compaction, as the bedding layer (Ferguson 2005). The thickness of the bedding layer is minimized to reduce susceptibility to vertical deformation.

**Edge Restraint.** Interlocking concrete pavement requires edge restraint to resist the lateral deformation

of the flexible material at its edges, which would be caused by the traffic load. Smith (2006) recommends cast-in-place or precast concrete curbs at least 150 mm (6 in.) wide and 300 mm (12 in.) deep. Plastic edge restraints held in place by spikes are not recommended for commercial and municipal applications. Raised curbs, typically about 150 mm (6 in.) above the surrounding pavement, have the benefit of physically confining traffic, but may be an obstacle for pedestrian access. Curbs constructed flush with the surrounding pavement allow for free drainage of overflows and debris, which could otherwise accumulate on the surface and contribute to clogging. Snow may also be pushed freely over flush curbs (Ferguson 2005). A supplement to structural edge restraints are physical or visual controls, such as wheel stops, bollards or vegetation, that keep vehicles away from pavement edges.

Curbs are often installed and then the paving units are laid between them. Blocks are placed individually by hand or in groups by specialized equipment. The joint fill material is spread into joints, and the block surface is vibrated with a plate compactor to seat the blocks, bedding, and joint fill into level position (Smith 2006). A slight slope in the block pavement surface reduces accumulation of debris that may contribute to clogging and allows overflows to discharge at the pavement's edge. Limiting the slope to no more than a few percent will promote infiltration of most rain and snowmelt and prevent the aggregate filling joints from washing out (Ferguson 2005).

**Base Course/Base Reservoir.** The base course builds up the thickness of the pavement in order to adequately distribute the traffic load over the subgrade and protect the pavement from the effects of frost. In a porous pavement that has to meet specific stormwater management objectives, the thickness of the base reservoir must also provide adequate capacity for water storage. Thicknesses required to distribute traffic loads and address the effects of frost will not be discussed here. However, it should be noted that porous pavements (unless designed with an impermeable geomembrane) admit water into the subgrade, affecting its moisture content and the load that it may bear (Ferguson 2005). The affect that the presence of water has on the strength of reservoir materials should

also be considered. Design adaptations (such as geotextiles or even geomembranes) may be needed for special subgrade conditions (Ferguson 2006). Ferguson (2006) also discusses design adaptations to prevent undesirable effects due to frost heaving.

The base reservoir provides most of the water storage capacity that is needed when rain and snowmelt quickly infiltrate the surface layer and only slowly exit by means of infiltration into the subgrade and/or outflow through a drainage pipe. The base aggregate is installed and compacted in lifts. Opengraded aggregate (e.g., ASTM No. 57 [Hinman 2005]) is used because aggregate of a single size has a high porosity, typically 30–40%. The percentage of the material's volume that is void space increases from about 30% for single-sized rounded particles to about 40% for single-sized angular particles (Ferguson 2005).

Depending upon the slope of the bottom of the reservoir and the location and size of outlet, not all of the base course may provide effective storage capacity. Consideration must be given to the position that the surface of stored water will take. Water stored only at the downstream end of a sloping reservoir also reduces the contact area with the subgrade through which infiltration may occur. On a sloping site, the subgrade can be terraced to obtain a flatter reservoir (Ferguson 2005) or baffles may be placed on the subgrade to restrict downslope flow (Hinman 2005).

**Drainage Pipe/Outlet.** A pipe or outlet is intended to discharge excess water from the base reservoir safely and to limit the depth and duration of ponding above it. An outlet at the bottom of the reservoir provides lateral drainage of all the water, reducing the opportunity for infiltration to the subgrade (Ferguson 2005). An outlet above the bottom of the reservoir will discharge when the storage capacity of the portion of the reservoir below the outlet and the infiltration capacity of the subgrade are exceeded. The portion of the reservoir below the outlet retains water for infiltration into the subgrade. If the capacity of the outlet is exceeded and the structure is completely saturated, the system will overflow at the surface. There should be provision for an overflow area or a drainage swale adjacent to the pavement area to handle overflows from heavy rainstorms (Smith 2006).

Smith (2006) recommends that a 150 mm (6 in.) diameter vertical perforated pipe be installed at the downslope end of all pavements as an observation well.

**Subgrade.** Subgrade preparation should assume saturated conditions. Subgrade compaction specifications are based on the strength and hydraulic conductivity characteristics needed for a particular project. Compaction is often required, and the associated reduction in infiltration rate must be accepted. In some porous pavement installations, increased pavement thickness has been specified to compensate for an uncompacted subgrade with better infiltration capacity. In these installations, the excavated surface is meticulously protected during construction to preserve its hydraulic conductivity. The subgrade under a curb's concrete footing should be compacted, even if the subgrade under the adjacent base reservoir is not compacted (Ferguson 2005).

**Sizing.** The required storage volume of the reservoir may be determined as the difference between the volumes of water entering and exiting the reservoir during the period of time when the inflow exceeds the outflow. The inflow volume is the sum of the runoff volume from adjacent contributing areas and the rainfall volume contributed directly to the pavement surface. The outflow volume is the sum of the outflow volumes exiting via the drainage pipe and infiltration into the subgrade. Assuming that the pavement does not receive any runoff from adjacent areas and drains only through infiltration to the subgrade, the storage volume needed would be:

$$V = P(A_p) - i(T)(A_p)$$

where  $P$  is the rainfall depth for the design storm event;  $A_p$  is the surface area of the pavement;  $i$  is the expected long-term infiltration rate for the subgrade in its compacted condition; and  $T$  is the filling time. Any consistent units for length and time may be used. The required volume of the reservoir ( $V_r$ ), which is equal to its surface area times its depth ( $d_p$ ), can be determined by dividing the volume of water to be stored by the porosity of the aggregate in the base reservoir ( $n$ ). Substituting  $n(A_p)(d_p)$  for the water volume in the above equation and rearranging

yields the following equation for the required storage depth in the reservoir:

$$d_p = [P - (i)(T)]/n$$

Drawdown time is the time it takes the filled reservoir to drain by means of infiltration into the underlying subgrade and/or outflow through the perforated outlet pipe. It is necessary to limit drawdown time to restore storage capacity for a subsequent event, to aerate the reservoir and subgrade for biodegradation, and reduce potential for frost heaving (Ferguson 2005). Shorter times are better to minimize saturated and weak subgrade conditions (Smith 2006). Maximum drawdown times of 1 to 3 days are common; however, different values may be used in some areas depending on the typical inter-event times.

If infiltration into the subgrade is the only outflow, the maximum allowable depth of the reservoir to meet the required drawdown time ( $t_d$ ) can be determined as:

$$d_{\max} = [i(t_d)]/n$$

It is also necessary to check that the required separation distance between the seasonally high ground water table and the bottom of the system is met. Smith (2006) provides a worked example using this approach and further details. Reservoir routing may be used to model storage and discharge during a storm event given the characteristics of the reservoir and outlets (Ferguson 2006).

### **Performance**

Ferguson (2005) provides numerous case studies that include both successful porous pavement installations and examples from which lessons about design, construction, and maintenance may be learned. He also summarizes a multitude of studies that have assessed the performance of porous pavement relative to hydrologic and water quality objectives.

## **GREEN ROOFS**

### **Function and Applications**

Extensive green roofs, which will be the focus here, have a relatively thin soil layer (2.5 to 15 cm or 1 to 6 in.) and are planted with species that are tolerant of harsh rooftop conditions and require little maintenance.

In contrast, intensive green roofs have a deeper soil layer and as such can be planted with a wider range of species including shrubs and trees. These rooftop gardens may be accessible green spaces but generally require more effort to maintain.

Green roofs offer a host of benefits including energy efficiency, moderation of the urban heat island effect, improved air quality, and other amenities associated with urban green spaces. Most relevant to this article is the role that green roofs can play in mitigating the effects of urbanization on the hydrologic cycle.

A portion of the rainfall intercepted by green roofs is stored and returned to the atmosphere through evapotranspiration (i.e., a portion is retained). The proportion of average annual rainfall that can be retained by green roofs depends upon the thickness and type of growth medium as well as the rainfall volume, intensity, and distribution through the year.

The portion of rainfall that is not retained by the green roof system becomes runoff, but drainage from the rooftop is delayed. If green roofs are implemented on enough rooftops, this can contribute to a reduction in peak flows. Green roofs are a particularly important low-impact development technique in intensively built-up areas where roofs account for a greater proportion of the impervious area and where there is little area available for implementation of other techniques. Green roofs also have the ability to filter particulate and numerous contaminants from rainwater. However, nutrients from fertilizers and organic matter in the growth media may be leached by rainwater.

Office buildings, malls, recreation centres, churches, schools, and other buildings with a large roof area are potential applications for green roofs (Figures 6 and 7). Manufacturers have greatly improved the quality of waterproofing membranes such that, with provision for careful quality control during the waterproofing stage, concern about leaks should no longer be a limitation. Load restrictions are usually the main limitation, particularly in retrofits. Structural analysis is necessary for all retrofit installations to determine the load-carrying capacity and therefore the allowable thickness of the growing media. In new construction, structural consideration should be given to allow for flexibility in design parameters



**FIGURE 6.** Extensive green roof at York University, Toronto, Ontario. (Photo courtesy of Toronto and Region Conservation Authority.)



(Banting et al. 2005). Although this may introduce extra cost to the building construction, it is often determined to be worthwhile given the reduced building cooling costs and other benefits associated with green roofs.

Green roof systems can be applied on roof slopes up to 40 degrees (Scholtz-Barth 2001), although on roofs with slopes greater than 20 degrees, a support grid system is needed to hold the substrate and vegetation layers in place (Peck and Kuhn 2002). Several studies have shown that slope (between 2 and 10%) has little effect on stormwater retention (Banting et al. 2005; VanWoert et al. 2005).

**FIGURE 7.** Extensive green roof with 10% slope at York University. (Photo courtesy of Toronto and Region Conservation Authority.)



## Components

There are several categories of green roof systems (Banting et al. 2005):

- Complete systems: all components are specific and integral to the design.
- Modular systems: pre-vegetated containers positioned above the existing roof.
- Pre-cultivated vegetative blankets: rolled onto existing roofs (additional barriers may be required).

The components vary between types of systems and may influence their effectiveness for rainwater management. Some systems have highly specialized components, and the product specifications of manufacturers should be consulted. Banting et al. (2005) list a number of commercial green roof systems. There are several common components to green roof designs: waterproof membrane and root barrier; drainage layer, growth medium and vegetation, in addition to the structural and insulation components of the rooftop.

**Waterproof Membrane and Root Barrier.** These seal the roof against moisture penetration and roots. Reinforced PVC (60 to 80-mil) with heat sealed seams is an example of a durable and waterproof membrane (Hinman 2005). Scholtz-Barth (2001) provides alternative waterproofing materials. The root barrier is critical in the case of roofing materials containing bitumen (or other organic materials), which may be a food source for plants and other organisms. Some of the new membranes developed for green roof applications are still bituminous but contain a root-detering chemical or another feature to prevent root damage (Peck and Kuhn 2002).

**Drainage Layer.** The drainage layer is important to ensure that the growth medium is not subject to prolonged saturation and to prevent leakage of the membrane through continuous contact with water or saturated medium (Peck and Kuhn 2002). It consists of aggregate or a manufactured product with channels that convey water to roof edges and drains at a controlled rate. Some products also have built in water reservoirs. Peck and Kuhn (2002) stress that "Parapets, edges, flashing, and roof penetrations made by skylights, mechanical systems, vents, and chimneys must be well protected with a gravel skirt

and sometimes a weeping drain pipe.” TRCA (2006) also cautions that building materials used in such structures should be protected with appropriate waterproofing to prevent leaching of constituents. For flatter roofs (<5 degrees), the drainage layer is essential to drain excess water away from the root zone (Scholz-Barth 2001). It is important to ensure that roof drains remain unobstructed. However, where feasible, flow restrictors may be considered to further attenuate flood peaks (TRCA 2006).

**Growth Medium.** The growth medium must support a healthy vegetative cover and achieve water infiltration and storage objectives. Substrate choice must consider the structural load for which the building was designed. Light-weight media typically have a high ratio of mineral to organic materials and may include gravel, sand, pumice, expanded slate, perlite, compost, and soil (Hinman 2005; Peck and Kuhn 2002; VanWoert et al. 2005). Mulch should be avoided; moisture control on a green roof is accomplished through proper design of the growth medium (Hinman 2005). TRCA (2006) identified 11 different commercially available growing media and tested the quality of leachate from each of these materials. Growing media with chemical fertilizers should be avoided. Increasing depth of growth media effectively increases the retention capacity of the green roof system (VanWoert et al. 2005). Water retention fabrics are also available that can enhance water holding capacity.

**Vegetation.** Vegetation must be adapted to the extreme conditions experienced on rooftops: thin soils, seasonally low water availability, high winds, and strong sun exposure. Mixtures of grasses, mosses, sedums, sempervivums, festucas, and wildflowers—plants that are native to drylands, tundras, alvars, and alpine slopes—are commonly used on extensive green roofs (Peck and Kuhn 2002). A diversity of species that can take advantage of seasonally wet and dry periods can be planted using vegetated mats, plant plugs, cuttings, or seeding. Extensive green roofs should be designed such that fertilization is not required after plant establishment as it may contribute to nutrient loads in runoff. Similarly, irrigation should only be required during plant establishment and, possibly, drought periods.

FLL (1995), available in an English version, can provide more detailed information on the design of green roof systems.

### **Performance**

Green roofs are more widely used in Europe. In Germany, an estimated 14% of all flat roofs are green (VanWoert et al. 2005). European research has consistently shown that green roofs can reduce annual rooftop runoff by 50% (Hinman 2005). Performance results are difficult to summarize due to the effects of climatic variability as well as design. Banting et al. (2005) cite a variety of studies that have investigated the performance of green roofs relative to rainwater management objectives, including their effectiveness for water quality improvement. Green roofs are more effective for short duration storm events (Hinman 2005) and are able to retain a greater proportion of rainwater during summer months (Banting et al. 2005). Green roofs can retain a greater proportion of rainwater in areas with lower annual precipitation and are more effective in drier years (B.C. 2002). Retention during individual storms is reduced by wet antecedent moisture conditions. VanWoert et al. (2005) used experimental roof platforms to investigate the effects of roof slope and media depth on stormwater retention.

## **BIORETENTION**

### **Functions and Applications**

Bioretention systems are vegetated, shallow depressions (Figure 8). Below the surface an engineered soil mix is used which supports plant and microbial growth, and stormwater quality and quantity control objectives. Bioretention takes advantage of the chemical, biological, and physical properties of plants, microbes, and soils to remove pollutants from stormwater runoff. It blends stormwater management function with a landscaped aesthetic. Hinman (2005) distinguishes between bioretention cells and bioretention swales. Bioretention cells, which will be the focus of this paper, may or may not have an under-drain but are not designed as a conveyance system. In contrast, bioretention swales are designed as part of a conveyance system.

Bioretention cells may be used to manage residential site runoff as well as parking lot and rooftop

**FIGURE 8.** Established bioretention cell, Milton, Ontario. (Photo courtesy of Fernridge Landscaping and Athyriumimages.)



runoff from commercial sites. They can be located within parking lot islands and cul-de-sacs and may be used in conjunction with roadside swales. Space constraints limit their use in ultra-urban developments (less than 5% pervious area). A minimum separation distance is needed between the seasonally high groundwater level and the bottom of the bioretention system. Their use may be restricted where groundwater contamination risks are high. Where the surrounding native soils have inadequate infiltration capacity, underdrains that direct water to the stormwater conveyance system or a receiving water, can be incorporated into the design. An underdrained system provides treatment of stormwater pollutants and flow detention, but reduced flow control benefits (Hinman 2005).

### Components

**Pretreatment.** Stormwater from impervious surfaces should be directed to the bioretention system through a pretreatment component, such as a vegetated filter strip, to extend the design life of the system. The filter strip slows the runoff facilitating the removal of coarse sediment and reducing erosion potential. Pretreatment measures that promote dispersed, sheet flow are preferred as they reduce disruption of the mulch layer and vegetation. Filter strip length will vary as a function of approach length, land use, and slope (Claytor and Schueler 1996). Where concentrated flows enter a bioretention

system (e.g., at curb cuts or pipe discharges), energy dissipation/erosion protection measures (e.g., rock pads) are used (Hinman 2005).

**Ponding Area.** Bioretention systems are contoured to allow for a shallow ponding area, just above the mulch layer, that provides surface storage and increases the amount of runoff that can be treated. Ponding depth is controlled by the hydraulic conductivity of the bioretention media and the native sub-soil (where there is no underdrain). A maximum ponding depth of 150 mm (6 in.) is recommended, which should drain in 3–4 hours (Claytor and Schueler 1996; PGC 2002). Moderate dewatering times are necessary to prevent stagnant standing water (i.e., provide mosquito control) and prolonged inundation of plants.

**Mulch Layer.** The mulch layer acts as a filter for suspended particulate, maintains moisture for vegetation, prevents surface sealing, and provides an environment for microbial decomposition. A mulch layer of well aged (minimum 12 months) hardwood that is shredded will minimize floating and vegetation disruption (PGC 2002). Fresh bark mulch can be used in situations where additional nitrogen removal is required (Claytor and Schueler 1996). The thickness of the mulch layer should not exceed 75 mm (3 in.), or oxygen and carbon dioxide transfers between the soil and atmosphere may be inhibited.

**Bioretention Media.** The soil layer must have an adequate infiltration rate to meet quantity objectives, provide a growing environment suitable for both plants and microbial communities, and have a balanced chemistry to promote contaminant removal. Coarse textured sand provides for a high infiltration rate; however, other components are needed to support vegetation growth, biological processes, and long-term pollutant removal (Hsieh and Davis 2005). The minimum suggested depth of the bioretention media is 64 mm (2.5 ft), which allows for adequate storage of water, a proper root zone for most vegetation, and adequate filtration above the native sub-soils (Claytor and Schueler 1996). If large trees and shrubs are to be planted, soil depths should be increased to 1.2 to 1.5 m (4 to 5 ft). The use of a mix of organic matter, sand and native soils improves soil

structures and will contribute substantially to macropore development (B.C. 2002). A uniform media profile is more cost effective; however, Hsieh and Davis (2005) suggest an alternative multi-layer media with an upper vegetation layer optimized for vegetation survival and a filter layer optimized for pollutant removal. A sandy loam, which is kept saturated near the bottom of the system, may be incorporated to enhance denitrification.

**Under-drain and Retention Zone Layer.** A pea gravel diaphragm (e.g., 6 to 13 mm or 0.25 to 0.5 in. double washed aggregate (Hinman 2005)), 75 to 225 mm (3 to 9 in.) thick (PGC 2002) between the bioretention media and gravel retention zone will reduce clogging potential. Filter fabrics are susceptible to premature clogging and are not recommended (PGC 2002). A 13 to 38 mm (0.5 to 1.5 in.) washed gravel is typically used for the gravel retention zone.

If the infiltration capacity of native sub-soils is inadequate and an underdrain is needed, the diameter (commonly 150 to 200 mm or 6 to 8 in.) is determined based upon the required hydraulic capacity. A perforated (e.g., 13 mm [0.5 in.] perforations at 150 mm [6 in.] centres) rigid PVC pipe may be used (PGC 2002) although Hinman (2005) suggests that slotted pipes are easier to clean and recommends 150 mm (6 in.), thick-walled PVC (slots 1–2 mm [0.04 to 0.07 in.] by 25 mm [1 in.] long, spaced 6 mm [0.25 in.] apart). Vertical, non-perforated, rigid pipes connected to the under-drain serve as observation wells to monitor dewatering times and system performance and as access points for potential maintenance and clean-out (PGC 2002).

**Vegetation.** The principal role of vegetation is to promote root activity and contribute organic matter to improve soil structure, increase infiltration capacity, and enhance pollutant removal. Dense vegetation can increase evapotranspiration from bioretention areas. The species selected must be tolerant of the designed ponding depth and duration of saturated soil conditions, as well as the low water conditions that may occur during the dry season. Vegetation planted at the lowest elevations will be subject to more frequent and deeper inundation. Selection will depend on the hardiness of species relative to climate zones and urban stresses. A variety of plants are used to

avoid monoculture susceptibility to insect and disease (PGC 2002). The use of native plants is preferred provided they serve the desired function. Regardless of drought resistance, plants require watering during the establishment stage, typically during the first growing season after installation (PGC 2002).

**Overflow.** An overflow outlet set at the elevation of the maximum ponding depth, can divert excess runoff. Alternatively an intake/bypass structure can divert excess runoff volumes to a safe overland flow path that does not pass through the bioretention cell (PGC 2002).

**Sizing.** Claytor and Schueler suggest sizing the surface area of a bioretention cell for the “water quality volume” ( $V_{wq}$ ), which is estimated for the Chesapeake Bay Watershed as the runoff generated from the contributing area in response to a storm with a 25.4 mm (1 in.) rainfall depth. Claytor and Schueler (1996) provide the following equation:

$$\text{Surface Area (m}^2\text{)} = V_{wq}(d_f)/[k(h_f + d_f)(t_d)]$$

where  $d_f$  is the depth of the planting soil;  $h_f$  is the average height of the water above the bioretention bed;  $t_d$  is the draw-down time; and  $k$  is the hydraulic conductivity. Any consistent length and time units may be used.

Additional calculations can be done to assess whether adequate storage is available within the bioretention media and on its surface.

Claytor and Schueler (1996) suggest a minimum width of 3.0 m (10 ft) and a minimum length of 4.5 m (12 ft). For widths greater than 3.0 m, a length-to-width ratio of 2:1 should be maintained to provide flow paths of adequate length and to maximize edge to interior ratio.

### Performance

B.C. (2002) demonstrated, based on modeling, that in order to achieve the objective of reducing total runoff volume from a single-family lot to 10% or less of total rainfall volume (1800 mm) on soils with low hydraulic conductivity (2.5 mm/hr), about 15 % of the lot area was needed for bioretention. For areas with annual rainfall of 700 mm, only 3% of the total lot area was used to achieve the target. Also refer to

Hunt and Jarrett (2004) and Morizaria-Luna et al. (2004) for results of case studies.

## RAINWATER HARVESTING

### *Function and Applications*

Rainwater harvesting (RWH) is the collection and storage of rainwater for beneficial use at or near the location of rainfall. It recognizes rainwater as a valuable resource rather than a problem to manage. RWH provides a usable source of soft water where other supplies are not available. It also provides the opportunity to diversify water supply, and to supplement groundwater or surface water supplies, particularly where there may be ecological constraints associated with these resources. Using rainwater can reduce the demand on potable water supply, treatment and distribution, reduce the operational costs associated with the provision of potable water, and potentially delay infrastructure expansion.

In the context of LID, RWH provides storage. Water that is used for landscape irrigation returns to the hydrologic cycle and contributes to infiltration or evapotranspiration. Where there is centralized wastewater treatment, water that is directed to indoor uses will bypass the local hydrologic cycle and re-enter it where the wastewater treatment plant discharges. Understanding the pre-development water balance and the effects of urbanization and other rainwater management techniques on the post-development water balance are important for effective integration of RWH. "In certain situations it may be possible to re-use virtually all rooftop runoff. However, it is important that rainwater re-use systems be designed to ensure that adequate baseflow is maintained in downstream watercourses" (B.C. 2002). In other words, it is not desirable to intercept and use so much rainwater that the pre-development infiltration component of the water balance cannot be met. However, after development in some watersheds infiltration can be maintained, but there remains an excess of runoff volume because evapotranspiration volumes are lower. Here, capture, use, and diversion of rainwater to a wastewater treatment plant can reduce erosion problems in local streams. Like green roofs, rainwater harvesting is particularly applicable in areas where rooftops are a significant proportion of total imperviousness (i.e., medium-to-high den-

sity developments). In fact, B.C. (2002) states that, "the primary LID objective of approximating pre-development hydrology is likely not feasible without reducing or eliminating the stormwater contribution from rooftops through rainwater harvesting applications."

### *Components*

The basic components of a RWH system are (Texas 2005):

1. Catchment surface: surface from which the rainwater is collected, typically a roof structure.
2. Conveyance system: a network capable of collecting and transporting the water from the catchment surface to the storage facility, including gutters (or eavestroughs) and downspouts.
3. Water quality components: mechanisms designed to remove particulate matter and reduce the introduction of contaminants into the storage structure, typically consisting of first flush devices and gutter guards.
4. Storage facilities: one or multiple tanks of varying material designed to safely store collected rainwater for future use.
5. Delivery system: on-site pump and piping network that delivers stored rainwater.
6. Treatment systems: for some uses little or no treatment may be required and for other uses, substantial treatment may be involved.

Sizing the RWH system should be based on catchment area, historical precipitation data, water demands, and capture efficiency, which is typically 75 to 90% (Texas 2005). For more detailed information on approaches for sizing, refer to the Texas (2005) and G.S.A (1999).

Since rainwater is generally collected from rooftops, appropriate roofing materials should be selected depending on intended use (Table 1). Installation of materials that could leach contaminants such as zinc or copper should be avoided (Hinman 2005). Rough surfaces catch and hold dirt and debris, thereby affecting water quality; galvanized steel and aluminum roofs are a good alternative and are commonly used (Bucklin 2003).

Gutters (eavestroughs) and downspouts are installed to convey rainwater from the roof to the storage tanks (Figure 9). Commonly used materials are

**TABLE 1.** Roofing materials.

Roof Material	Intended Use	Special Consideration	Reference
Enameled steel	Potable/non-potable	Smooth surface, low contaminant introduction	Puget Sound 2003
55% aluminium–45% zinc alloy coated steel (enameled or epoxy coated) Galvalume®	Potable/non-potable	Smooth surface, low contaminant introduction	Texas 2005
Clay	Potable/non-potable	Porous materials—reduction in capture efficiency	Texas 2005
Concrete tiles	Potable/non-potable	Porous materials—winter water can have elevated lime content	G.S.A. 1999
Asphalt shingle	Non-potable (irrigation)	Contaminant leaching	Texas 2005
Copper	Non-potable	Discoloration of porcelain fixtures	Texas 2005; Puget Sound 2003
Wood, tar, and gravel	Irrigation	Contaminant leaching, taste impairment	Texas 2005; G.S.A. 1999
Slate (no toxic sealants used)	Potable/non-potable	Cost considerations	Texas 2005

half-round PVC, seamless aluminum, and galvanized steel, all of which are suitable for RWH and potable and non-potable uses. In retrofit situations, caution should be taken to determine if lead solder was used in installation of older style metal gutters (Texas 2005).

The regular maintenance and cleaning of downspouts and gutters is a necessity in all RWH operations, especially those where the ultimate use is human consumption (G.S.A. 1999; Texas 2005). Gutters and downspouts should be kept in good repair, free from dust, soot, bird droppings, leaves and

any other foreign material that may degrade water quality (Bucklin 2003; Texas 2005). Gutter guards can be used to prevent unnecessary introduction of leaves from overhanging trees (Bucklin 2003).

Typically, the first flow of water is the most highly contaminated and is diverted away from the cistern or storage facility by first flush devices (Bucklin 2003; Texas 2005). Number of dry days, particulate deposition on the catchment surface, and the catchment surface material itself will determine the size, type, and location of the contaminant diverting device (Texas 2005). Discarded water can be directed to pervious areas for infiltration and natural filtration.

Tanks (or cisterns) can be above ground or below (Figure 10), and have a pump or handpump. Above ground tanks can be made of polyethylene or galvanized steel, with a polypropylene lining, while underground tanks are typically manufactured of polyethylene, fiberglass, or concrete (Table 2). Multiple tank systems may be less expensive than a single tank and allow the system to remain operational while one tank is being maintained (Hinman 2005). Regardless of their location, all tanks should be non-reactive, watertight, and opaque to prevent algal growth, and should have smooth interior surfaces, lids to restrict entry, and an approved food grade lining for potable use (Bucklin 2003; Texas 2005; G.S.A. 1999). If the collected water is for potable use, tanks should have access for cleaning and maintenance (Texas 2005).

**FIGURE 9.** Redirection of gutters to first flush device. (Photo courtesy of Chris Despins, University of Guelph.)



**FIGURE 10.** Installation of concrete tank for rainwater harvesting system at a single family home, Guelph, Ontario. (Photo courtesy of Chris Despins, University of Guelph.)



Tank disinfection and flushing after construction is recommended. Cisterns in many parts of the world (Japan, Mediterranean and American Southwest) are designed to have aesthetic value as well as function (Wash 2001).

Water delivery to the area of use is generally accomplished through a combination of pump, pressure tank (275–400 kPa or 40–60 psi) and check valve or a self priming on-demand pump. Pumps placed in the tank deliver water either directly to the area of use (with the on-demand pump) or to a pressure tank (typically 150 L or 40 gallons) where it is stored for eventual use (Texas 2005).

Treatment systems depend upon the quality of the stored water, the intended use and water quality standards for various uses. When potable water is needed, treatment may include sand or membrane filters (re-

verse osmosis or nonofiltration) and disinfection using ozone, ultraviolet, or chlorine (Texas 2005). Description of these systems is beyond the scope of this article.

### Performance

Information on performance, relative to stormwater management objectives, for large-scale rainwater harvesting is limited. B.C. (2002) and Hinman (2005) summarize some findings based on modeling analyses.

### CONCLUSIONS

Low-impact development techniques, which support a shift to control of runoff volume and management of the post-development water balance, offer the potential to better mitigate the effects of urbanization on aquatic ecosystems. Stormwater management objectives and performance and design criteria will vary between jurisdictions. The combination (and extent of implementation) of LID techniques needed to achieve water balance objectives and the extent to which they can contribute to mitigation of flood risks will depend on local conditions. The potential of LID remains largely untested because it has not yet been “adopted widely enough or strategically enough to assess its impacts on receiving streams” (Walsh et al. 2005). There remain challenges to implementation of some techniques, such as concerns related to maintenance of measures located on private property. However, there is growing awareness of the potential benefits of these techniques. Some jurisdictions offer water and sewer charge reductions for retaining stormwater on-site and others provide incentives for implementation of specific techniques, such as green roofs.

**TABLE 2.** Tank materials. (Source: Texas (2005).)

Tank Material	Intended Use	Special Consideration
Fiberglass	Potable/non-potable	Proven durability, cost prohibitive @ sizes < 1000 gallons
Polypropylene	Potable/non-potable	Above/below ground installation, UV stabilization required
Wood	Non-potable	Above ground urban installation, cost prohibitive
Galvanized Steel	Potable/non-potable	Above grade installation, non cost prohibitive
Concrete	Potable/non-potable	Above or below ground installation, cracking can occur
Ferrocement (sprayed concrete and metal composite)	Potable/non-potable	Cost effective for larger tanks

## REFERENCES

### Background and Multiple LID

- Aquafor Beech Ltd. 2006. "Stormwater Management and Water-course Impacts: The need for a water balance approach." Prepared for the Toronto Region Conservation Authority.
- British Columbia (B.C.). 2002. *Stormwater Planning: A guidebook for British Columbia*. Ministries of Community, Aboriginal and Women's Services, and Water, Land and Air Protection.
- Centre for Watershed Protection (CWP). 1999. "Better Site Design." Watershed Leadership Kit Volume 1.
- Hinman, C. 2005. *Low Impact Development: Technical Guidance Manual for Puget Sound*. Prepared by the Puget Sound Action Team and Washington State University. Publication No. PSAT 05-03.
- Konrad, C.P., and D.B. Booth. 2005. "Hydrologic changes in urban streams and their ecological significance." American Fisheries Society Symposium. 47, 157–177.
- 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 search for a cure." J. N. Am. Benthol. Soc., 24(3):706–723.

### Porous Pavement

- Ferguson, B. K. 2005. *Porous Pavements*. Boca Raton, Florida: CRC Press. 577 pp.
- James, W., and C. Gerrits. 2003. "Maintenance of Infiltration in Modular Interlocking Concrete Pavers with External Drainage Cells," in Practical Modeling of Urban Water Systems, Monograph 11: 417–435. Computational Hydraulics International.
- Smith, D.R. 2006. "Permeable Interlocking Concrete Pavements: selection, design, construction, maintenance." 3rd Edition. Interlocking Concrete Pavement Institute (ICPI).
- Toronto Region Conservation Authority (TRCA). 2005. Permeable Pavement and Bioretention Swale Demonstration Project at Seneca College, King Campus: Interim Report #1.

### Bioretention

- Claytor, R.A., and T.R. Schueler. 1996. Design of Stormwater Filtering Systems. Chesapeake Research Consortium.
- Hsieh, C., and A.P. Davis. 2005. "Evaluation and optimization of bioretention media for treatment of urban storm water runoff." Journal of Environmental Engineering, 131(11): 1521–1531.

- Hunt, W.F., and A.R. Jarrett. 2004. Evaluating Bioretention Areas from Two Field Sites in North Carolina. ASCE: Critical Transitions in Water and Environmental Resources Management: Proceedings of the World Water and Environmental Resources Congress June 27–July 1, 2004
- Morizaria-Luna, H.N., K.S. Schaepe, L.B. Cutforth, and R.L. Veltman. 2004. "Implementation of Bioretention Systems: A Wisconsin Case Study." Journal of the American Water Resources Assoc., 40(4):1053–1061.

### Green Roof

- Banting, D., H. Doshi, J. Li, P. Missios, A. Au, B. Currie, and M. Verrati. 2005. Report on the Environmental Benefits and Costs of Green Roof Technology for the City of Toronto.
- DeNardo, J.C., A.R. Jarret, H.B. Manbeck, D.J. Beattie, and R.D. Berghage. "Stormwater mitigation and surface temperature reduction by green roofs." Transactions of the ASAE, 48(4):1491–1496.
- Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL). 1995. "Guidelines for the Planning, Execution and Upkeep of Green-Roof Sites." Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau. Bonn, Germany.
- Peck, S. and M. Kuhn. 2002. "Design Guidelines for Green Roofs." Prepared for the Ontario Association of Architects and the Canada Mortgage and Housing Corporation.
- Scholz-Barth, K. 2001. "Green Roofs: Stormwater management from the top down." Environmental Design & Construction, 4(1).
- Toronto and Region Conservation Authority. 2006. "Evaluation of an Extensive Greenroof." York University, Toronto, ON.
- VanWoert, N.D., D.B. Rowe, J.A. Andresen, C.L. Rugh, R.T. Fernandez, and L. Xiao. 2005. Journal of Environmental Quality, 34:1036–1044.

### Rainwater Harvesting

- Bucklin, R.A. 2003. "Cisterns to collect non-portable water for domestic use." University of Florida: IFAS Extension.
- Government of South Australia (GSA). 1999. "Rainwater Tanks . . . their selection, use, and maintenance." Department of Environmental Heritage and Aboriginal Affairs.
- Texas Water Development Board. 2005. The Texas manual on rainwater harvesting.