Rideau Valley Conservation Authority

Literature Review: Sustainable Drainage and Low-Impact Development Technology in the Rideau Lakes Township

Prepared for: Rideau Lakes Township Council

Submitted by: Sustainable Drainage Committee

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Cataraqui conservation

Rideau Lakes

RLAC [Placeholder Logo]

Table of Contents

Acronyms

- BMP: Best Management Practices
- C: Carbon
- CB: Catch Basin
- CBI: Catch Basin Insert
- CFW: Constructed Farm Wetlands
- Cl: Chloride
- CW: Constructed Wetland
- FTW: Floating Treatment Wetlands
- GA: Genetic Algorithm
- GI: Green Infrastructure
- GR: Green Roof
- IT: Infiltration Trench
- IESF: Iron Enhanced Sand Filters
- LCA: Life Cycle Assessment
- LCC: Life Cycle Costing
- LID: Low Impact Development
- N: Nitrogen
- P: Phosphorus
- PAH: Polycyclic Aromatic Hydrocarbons
- PP: Permeable Pavement
- RB: Rain Barrel
- RLT: Rideau Lakes Township
- SNAP: Sustainable Neighbourhood Action Program
- STEP: Sustainable Technology Evaluation Program
- SUDS: Sustainable Urban Drainage Systems
- SW: Stormwater
- SWM: Stormwater Management
- SWMM: Stormwater Management Model
- SWMP: Stormwater Management Pond
- TKN: Total Kjeldahl Nitrogen
- TN: Total Nitrogen
- TP: Total Phosphorus
- TPH: Total Petroleum Hydrocarbons
- TSS: Total Suspended Solids

- UHI: Urban Heat Island

Background

Runoff from impervious surfaces is a major source of degradation to freshwater bodies (US EPA, 2002). Current research suggests Low Impact Development (LID) as a recommended solution (Dietz & Clausen, 2008). This report aims to provide an overview of the body of literature that focuses on LID techniques that are applicable and relevant to the Rideau Lakes Township (RLT). This report will also provide an overview of existing resources and best management practices that other municipalities and organizations have already developed.

The Hydrology of Imperviousness

In an untouched ecosystem, precipitation events are absorbed by plants and microorganisms with minimal runoff. In these ecosystems, precipitation is either used by vegetation or organisms or infiltrates deep into the soil. These processes help to filter the water and/or replenish groundwater reservoirs (Exum et al., 2005). When the natural cover is removed to accommodate urbanization, including new roads and/or buildings, the increase in impervious surfaces leads to hydrologic alteration and increased runoff. Hard, impervious surfaces include concrete, asphalt, rooftops, and compacted gravel. Increased runoff subsequently increases erosion, decreases water quality, and negatively impacts aquatic life (Schueler, 2000; Fletcher et al., 2013). Waterbodies adjacent to areas of high imperviousness can experience increased temperatures and pollution, including nutrients, metals, and hydrocarbons (Schueler, 2000). In Ontario, urbanization and population expansion are a predictor of elevated chloride (Cl) concentrations from winter road salt application. Additionally, lakes, streams, and groundwater near roadways meet or exceed Cl guidelines and are continuing to increase (Sorichetti et al., 2022). Other challenges include altered geomorphology, altered terrestrial inputs, and loss of riparian habitat (Fletcher et al., 2013).

The hydrological changes at the catchment level due to development are illustrated in Figure 1. In a natural environment (pre-development), storm responses are small with low peak flow rates, and baseflows are larger. In an urbanized environment (post-development), base flows are lower, and storm responses are much higher. This means sudden surges in large water volumes, increasing water velocity, and flooding. As an example, when imperviousness increases from 0% to 100% in areas not serviced by storm sewers, peak storm flows increase an average of 2.5 times. In areas serviced by storm sewers, the average change for peak stream discharges is even greater: 8 times more at 100 percent imperviousness (Leopold, 1968; Berry and Horton, 1974). A case study comparing one acre of low impervious area (6%) to one acre of high impervious area (95%) found that the latter can create 16 times more stormwater (SW) runoff. Changes in water flow affect water quality, too. In the same study, the annual phosphorus (P) load increased four times, while the annual nitrogen (N) load increased 7.7 times (Barnes et al., 2002).

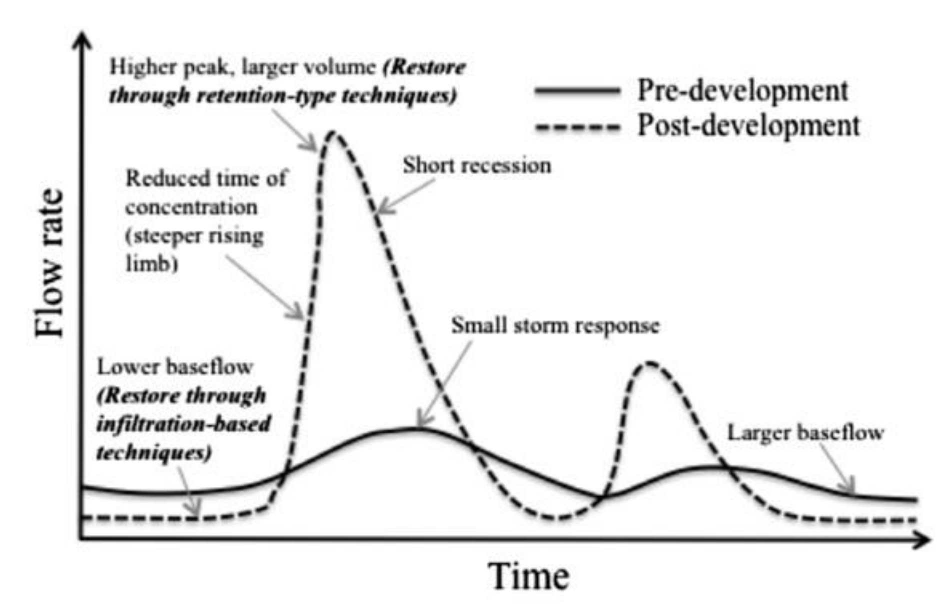


Figure 1: Catchment Scale Hydrological Changes due to Urbanization (Fletcher et al., 2013)

The effects of imperviousness are not limited to highly urbanized big cities. Although total impervious area is highly correlated with the level of urbanization present (Coles et al., 2004), non-urban impervious surface areas have been shown to contribute 5–20% of the “hidden” runoff volumes and nutrient emissions from all impervious areas (Nguyen et al., 2022). As much as 70% of the total runoff and nutrient emissions nationwide can originate from low-to-medium populated impervious surfaces as opposed to major urban catchments (Nguyen et al., 2022). Therefore, increasing imperviousness is problematic even in low-density population areas.

Several authors have proposed a threshold degradation value of 10% imperviousness at the catchment level (Booth and Reinelt, 1993; Klein, 1979; Schueler, 2000; Wang et al., 2001; Exum et al., 2005). While variability in measurement methods makes a definitive threshold inaccessible, there is a clear inverse relationship between watershed health and imperviousness (Dietz & Clausen, 2008).

Grey vs. Green Stormwater Management

Traditional stormwater management (SWM) techniques, also known as grey infrastructure or end-of-pipe practices, include gutters, SW sewers, tunnels, culverts, detention and retention basins, pipes, and mechanical devices (Yang et al., 2020). Conventional SW techniques are designed to manage peak flow rates, but current designs do not mitigate the increases in SW volume associated with development (Dietz & Clausen, 2008). These systems remove runoff through the direct collection, conveyance, detention, and discharge into natural water bodies (Guan et al., 2015). As such, LID technology has been developed in response to these issues arising from imperviousness, SW runoff, and their effect on water quality.

LID techniques are accepted as a promising strategy for sustainable urban SWM (Baek et al., 2015; Eckart et al., 2017; Schirmer & Dyer, 2018). Conceptualized LID management has been noted as a key factor in successful watershed management, and LID has been developed and implemented at increasing rates around the world for decades. In many areas, LID techniques can also be referred to as Water Sensitive Urban Design, Integrated Urban Water Management, Sustainable Urban Drainage Systems, Best Management Practices (BMPs), Stormwater Control Measures, Green Infrastructure (GI), etc. (Fletcher et al., 2014).

The widely used and accepted terms in Canada are LID and GI. LID is the term used in legislature around North America. *The Low Impact Development Stormwater Management Planning and Design Guide* (LID SWM Planning and Design Guide) by Credit Valley Conservation (CVC) and TRCA (2010) is the leading guidance manual for LID in Canada. “Low-Impact” implies that although there may still be an impact on the natural environment, the impact is suggested to be less than that of traditional grey infrastructure. The term “Development” originally referred to new developments but now includes retrofit measures as well. The currently accepted definition of the term “LID” is to design with nature to achieve a natural hydrology by using site layout and integrated control measures. This suggests that the overarching goal is to achieve a functionally equivalent hydrologic landscape (Fletcher et al., 2014).

For these reasons and because this is a technical document, LID will be the primary vocabulary used to discuss sustainable stormwater strategies and technologies. However, it should be noted that LID and Sustainable Drainage are synonyms. In documents that correspond with this review, “Sustainable Drainage” may be used as a substitute to the term “LID.”

Alternatively, GI is defined as green technologies and natural vegetative systems designed to provide society with multifaceted environmental, social, and economic benefits. GI includes a host of other strategies that extend beyond LID and sustainable SW runoff management, including pollinator gardens, green walls, and xeriscaping (FGF & GIOC, 2017). Although similar, it should be noted that all LID techniques utilize GI methods, but not all GI techniques can be considered LID.

The objective of LID is to imitate pre-development hydrology, including pre-development runoff volumes (Dietz & Clausen, 2008) through interception, infiltration, filtration, evapotranspiration, storage and detention, absorption, adsorption, precipitation, biodegradation, phytoremediation, and percolation, etc. (Ahiablame et al., 2012; Yang et al., 2020; Chen, 2021). LID aims to integrate strategies in the early stages of site planning and design, manage water at the source, focus on prevention, reduce construction and maintenance costs, and empower communities through education and participation (Ahiablame et al., 2012). LID principles also promote environmentally friendly design, natural water features, and natural hydrologic functions (Ahiablame et al., 2012). Research conducted on LID shows pollutant attenuation, reduced flow volumes, reduced peak flow rates, and ecological improvements (Davis et al., 2001; Dietz and Clausen, 2005, 2006; Dietz, 2007; US EPA, 2000; Liu et al., 2020; Ma et al., 2019; Zimmerman et al., 2010; Morris et al., 2018). LID has also proven effective in residential zones (Hood et al., 2007; Zhang et al., 2016). It can help mitigate climate change and associated changes with vegetation through carbon (C) uptake, surface cooling, shade, and evapotranspiration (Liu et al., 2020). LID manages urban stormwater better than traditional municipal utilities, both in small-scale urban communities and in large-scale urban districts (Eckart et al., 2017). Furthermore, the far-reaching environmental benefits are complemented by social and economic benefits such as aesthetics, improved quality of life, increased property values, improved life cycle assessment (LCA) results, reduced lifecycle costing, and overall cost savings (Liu et al., 2020; US EPA, 2007).

LID technology has been accepted by the Ontario Ministry of the Environment, Conservation, and Parks as part of the BMPs for SWM (MECP, 2022). Major municipalities across Ontario have already begun implementing robust LID BMP guidelines and programs, including Toronto (CVC & TRCA, 2010; STEP, 2022), Kitchener (Aquafor Beech Ltd. & Freeman Associates, 2015; Kitchener, 2021), Ottawa (City of Ottawa, 2019; City of Ottawa, 2022), and Hamilton (City of Hamilton, 2017).

The Township of Rideau Lakes and Its Watersheds

RLT covers approximately 711.81 square kilometers (Statistics Canada, 2022). Within it exists portions of the Rideau River, Cataraqui River, Gananoque River, Tay River, and Irish Creek watersheds. The Rideau River watershed is made up of over 31 lakes, including Big Rideau Lake, and several connecting streams covering approximately 455 square kilometers. This portion of RLT is located on bedrock outcrops covered by shallow soils (RVCA et al., 2008).

Across the entire region, the geology is primarily shallow till and rock ridges, with limestone plains, intermixed with minor sections of kame moraines, drumlinized till plains, clay plains, sand plains, and beaches (Ontario Geological Survey; Figure 2). Demographically, the 2021 population of RLT was 10,883, residing in 6,781 private dwellings. The population density per square kilometer is roughly 15.3 (Statistics Canada, 2022).

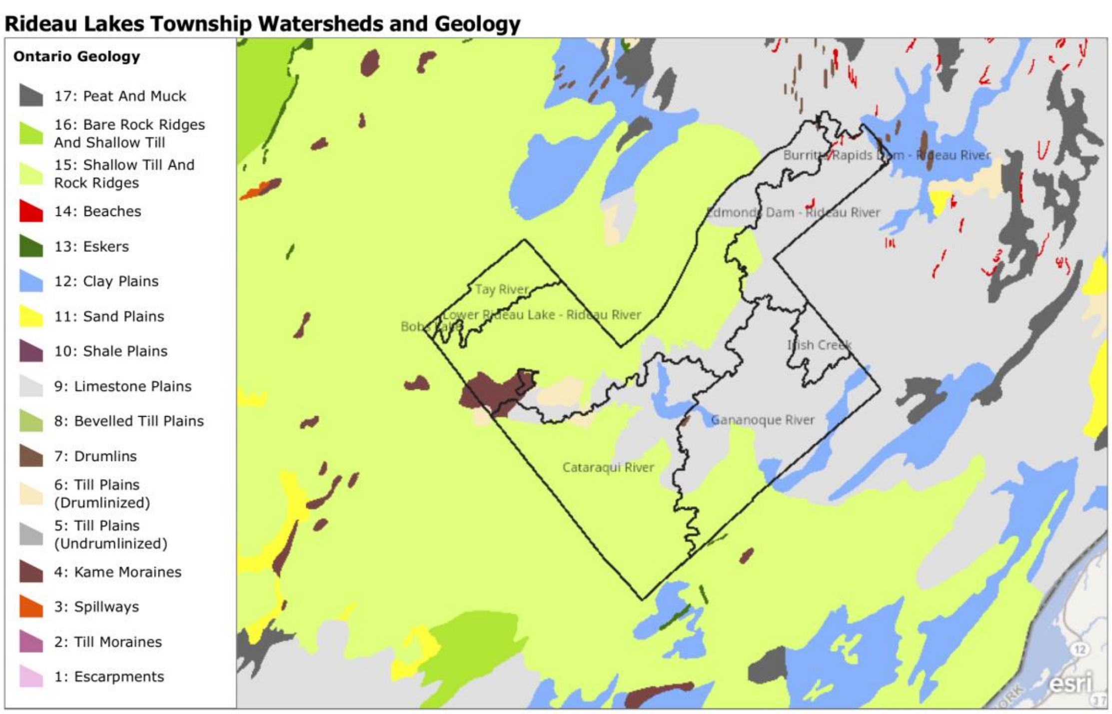


Figure 2: Rideau Lakes Township Watersheds and Geology

In catchments like Rideau Lakes with urbanized centers in rural catchments, urban impervious surface and rural agricultural runoff can significantly contribute to nutrient pollutants (Al Bakri et al., 2008). Considerations should be given to the distance of urbanized areas from headwaters and outflow points (i.e., rivers and lakes) when analyzing SW runoff water quality data (Al Bakri et al., 2008).

LID Practices

Fletcher et al. (2013) categorized structural SWM into two categories: infiltration-based and retention-based. Infiltration-based methods convey water into the soil to help to restore baseflows through sub-surface flow and groundwater recharge. Retention-based methods retain SW to reduce overall outflow (Fletcher et al., 2013; Eckart et al., 2017; Ahiablame et al., 2012). Structural and non-structural LID practices are summarized in Table 1. Not all retention-based methods are LID, as SW ponds and wetlands are commonly used grey infrastructure techniques. The difference depends on the design specifications (i.e., treatment, outflow, ecosystem services, etc.), as the terms wetland and pond may be used loosely and inconsistently. This review will also look at a few end-of-pipe practices, including ponds and wetlands, pre-treatment catch basin (CB) filtering technology, and new innovations in filter media. Non-structural LID practices that should be respected during design and implementation include minimizing site disturbance, preserving natural features, reduction and disconnection of impervious surfaces, strategic grading, incorporating native vegetation, soil amendment, and minimizing grass lawns (Ahiablame et al., 2012).

Structural Practices		Non-Structural Practices
Infiltration-Based	Retention-Based	
• Swales • Soakaways • Infiltration trenches • Infiltration chambers • Bioretention gardens • Sand filters • Permeable pavements	• Green roofs • Rainwater harvesting (I.e., rain barrels, tanks) • Wetlands • Ponds	• Minimizing site disturbance • Preserving natural features • Reduction and disconnection of impervious surfaces • Strategic grading • Incorporating native vegetation • Soil amendment • Minimizing grass lawns

Table 1: Summary of Structural vs Non-Structural LID Practices

A treatment train is a series of green or grey stormwater treatment technology used together to achieve water quality objectives. In green, grey, and end-of-pipe practices, treatment trains are recommended to improve outcomes for stormwater management.

Swales

Swales are similar to traditional rural ditches; however, ditches are used primarily for conveyance and not treatment (STEP, 2022a; Ekka & Hunt, 2020). Swales have specific design considerations that offer more services than ditches. In this way, all swales are ditches, but not all ditches are swales. Primarily, swales are used as a drainage channel to convey water away from roads with the added benefits of attenuation, filtration, sedimentation, detention, and infiltration, and they may also offer groundwater recharge and pollution removal (US EPA, 2000; Ekka & Hunt, 2020; Duffy et al., 2016). Swales improve water quality by slowing water to allow sedimentation, filtering through subsoil matrix, and/or soil filtration. The selection of a swale type depends on the site constraints, local climate, and available funding for design, construction, and operation (Ekka et al., 2021).

There is room for miscommunication in the literature due to inconsistent use of terms to describe different types of swales. The terms recommended and described by Ekka & Hunt (2020) will be used for this literature review. Various other terms include but are not limited to (Storey et al., 2009):

- Grass strip biofilter
- Grass swale biofilter
- Grass-lined swale
- Grass drainage swale
- Dry swale
- Wet swale
- Water quality swale
- Grass drainage channel
- Grass channel
- Vegetated channel
- Wetland channel
- Biofiltration swale
- Bioinfiltration swale
- Drainage swale
- Vegetated systems
- Biofilters
- Buffer zone
- Irrigated grass buffer strip
- Natural area conservation
- Overland flow filtration
- Overland infiltration zone
- Vegetated filter strip

Swales may be subdivided into two main types: grass swale and bioswale. A bioswale is a deliberate infiltration device, while a grass swale can be an infiltration device depending on the permeability of underlying soils or the use of velocity controls such as check dams or check-berms (Ekka & Hunt, 2020; Storey et al., 2009; Revitt et al., 2017). A grass swale with check dams may be called an infiltration swale, not to be confused with engineered bioswales (Ekka & Hunt, 2020). A grass swale may also be called: a drainage ditch, swale, dry swale, standard swale, and vegetated swale (Ekka & Hunt, 2020). Figure 3 features a typical grass swale cross-section.

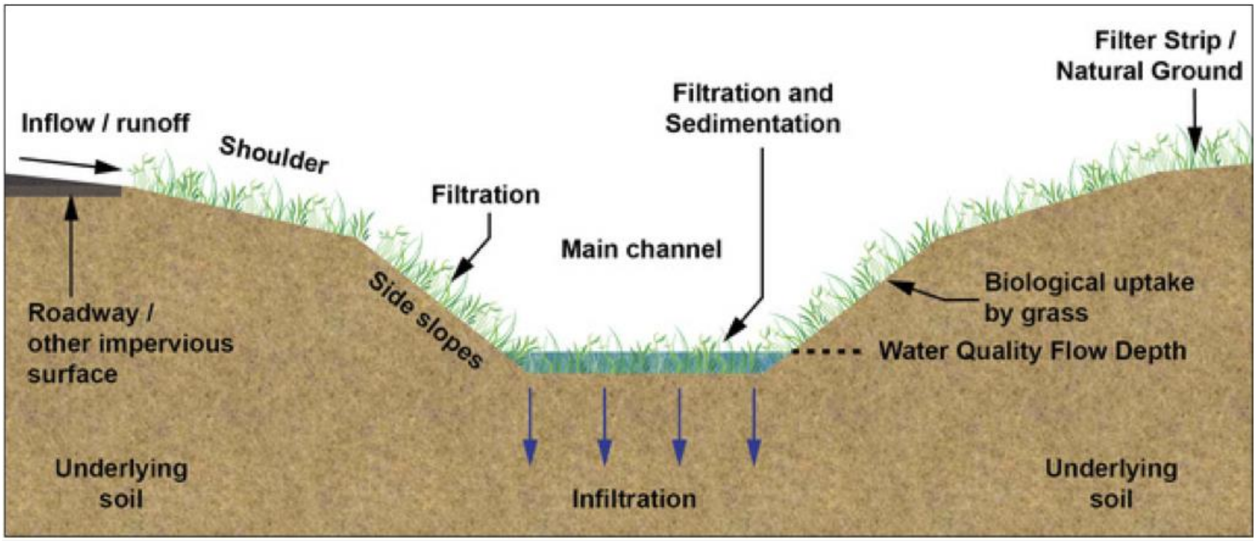


Figure 3: Typical grass swale cross section and stormwater treatment process (Ekka & Hunt, 2020)

A wet swale is similar to a grass swale; however, it uses wetland soils, hydrology, vegetation, and depends upon the regular presence of standing water (Tang et al., 2016). A wet swale may be called: wetland swale, grass swale, planted swale, or vegetated swale (Ekka & Hunt, 2020).

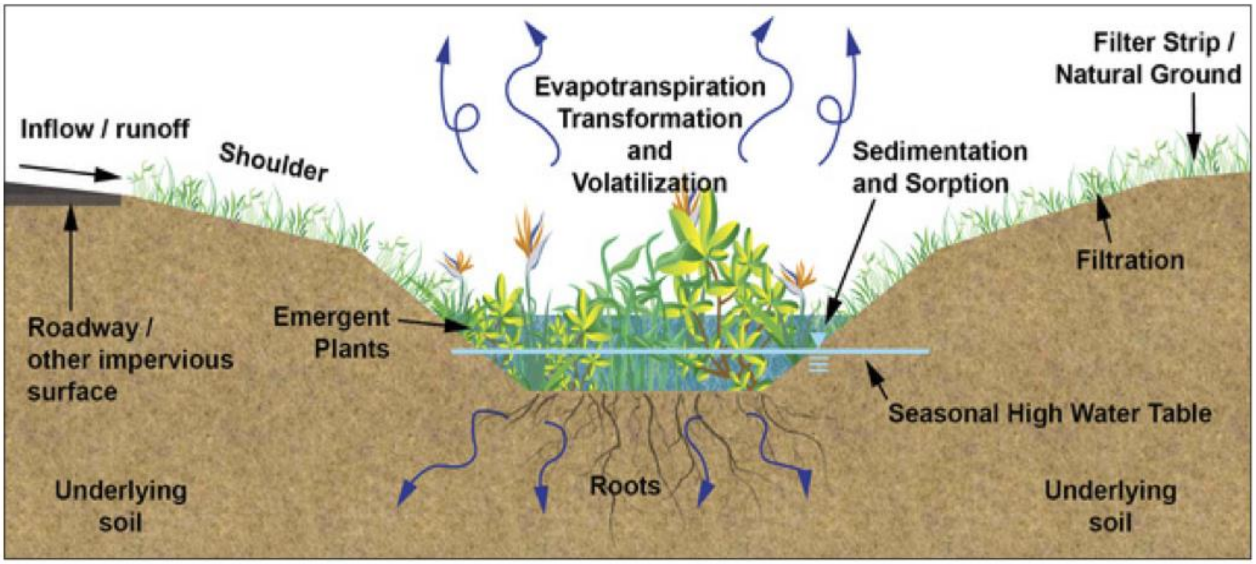


Figure 4: Typical wet swale cross section and stormwater treatment process (Ekka & Hunt, 2020)

A bioswale incorporates a bioretention element (Christianson et al. 2004). They are referred to as dry swales in the LID SWM Guide (CVC & TRCA, 2010). Bioswales have an engineered subsurface or under-drain system and specialized soil structure (I.e., filter fabric, gravel, perforated pipe, etc.) (Storey et al., 2009; Revitt et al., 2017; Ekka & Hunt, 2020). Bioswales are similar to enhanced grass swales in terms of the design of their surface geometry, slope, check dams, and pre-treatment devices, and similar to bioretention gardens in terms of the design of the filter media bed, gravel storage layer and optional underdrain components. A bioswale may be called a dry swale, infiltration swale, filtration swale, or filtering swale (Christianson et al. 2004).

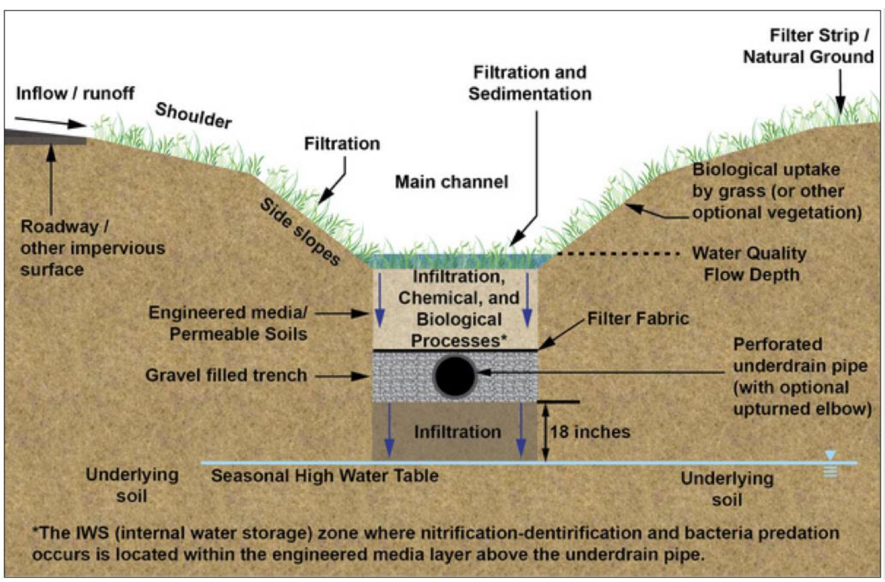


Figure 5: Typical bioswale cross section and stormwater treatment process (Ekka & Hunt, 2020)

Filter Strips

Filter strips often accompany swales. They are gently sloping, densely vegetated areas that receive sheet flow across their surface area, use vegetation to slow runoff velocities, and filter out sediments and pollution. Filter strips are commonly used as a pre-treatment device in a treatment train. They may be positioned alongside roadways and parking lots or act as a buffer for swales (Claytor & Schueler, 1996; Storey et al., 2009).

Figure 6: Filter strip along a residential road (left) and as a pre-treatment to a bioswale (right) (CVC & TRCA, 2010)

Permeable Pavements

Permeable pavements (PPs) are an alternative to impermeable pavements that permit water to infiltrate into a reservoir below the surface (STEP, 2022b). Permeable paving works by filtration, storage, or infiltration of runoff and can reduce or eliminate surface SW flows (CVC & TRCA, 2010). PP can help manage precipitation that falls onto the surface while also receiving runoff from adjacent conventional paving or downspouts. In particular, PPs are effective for areas with limited space for other LID (CVC & TRCA, 2010). Depending on the native soil and/or site conditions, the system may be designed for full or partial infiltration or detention and filtration only (STEP, 2022b). PPs may also be used for low traffic roads, parking, driveways, pedestrian plazas, and walkways. The four main categories include modular interlocking concrete block pavement, porous asphalt, pervious concrete, and plastic or concrete grid systems (STEP, 2022c; Dietz, 2007). Permeability varies based on constituent parts (STEP, 2022c).

Interlocking concrete block pavement (I.e., block pavers) are impermeable interlocking brick with gaps between them that allow SW to infiltrate into an aggregate reservoir. The spaces are filled with permeable aggregate and makeup approximately 10% of the surface area (CVC & TRCA, 2010).

Figure 7: Permeable Interlocking Concrete Paver in Mississauga (CVC & TRCA, 2010).

Pervious concrete is constructed similarly to conventional concrete. However, it is mixed with little or no sand, resulting in an open-cell structure through which water can easily move. This type of pavement is commonly used in parking lots and light traffic areas (Li et al., 2017). The pavement mix has reduced or no fine sediment to create void space through which the water drains to the underlying reservoir (CVC & TRCA, 2010).

Porous asphalt also has reduced or no fines and large spaces between particles to create void space through which water drains to subsurface layers. This base aggregate layer serves as a structural layer as well as a temporary storage container for SW (Skaf et al., 2019; CVC & TRCA, 2010). Porous asphalt is normally constructed from an open-graded layer of coarse aggregate, held together by an asphalt binder, with effectively interconnected voids that allow water to move freely (Skaf et al., 2019). Porous asphalt works well in areas with low traffic and vehicular activity (Skaf et al., 2019).

Figure 8: Pervious Concrete (left) and porous asphalt (right) (CVC & TRCA, 2010)

Lastly, plastic or concrete grid systems (i.e., grid pavers) are made with an open-cell grid, either plastic or concrete, filled with pea gravel, sand, or topsoil and grass (CVC & TRCA, 2010). These can distribute loading weight more effectively and prevent soil compaction below the grid. Aggregate fill works best for high-traffic areas. Typically, grid pavers are constructed from recycled materials (University of Rhode Island, 2018).

Figure 9: Concrete grid system with grass (left) and plastic grid system with aggregate (right) (CVC & TRCA, 2010)

Bioretention Gardens

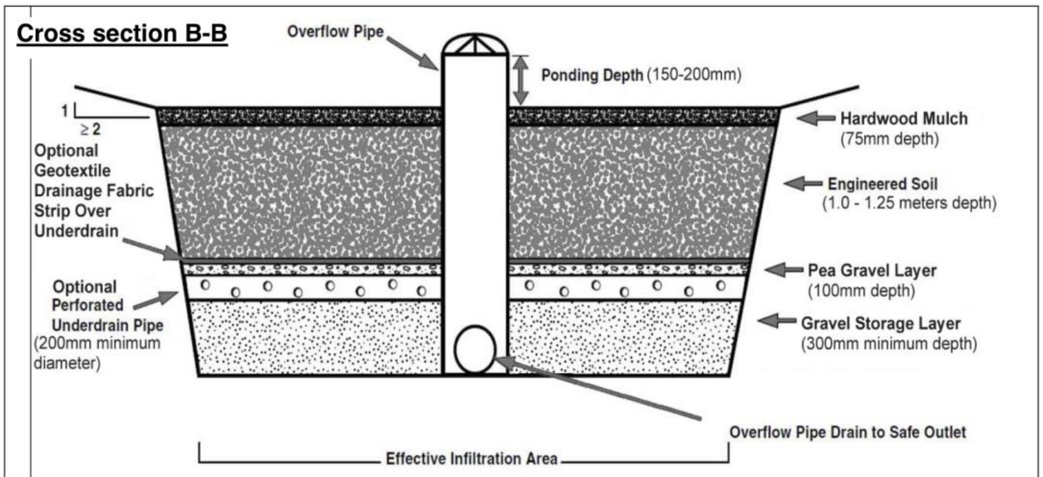
Bioretention gardens are landscaping features that create permeable surfaces and water retention or detention spaces. Other names for this LID method include rain garden, bioswale, infiltration swale, tree box filter, or SW filter (Moore, 2017). These are effective for capturing runoff, temporary storage, infiltration, evapotranspiration, groundwater recharge, stream channel protection, peak flow reduction, and pollutant reduction (Ahiablame et al., 2012; Dietz & Clausen, 2005; Dietz, 2007; Davis, 2008; Davis et al., 2009; CVC & TRCA, 2010).

Although there are various forms of bioretention gardens that have different features depending on the extent of engineering and vegetation types, rain gardens are the simplest and most accessible form. At a glance, a rain garden looks like a regular garden but has specially selected plants and substrates and is typically positioned somewhere strategic such as at the end of a downspout. More specifically, rain gardens are planted on a 1.5 m depression in amended soil to increase absorption, with water-tolerant plants and a stone splashpad to prevent soil erosion (STEP, 2022d). Rain gardens are designed to capture runoff on low- to medium-density residential lots. They are simple enough to be designed by the homeowner or a professional landscaper. Volume reduction occurs through infiltration and evapotranspiration (STEP, 2022e). They are designed to capture small storm events, and an overflow or bypass is necessary for large storm events (CVC & TRCA, 2010).

Figure 10: Residential Rain Garden (left) and Commercial Rain Garden (right) (CVC & TRCA, 2010)

Similar to rain gardens, infiltrating bioretention gardens require a gravel layer and are much deeper than rain gardens with greater infiltration and volume capacity. Full infiltration bioretention gardens provide the highest level of SW volume control. This model is robust enough to support trees and can accept a considerable amount of water from larger impermeable areas such as parking lots. Infiltration bioretention gardens must be engineered with appropriate aggregates and substrates, an overflow pipe, and potentially monitoring or inspection wells (STEP, 2022f).

Partially infiltrating bioretention gardens contain a gravel water storage area and an underdrain that helps to empty the garden between storm events. Customizations in piping and substrates can improve filtering abilities. Partial volume reduction occurs by infiltration and evapotranspiration (STEP, 2022e).



Source: adapted from Wisconsin Department of Natural Resources bioretention details

Figure 11: Infiltrating Bioretention Garden Cross Section (CVC & TRCA, 2010)

Biofilters do not infiltrate and are made with a gravel layer, underdrain, and an impermeable liner. A biofilter may also be called a SW planter. They function like planters and do not allow infiltration (STEP, 2022e; Claytor & Schueler, 1996; CVC & TRCA, 2010). The restrictions on the structure are ideal for heavily contaminated areas or urban areas with lots of underground infrastructure. Volume reduction only occurs through evapotranspiration (STEP, 2022e).

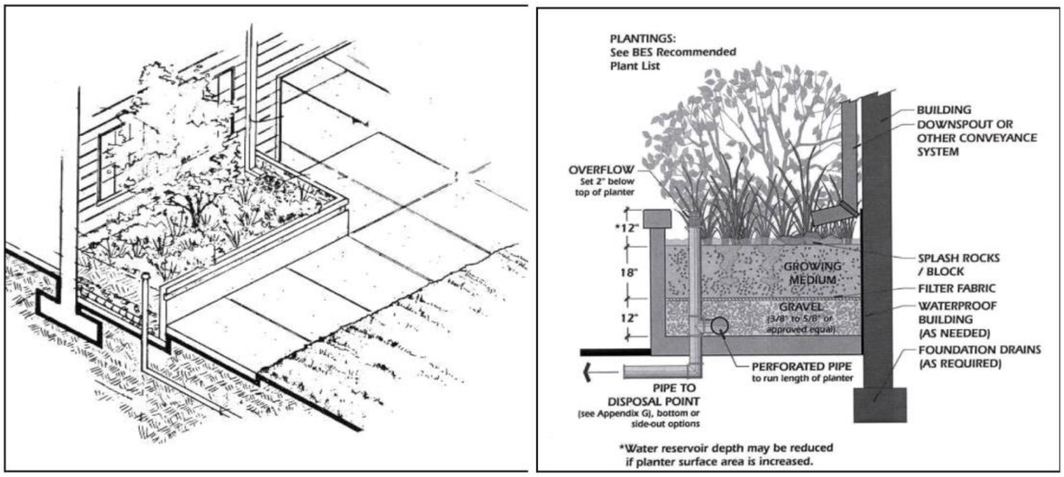


Figure 12: Planter Box Biofilter (non-infiltrating) (CVC & TRCA, 2010)

All forms of bioretention gardens can be customized and adapted to many development contexts and double as snow storage and treatment areas. For example, low-density developments may have open edges with gentle slopes, but high-density developments may have vertical sides and a hard edge (CVC & TRCA, 2010).

Green Roofs

Green roofs (GRs), also known as living roofs or rooftop gardens, replace conventional impermeable roof surfaces with vegetation and planting medium, a waterproof membrane, and a drainage filter layer (STEP, 2022g). GRs act like lawns or meadows by storing rainwater in the growing medium and ponding areas. They temporarily store rainwater, which is then evapotranspirated, evaporated, or slowly drained (CVC & TRCA, 2010).

GRs may be extensive or intensive. Intensive GRs have a thicker planting medium (>15cm) that accommodates larger plants with deeper root systems and often include walking and seating areas. Extensive GRs have a shallower planting medium suited for low-growing, drought-resistant plants. Intensive GRS are more common on commercial buildings, and extensive GRs are more common on residential buildings (STEP, 2022g; CVC & TRCA, 2010; Ahiablame et al., 2012).

Figure 13: Chicago City Hall Intensive Green roof (left) and York University Extensive Green Roof (right) (CVC & TRCA, 2010)

Water Harvesting Systems

Rainwater harvesting is the practice of intercepting, conveying, and storing rainwater for future use (CVC & TRCA, 2010). Gutters or conduits are directed from a catchment surface (i.e., roof) to a storage container for later use (STEP, 2022h). Containers may range in size from a rain barrel (RB) to a large, industrial cistern (CVC & TRCA, 2010). Domestic rainwater harvesting has gained popularity in recent years as a source of water (Cook et al., 2013). In rural Ontario, rainwater harvesting has been practiced for over 100 years (CVC & TRCA, 2010). Water harvesting in urban areas can reduce SW runoff and potable water demands. The water harvesting system may be connected to the house for non-potable use, in toilets or urinals, for example, or outdoors for use in the garden or for pressure washing (Campisano & Modica, 2016; STEP, 2022h). Water used for landscaping either infiltrates into the soil or evapotranspires through vegetation (CVC & TRCA, 2010).

Figure 14: Typical residential rain barrel set up (CVC & TRCA, 2010)

Soakaways, Infiltration Trenches, and Infiltration Chambers

Soakaways are rectangular or circular excavations with a geotextile lining and filled with a void-forming material such as granular stone. They receive runoff from a perforated pipe inlet, allowing water to infiltrate the surrounding soils. Water inflow may come from rooftops, walkways, driveways, or rainwater harvesting overflows. Other names include infiltration galleries, dry wells, or soakaway pits (CVC & TRCA, 2010).

Figure 15: Residential soakaway pit (City of Ottawa, 2022)

An infiltration trench (IT) is a channel made of gravel, covered with soil and vegetation, and underlain by a geotextile fabric to help prevent clogging (Eckart et al., 2017; CVC & TRCA, 2010). The gravel maximizes infiltration and creates significant storage in the pore spaces. These trenches work via storage and filtration, which slow the velocity of SW runoff. The reduced velocity allows sedimentation of suspended solids and other contaminants (Barkdoll et al., 2016). Runoff is usually received from the same sources as soakaways (CVC & TRCA, 2010).

Figure 16: Infiltration trench example from Cahill Associates (CVC & TRCA, 2010)

The choice of a soakaway or IT depends on the geometry of the available space. If one large area is available, a soakaway would be appropriate. However, an IT is considered suitable if the available space comes in the shape of long, thin strips (CVC & TRCA, 2010).

Infiltration chambers, also called infiltration tanks, are large in size and usually situated under parking lots or landscaped areas. They create void spaces for water that create temporary storage and allow for slow infiltration to the soil. Structures are usually open-bottomed with perforated side walls and optional underlying granular stone reservoirs. They may be individual or in a series of trenches or beds. With adequate pre-treatment, they can receive water from rooftops, walkways, parking lots, and roads.

Figure 17: Infiltration chamber example by StormTech (CVC & TRCA, 2010)

Perforated pipe systems are similar but designed for conveyance and infiltration. They consist of perforated pipes laid in gently sloping granular stone beds lined with geotextile fabric. This design allows infiltration into the gravel bed and underlying native soil and conveys water from source areas or other pre-treatment practices to an end-of-pipe facility or receiving waterbody (CVC & TRCA, 2010).

Downspout Disconnection & Redirection

Downspouts may be connected directly to a piped system that connects to the sewer system or directed to impervious surfaces, such as a driveway, that direct water off-property and toward catch basins. A "connected" downspout means that the water goes directly into the sewer system, often by pipe. In the RLT, it is more likely that downspouts are directed to sewers via the sump pump of a property or directed down a driveway to the street and into a catch basin. "Disconnecting" means changing the downspout so that it doesn't go to a sump pump or sewer-connected pipe. "Redirection" means directing the downspout toward a permeable surface rather than a hard surface, like a driveway. Disconnecting and redirecting downspouts to pervious surfaces prevents SW from entering the sewer system. Water can be redirected to a designated splash pad or pea gravel area to slow and spread the water onto a lawn. For improved performance, it can be directed to other LID such as soakaways, ITs, swales, or rain gardens (CVC & TRCA, 2010).

End-of-Pipe Practices

End-of-pipe practices involve mitigating pollution in SW at the point where effluent will enter the environment. In other words, the SW first travels through the "pipe system" untreated and then receives some degree of pollution control before the water escapes to the environment. In some cases, there is no pollution treatment at all. An example could be highway runoff entering a SWM pond for sediment settling before being released to a lake. The practices listed below have been included in this review as a part of the treatment-train approach. Many of these practices have the potential to offer innovative solutions that meet SW goals above and beyond baseline regulatory requirements.

Ponds and Wetlands

Stormwater management ponds (SWMPs) are common in Canada and other highly developed countries (Tixier et al., 2011). Originally invented to reduce peak flows and control flooding events, new research suggests that they can also incorporate treatment measures that are designed to protect downstream receiving water bodies (Tixier et al., 2011; Marsalek et al., 2005). These features may also be incorporated and designed to provide aesthetic or recreational opportunities, groundwater recharge, and aquatic habitat (Marsalek et al., 2005).

The *Stormwater Management Planning and Design Manual* (Ontario, 2003) classifies wetlands, wet ponds, dry ponds, and infiltration basins as end-of-pipe solutions as they can help to deal with water flow rates, not volume, and prevent flooding. Designs range from wetland to wet pond and are differentiated by their depth ratios. Wet ponds have the greatest percentage of deep-water zones with minimal vegetated, shallow borders. They have a permanent pool of water and allow sediments to settle before discharging. Shallow zones dominate surface wetlands. A dry pond is a grassy depression that may hold water for up to a week. It has no standing water and is primarily used for erosion and flood control. Infiltration basins are above-ground ponds constructed on highly pervious soils. Infiltrating water either recharges groundwater or travels via an underground perforated pipe network to a discharge outlet.

Constructed Wetland

A constructed wetland (CW) is designed and engineered to treat wastewater and manage runoff by removing sediments and pollutants. Different types of CWs vary in their difference from SWMPs. CWs may be divided into two types: surface and subsurface, where subsurface may have vertical or horizontal flow (UN-Habitat, 2008). In general, wetlands constructed to treat SW use a free water surface design. The inlet is a sedimentation pond, and water flows through a vegetated macrophyte zone for both flow attenuation and water treatment (Yang et al., 2022).

Horizontal subsurface flow CWs have an inlet on one end and an outlet on the other, leading to primarily horizontal flow through aerobic, anoxic, and anaerobic zones. Wastewater is cleaned as it passes through the rhizosphere, or root zone (UN-Habitat, 2008).

Vertical subsurface flow CWs, also called planted filter beds, have a flat bed of sand or gravel with vegetation at the top. They receive an intermittently dosed mechanical flow of water from above with outflow through a drainage pipe at the bottom. The system runs dry between doses, introducing oxygen to the filtration bed (UN-Habitat, 2008). The media (sand and gravel), plants, and microorganisms all play an important role in improving water quality (Perdana et al., 2018). Subsurface flow CWs can be used in a treatment train with another type of SWMP to improve overall water quality.

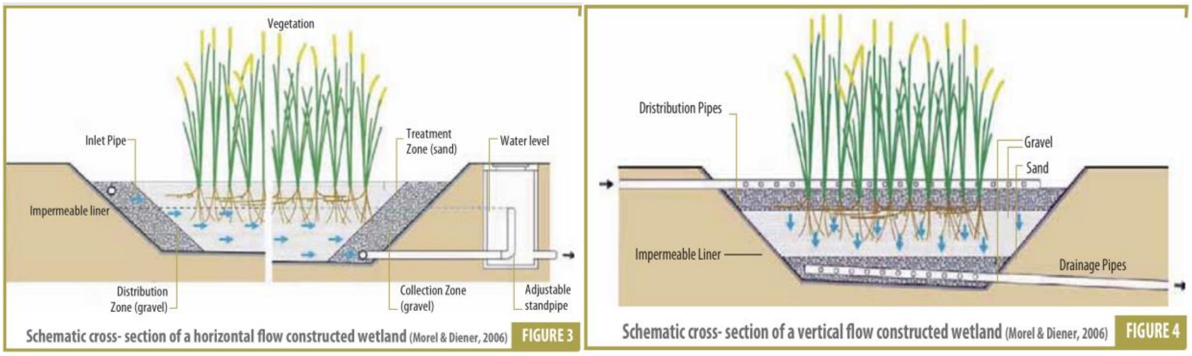


Figure 18: Horizontal flow CW (left) and vertical flow CW (right) (UN-Habitat, 2008)

Floating Treatment Wetlands

Floating treatment wetlands (FTW) consist of floating, porous mats planted with wetland vegetation that may be added to new or existing wet ponds to improve water quality treatment (Maxwell et al., 2020). They function similarly to subsurface flow CWs regarding rhizosphere contact and the influence of biofilms (Sharma et al., 2021). FTWs may be constructed using recycled PET bottles (Ziajahromi et al., 2020).

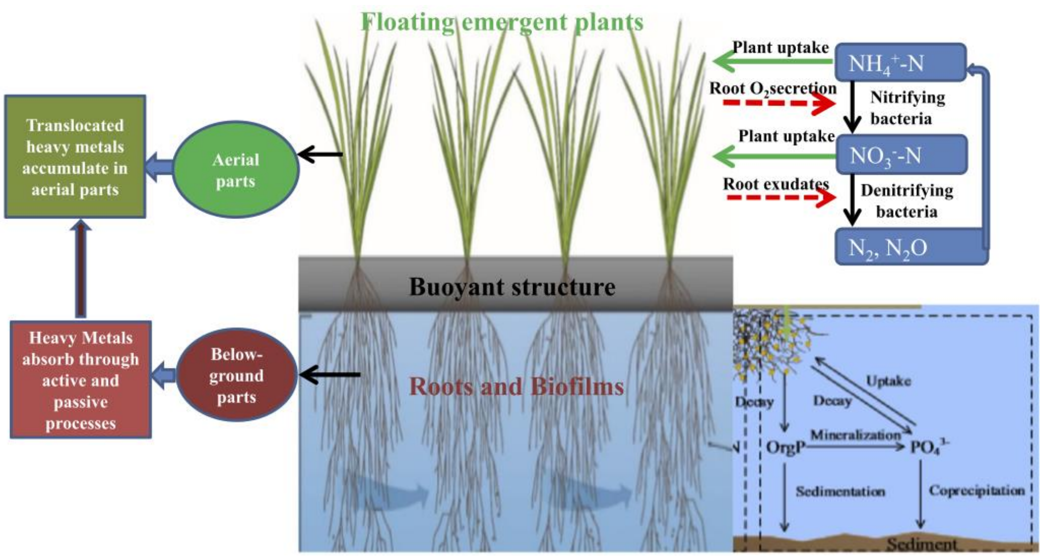


Figure 19: FTW diagram (Sharma et al., 2021)

Stratification and Aeration

Circulating or aerating water in ponds can oxygenate the water and prevent stratification of the water column, which is the division of water into layers by temperature and density. Cold water sits at the bottom (hypolimnion), and warm water sits at the top (epilimnion). Decomposition in the bottom layer uses up oxygen and can lead to anoxic conditions, which is dangerous for aquatic life and releases hydrogen sulfide gas. When the seasons change and temperature regimes shift, the pond may “turn over,” bringing up the anoxic water and killing fish (Clemson University, 2022).

Mechanical circulation and aeration can help prevent stratification, specifically in small, human-made ponds and wetlands. Diffusion systems pump air into the bottom of a pond that bubbles up to the surface, resulting in gentle water mixing and aeration. The downside is that circulation systems can keep sediment in the water column, reducing water clarity and potentially causing shoreline erosion. The requirement for energy means an increase in GHG emissions associated with operating the pond (Clemson University, 2022). Aeration devices are never recommended for natural water bodies.

Fountains are not considered an aeration device, as they only operate in the epilimnion at the top of the pond, which already freely exchanges oxygen with the surrounding air. They are primarily considered an aesthetic choice and do very little to prevent stratification (Clemson University, 2022).

Pre-Treatment Technologies

Catch basins (CB), also known as storm drains, are an essential part of drainage systems, especially in older areas. Traditionally, they are an end-of-pipe technology that focuses on moving the water quickly away from private or public property. They are made from various materials, including steel-reinforced or non-reinforced concrete, brick and mortar, plastic, or polymer materials. CBs may catch, hold, filter, direct, and transport water to local waterways or treatment facilities through underground pipe systems. CBs consist of a runoff grate, an inflow pipe, an outlet trap to retain some sediment and debris, and an outlet pipe (Everly, 2020).

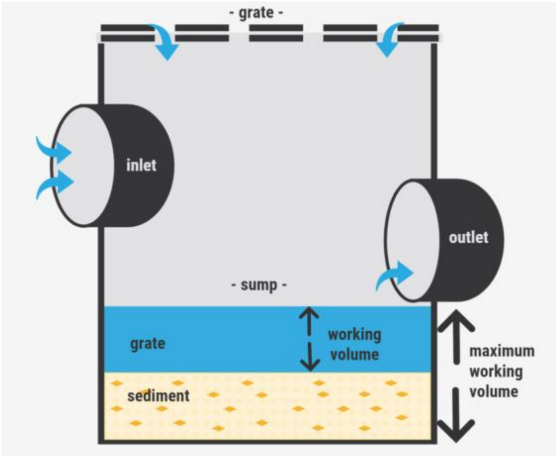


Figure 20: Basic CB cross section (Rothman, 2022)

Many pre-treatment CB technologies have been developed in response to the issues caused by this typical, end-of-pipe grey infrastructure. Pre-treatment should be considered where collected and conveyed runoff is concentrated as overland flow with an increased flow rate.

Pre-treatment associated with CBs is categorized as concentrated underground flow or pipe flow and includes CBI, oil and grit separators, utility hole baffles, isolated chamber row filters, membrane filters, and media filters. CBI, membrane filters, and media filters are more commonly used as "stand alone" water quality treatment practices when space for LID is not available but may also be used downstream to improve sediment and pollutant removal where needed based on receiving water sensitivity. These CB pre-treatment solutions are described below (STEP, 2022i):

- CBIs work well to improve water quality in retrofit situations. There are many types of CBIs that may target large debris and trash, small sediments, nutrients, etc.

- Oil and grit separators generate a water vortex that uses centrifugal force to separate sediments into an alternate chamber. Floating debris, oil, and grease are trapped behind a baffle or in a small tank area, towards the top of the main vortex chamber.
- Utility hole baffles slow flow, which allows heavier particles to drop out of the water column and may include skimmers to trap debris, oil, and grease.
- Isolated chamber row filters are large, underground structures that have separate cylindrical chamber rows with geotextiles, not connected by pipes to the other chambers. They isolate the bulk of sediment and associated pollutants, which may be removed through backflushing.
- Membrane & Media Filters are used either beneath the CB grate or nearby along the underground pipe system. There are a variety of proprietary designs and media mixes that come in various forms. Each one has different filter capabilities and capacities. Membrane filters use advanced filter technology that has been adapted from water treatment plants.

Figure 21: CBI example featuring StormSack (Echelon Environmental, 2022)

Filter Media

Sand filters in Ontario are a pre-treatment, end-of-pipe SWM solution. They offer water quality control, with no benefits to erosion or water quantity control (Ontario, 2003). There are many types of sand filters, including surface sand filter, underground sand filter, perimeter sand filter, organic filter, bioretention filter, and pocket sand filter (Eckart et al., 2017; Ontario, 2003). Sand filters with varying designs and filter media may be used as part of an LID treatment train.

Surface and underground sand filters are the most common (Ontario, 2003). Surface sand filters consist of two chambers: a pre-treatment sedimentation chamber and a pollutant filter bed. Underground sand filters are fitting for space-limited sites. The sand filter is placed in an underground vault that can be accessed by utility hole. A perimeter sand filter is made up of two parallel trenches, usually installed around the perimeter of a parking lot. A pocket sand filter is a cheaper, more simplified design that can be used for smaller sites (Claytor & Schueler, 1996).

An organic filter is the same as the surface sand filter, except it utilizes compost or peat to improve the filtration of nutrients and trace metals. Bioretention filters are like surface filters but include open space and landscaping areas (Ontario, 2003).

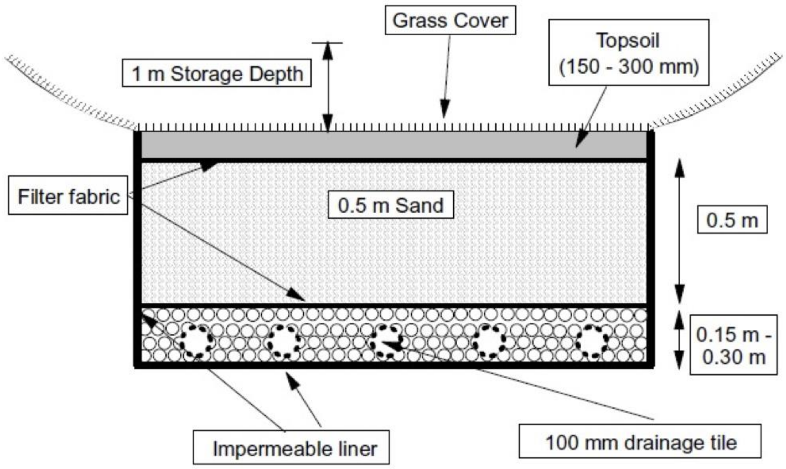


Figure 22: Basic sand filter cross section (Ontario, 2003)

Benefits and Considerations of LID Practices

General Benefits of LID

Beyond SWM, various LID practices have been shown to provide other far-reaching benefits, including reduced energy consumption, reduced urban heat island (UHI) effect, improved air quality, improved community livability, improved public health, wildlife habitat, improved aesthetics, increased park space, and citizen community involvement (Eckart et al., 2017; CNT, 2010).

Conventional SWM methods aimed at reducing flooding and improving drainage are incredibly costly. LID reduces the burden on this conveyance network by keeping water where it falls, proving more cost-effective than traditional methods alone (Eckart et al., 2017). Eckart et al. (2017) summarized several case studies with impressive examples of the cost efficiency of LID-based systems. Xu et al. (2019) cited numerous sources repeatedly demonstrating that GI outperforms grey infrastructure when considering environmental impact and LCA analysis. Compared to a detention pond, the life cycle impacts of LIDs are 20% lower, and the benefits of LIDs are 300% higher (Xu et al., 2019). Another study by Abdeljaber et al. (2022) conducted an eco-efficiency analysis. For a 30-year period, all LID options considered were more cost-effective with lower environmental impacts than traditional stormwater systems.

LID practices can be used strategically depending on land use. Vegetated LID technology has been shown to have the most benefits to biodiversity near waterways, to social and public health in heavily developed areas, and water quality in commercial and industrial areas (Jessup et al., 2021). Commercial areas tend to have more engineered LID solutions, green spaces tend to be soil and vegetation-based, and residential areas are a mix of both (Kong et al., 2021).

There are many advantages of using a variety of LID technology over a large area. Overall, it was shown that LID solutions at the catchment level reduced pollutant levels, reduced water volumes, and improved the water quality of receiving bodies (Kong et al., 2021). Areas with focused LID technology have been shown to remove 95% of suspended solids (SS) (Ma et al., 2019). Catchment-wide LID practices could mitigate stream salt contamination by dilution from enhanced groundwater recharge (Gu et al., 2019). For all LID techniques, the operation phase of the life cycle is more environmentally friendly because of reduced air and water pollutants (Xu et al., 2019). These findings are echoed in a specific case study conducted at a site in Mississauga, Ontario, by Bhatt et al. (2019). LID technology can make a positive impact on the annual hydrologic budget at the watershed scale of traditional subdivisions (Dietz & Clausen, 2008). Standard, routine inclusion of LID technology in SWM planning can also make our communities more adaptive under future climate change model scenarios (Pyke et al., 2011). For example, LID practices show significant potential at the regional scale to reduce GHG emissions and store C (Xu et al., 2019).

General Considerations for LID

All initiatives come with inherent risks, and LID technology is no exception. In general, our communities will be more adaptable under climate change with the help of sustainable drainage initiatives (Pyke et al., 2011); however, the capacity of LID systems to reduce both volume and peak discharge rates diminishes with increasing storm intensity with climate fluctuations. LIDs perform best in warmer weather with smaller storm events of low intensity, duration, and moisture level (Sohn et al., 2019).

A major concern with any SWM strategy, including LID, is the potential to contaminate groundwater with stormwater pollutants (CVC & TRCA, 2010). One study also showed the potential for increased human exposure to pathogens via LID technology (Ishaq et al., 2020). It should be noted that finer particles are more likely to contain heavy metals and to bypass LID technology. As a result, special considerations should be given to fine particles in the 10 - 105 µm range (Ma et al., 2019). When considering nutrient removal, N in its various forms and dissolved P is challenging to remove, and some LID practices can cause N or P leaching (Kim et al., 2003; Kong et al., 2021).

Swales

Benefits

Swales are one of the most affordable LID in the LCA operation phase (TRCA & UT, 2013). The infiltration rate of underlying soils determines the water balance benefit from swales. Runoff reduction for grass swales ranges between 0-41% and 20-99% for bioswales. The conservative estimate of runoff reduction for grass swales on high permeability soils (sand to loam) is 20%, and 10% for lower permeability soils (loam to clay). For bioswales, the conservative estimate is 45% with an underdrain and 85% without an underdrain (CVC & TRCA, 2010).

Monrabal-Martinez et al. (2018) found that the longitudinal slope of bioswales did not affect the infiltration capacity and managed the inflow entirely. As an example, the same bioswales could capture 90% of the runoff generated by a 12.2 mm/h storm on a road with 40x the surface area. Grass swales cannot completely manage water inflow.

Pollutant removal by grass swales is moderate for most pollutants (Deletic & Fletcher, 2006). Site-specific factors such as slope, soil type, infiltration rate, swale length, and vegetative cover affect pollutant removal (CVC & TRCA, 2010). Extended retention time and increased infiltration in a grass swale have been considered the most important factor in pollutant removal (Bäckström, 2003; CVC & TRCA, 2010; Deletic & Fletcher, 2006; Schueler, 1994). The reaction can be prolonged by decreasing the longitudinal slope and increasing the length of the swale (Stagge et al., 2012). Check dams improve hydraulic performance in small to moderate storms up to 30 mm (Davis et al., 2012). However, Stagge et al. (2012) showed minimal water quality impacts using check dams. Davis et al. (2012) showed that most water quality improvement is due to swales but check dams can positively impact performance. Further, pre-treatment, such as filter strips or gravel diaphragms to slow flow velocity and improve sheet flow, can enhance pollutant removal rates (CVC & TRCA, 2010). Pollutant removal rates for bioswales can be high as a result of the bioretention element. Specific pollutant removal rates in swales from various studies are outlined below:

- Swales have been well studied for their ability to successfully remove total suspended solids (TSS) and metals from road runoff through settling (Gavrić et al., 2019; Li et al., 2016; Stagge et al., 2012).
- The average nutrient and TSS retention in swales ranged between 14% and 98% across multiple studies (Ahiablame et al., 2012).
- Median pollutant mass removal rates of swales from available performance studies are 76% for TSS, 55% for total phosphorus (TP), and 50% for total nitrogen (TN) (Deletic & Fletcher, 2006).
- Swales have similar C sequestration density and accumulation values to grasslands. C density does not differ between grass or wet swales, but wet swales are more effective for % total C (Bouchard et al., 2013).
- In a lab study with constructed swales (Fardel et al., 2020), standard grass swales and bioswales (made of a sandy central part bordered by silt loam embankments) were tested for their ability to infiltrate SW and filter micropollutants: zinc, polycyclic aromatic hydrocarbons (PAHs) and glyphosate (common pesticide).
    - Standard grass swales removed 33–67% of micropollutants and partially managed SW by infiltration.
    - Bioswales removed 65-100% of micropollutants and completely managed the SW runoff by infiltration.

According to a literature review conducted by Ekka et al. (2021), well-maintained infiltration swales (grass swales with check dams) are the best option for runoff volume reduction and removal of sediment and heavy metals. Wet swales are the most effective swale alternative for N treatment, and bioswales are considered the most effective in treating pollutants, P, and bacteria (Ekka et al., 2021).

The number of species, species richness, and diversity were higher in bioswales than in either gardens or lawns in an urban setting, indicating that swales can contribute to urban biodiversity (Kazemi et al., 2011).

Considerations

Despite a wide body of literature, water quality and swale pollutant removal is inconsistent and poorly understood (Gavrić et al., 2019). High degrees of variability in swale design, runoff characteristics, and vegetation and soil conditions contribute to inconsistent results for nutrient removal (Ekka et al., 2021; Gavrić et al., 2019; Stagge et al., 2012).

Heavy metal removal ability for swales is primarily driven by sediment adsorption processes, so swales do not perform efficiently when it comes to dissolved heavy metals (Ahiablame et al., 2012). Swales receiving runoff from zinc roofs have shown high zinc concentrations (up to 27.9 g/kg dry mass) at inflow zones after 15 years of use. The risk of groundwater contamination, in this case, is high because contamination exists even in deeper soils, and sorption potential is exceeded (Rommel et al., 2019).

There are a few risks associated specifically with swales in cold climates. Snow may be contaminated with heavy metals and other pollutants from salt and grit application, and studded tires and vehicles release more metals in cold seasons. Contaminated snow shoveled into swales can result in high concentrations of heavy metals in swale soil (Gavrić et al., 2021). Swales can also accumulate Cl during the winter and release it throughout the rest of the year (Stagge et al., 2012).

Frequent warming and cooling render soils particularly vulnerable to frost (Zaqout et al., 2022). Peak flow attenuation is three times lower in winter compared to summer, primarily due to frost formation and reduced soil porosity (snow was a lesser factor) (Zaqout & Andradóttir, 2021). However, vegetated areas with high near-surface porosity within the intertwined root layer and high drainage underlying soil maintain swale performance during winter (Zaqout et al., 2022). Further, swales with engineered filter media will perform better in winter than traditional SWM swales (Roseen et al., 2009).

Permeable Pavements

Benefits

PPs provide water balance benefits through water storage, evaporation, and infiltration. Systems with underdrains and/or liner will have varying water balance benefits based on infiltration rate and storage volume. Runoff reduction rates without underdrain are 72-100% and 45-99% with an underdrain. The conservative estimate for LID screening is 85% without underdrain and 45% with underdrain. Stream channel erosion prevention depends on runoff reduction (CVC & TRCA, 2010).

Regarding flood mitigation, PPs have consistently shown a minimum degree of volume reduction regardless of location or design: ~30% volume reduction with sandy soil and ~70%+ peak flow reduction (with high variability) (Drake et al., 2013). All PP systems tested had the ability to alleviate stormwater runoff by changing around half the precipitation to subsurface discharge at a base flow level of 0.3 mm/h or less, and total volume reduction by evaporation ranged from 3% to 37% (Stovring et al., 2018). They also introduce peak flow median lag time of 1:38 h, spanning 0:39–3:16 h (Stovring et al., 2018). Under certain substrates, PPs may provide improved tree growth, contributing to urban evapotranspiration effects (Drake et al., 2013).

Pervious concrete permeability ranged between 900 to 21,500 mm/hr (Roseen et al., 2012; Selbig & Buer, 2018; STEP, 2022c) and remained in excess of 5000mm/hr when frozen (Houle et al., 2009). Porous asphalt has the largest void space and highest permeability (Selbig & Buer, 2018), its infiltration capacity ranges from 14,900 to 26,900 mm/h, and the hydrologic performance does not change seasonally due to freeze-thaw effects (Roseen et al., 2012). Surface infiltration capacities may remain in excess of 5000 mm/hr when frozen (Houle et al., 2009). Porous asphalt stores heat and releases it, melting ice and snow (Roseen et al., 2012), which results in requiring 0 to 25% of the salt routinely applied to normal asphalt (Houle et al., 2009). Porous pavement systems are the most cost-effective LID practice for peak flow reduction (Xu et al., 2019).

Pollution removal capacity depends on infiltration capacity. Since partial infiltration designs create more runoff, the pollution removal for these examples will be lower (CVC & TRCA, 2010). All PPs showed a reduction of pollutants, including TSS, SSC, TP, *E. coli*, and *Enterococci* (Selbig & Buer, 2018). Infiltrated water was consistently basic pH (8-9.5) compared to acidic asphalt runoff (Drake et al., 2013). Average runoff reduction across numerous studies on porous pavements ranged from 50-93%, in some cases achieving pre-development hydrology (Ahiablame et al., 2012). Average TSS reduction between 0-94%, average metal reduction between 20-99%, grease attenuation, and *E. coli* mitigation have been demonstrated in a body of literature (Ahiablame et al., 2012).

Permeable interlocking pavements removed 60% TSS, reduced TP 20%, and reduced metals 42%, but were least effective at removing E. coli. Pervious concrete removed 60% of TSS, reduced TP 43%, and reduced metals 49%. Pervious concrete showed elevated pH values (median 10.2), likely contributing to P precipitation, and was the most effective at reducing E. coli. Lastly, porous asphalt removed 60% TSS, reduced TP 20%, reduced metals 40%, and was moderately effective at reducing E. coli (Selbig et al., 2019).

Concrete/plastic grid systems offer a stable, highly porous, strong, abrasion resistant, rut proof, aesthetically pleasing and inexpensive alternative to porous asphalt or concrete. This is a good low-cost alternative for municipalities meeting SW goals (Handlos, 2014). A cross-section with 12-inch (305-mm) deep base course (at 20% void space) and the one inch of Gravel Paver (at 35%) would store 2.75 inches (70 mm) of rain (Terrafix, 2022). Similarly, a one-inch (25-mm) Grass Paver with sand and a 12-inch (305-mm) base course can store 2.6 inches (66 mm) of water (13 inches x approx. 20% void space) (Terrafix, 2022). The cellular grid reduces compaction of the soil to maintain permeability, while the grass roots improve water infiltration due to their channels (Walker, 2013). They are recommended for use in parking lots, driveways, fire lanes, and pathways (University of Rhode Island, 2018).

Interestingly, porous surfaces absorb sound energy and dissipate air pressure around tires. For this reason, tire noise is lower in loudness and pitch for porous pavement (Ferguson, 2005).

Considerations

Clogging is a significant concern in the long-term performance of PP. Porous asphalt is least sensitive to clogging but most difficult to maintain, permeable interlocking pavements are moderately sensitive to clogging but joint aggregate can be easy to replace, while pervious concrete is the most sensitive to sediment loading but easiest to maintain (Selbig & Buer, 2018). In one study, the median infiltration rate of the PP decreased 96% over 20 months due to clogging, attributed to lack of proper maintenance and improper loading ratio, which was much too high at 27.6:1 (Tirpak et al., 2021).

Road salt can permeate and migrate through the bedding and into the groundwater system. However, if the surface is well-draining, there will be less frozen area and a lesser need for road salt compared to impervious pavement (Roseen et al., 2007).

Porous materials have less thermal conductivity and thermal capacity than traditional impervious pavement, which has the potential to reduce the UHI (Ferguson, 2005). However, PPs do not consistently mitigate the UHI effect (Drake et al., 2013; Selbig & Buer, 2018). Mitigation of UHI depends on water storage and corresponding evaporative capacity, which varies (Selbig & Buer, 2018).

Kuruppu et al (2019) reviewed the literature to summarize limitations in understanding about PPs. They found a lack of in-depth scientific understanding and economic uncertainties, lack of availability of cost data and difficulties estimating intangible benefits, challenges in co-optimizing environmental, hydraulic, and structural performances by modifying design, and difficulties of simulating actual field conditions to investigate the clogging phenomena via laboratory experiments. There is no standard model for design variations vs structural, hydraulic, and environmental performance, no standard maintenance procedure to restore infiltration capacity, and a limited bearing capacity for higher vehicular loads and speeds.

PPs can be very expensive, and their benefits may not outweigh costs. One study showed that PP had the worst cost-effectiveness ratio out of the LID studied (Yang et al., 2020). Another study showed that considering life cycle environmental and economic performance, permeable interlocking concrete pavements were the most expensive over a 30-year period but offered the least runoff reduction (Abdeljaber et al., 2022). TRCA & UT (2013) also showed that PPs are comparatively more expensive according to LCA, but some costs can be offset when considering that the area would have had a paving cost either way to provide a parking surface.

Bioretention Gardens

Benefits

Bioretention gardens can be efficiently used to capture runoff, promote infiltration, promote evapotranspiration, recharge groundwater, protect stream channels, reduce peak flow, and reduce pollutant loads owing to native and perennial vegetation such as grasses, shrubs, sedges, rushes, and perennial stands, planted on a variety of medium configurations (e.g., mixture of soil, sand, mulch, and organic matter) (Dietz and Clausen 2005; Dietz 2007; Davis 2008; Davis et al. 2009).

Infiltrating bioretention gardens offer the greatest water balance benefit via evapotranspiration and infiltration, while those with an underdrain and/or impermeable liner are limited to their storage volume. All types offer water quality improvements and pollution filtration. Runoff reduction and stream channel erosion benefits depend on infiltration and storage rates. Runoff reduction ranges between 20-99% and the runoff reduction estimate for LID screening is 85% without an underdrain, or 45% with an underdrain (CVC & TRCA, 2010; Ahiablame et al., 2012). During small events, bioretention facilities can readily capture the entire inflow volume (Davis 2008). Li et al. (2009) showed between 20 % to 50 % of received stormwater runoff is mitigated through exfiltration and evapotranspiration. Chapman and Horner (2010) showed that 48 % to 74 % of runoff that flows through bioretention systems left in the form of infiltration and evaporation.

Laboratory and field studies show that bioretention practices have the potential to be the most effective pollutant removal LID. Pollutants are removed via sedimentation, filtering, soil adsorption, microbial processes and plant uptake (CVC & TRCA, 2010). According to the literature review by Aiablame et al. (2011), average metal reduction in bioretention varies between 30% and 99% and average retention of bacteria in bioretention ranges from 70% to 99%. Luell et al. (2011) found that 84% to 50% of TN and TSS, respectively, were retained by the bioretention systems. Other studies reported up to 76% reduction for TSS (Line & Hunt, 2009), between 70% and 85% of P, and 55% to 65% of total Kjeldahl nitrogen (TKN) (Davis et al., 2006). This efficiency is relatively well documented for most nutrients, except for nitrates (NO3–N) for which a reduction of less than 20% is reported (Davis et al. 2006). Bioretention performed better at removing microplastics than a sand filter in a treatment train paired with pre-treatment buffer strip (Lange et al., 2022).

Bioretention gardens are suitable for residential and commercial settings (Dietz, 2007) and can also be used for agricultural water quality improvement (Ergas et al., 2010). One model showed that up to 21% of impervious areas could be redirected to rain gardens (Autixier et al., 2014).

Bioretention gardens reduce the UHI effect since they absorb less radiation than pavement and evapotranspiration has a cooling effect on the ambient air. By intercepting runoff, bioretention practices protect aquatic life from thermal impacts on receiving waters (CVC & TRCA, 2010). In winter months, bioretention effectively captures and treats runoff between –5 to 10°C (CVC & TRCA, 2010; Roseen et al., 2009).

Considering LCA costs, bioretention gardens are one of the cheapest options for operation. LCA of bioretention gardens compared to traditional wastewater facilities show that bioretention gardens have 62 to 98% less environmental impact, with maintenance and climate change being the biggest offenders (Xu et al., 2019).

Considerations

Pollutant reduction ability depends on the growing medium and maintenance protocols used (i.e., fertilizer application). Leaching from the soil substrate can result in excess nutrient release, especially P (CVC & TRCA, 2010; Dietz & Clausen, 2005; Hunt et al., 2006). Bioretention gardens have also been shown to be net producers of N and ammonia (Davis et al., 2001; Dietz & Clausen, 2005). Organic and ammonia N captured during storm events can be converted to nitrate by natural processes and this nitrate is released upon subsequent rain events (Kim et al., 2003).

Bioretention gardens are not effective for large storm events (Autixier et al., 2014) and should be designed with an outflow for these cases.

LCA has shown that the largest environmental impact of bioretention gardens is during the installation phase, but the operation phase can offset C emissions in four years (Xu et al., 2019).

Green Roofs

Benefits

GRsimprove energy efficiency, reduce UHI effects, and create greenspace for passive recreation, aesthetic enjoyment, and habitat, and improve water quality, water balance, and peak flow control benefits (CVC & TRCA, 2010). Performance is influenced by several factors such as roof geometry, thickness of the substrate, porosity, degree of saturation, soil type, drainage system and selected plants (Alim et al., 2022).

Runoff reduction ranges between 50-85%, and the conservative runoff reduction estimate for screening purposes is 45-55%. Runoff reduction helps to reduce stream channel erosion (CVC & TRCA, 2010). The worldwide average water retention capacity of GRs is around 66.2% (Alim et al., 2022). Average rainfall retention by GRs in general varies between 20-100%. During a rainfall event, once the water holding capacity of the roof material is reached, the excess water is converted into runoff (Ahiablame et al., 2012).

GRs may be a source or sink of nutrients depending on composition of the substrate, depth and geometry of the structure, vegetation planted, maintenance practices, rainfall intensity and frequency, and any fertilizer application (Alim et al., 2022). A GR may act as a source of pollution only when it is saturated. Initially, it contains elevated concentrations of pollutants, but they drop significantly over time. As substrate depth increases, the potential for the substrate to be a source of pollution also increases. In other words, GRs tend to be a sink for pollutants closer to the surface, and vice versa with depth (Alim et al., 2022). Extensive and intensive vegetated roofs act as a sink for nitrate N and ammonium N. Intensive roofs are a TN sink. P releases have been noted from extensive roofs, but not intensive. Both extensive and intensive roofs release DOC. Neither is a significant source of metals, and they both increase water pH (Berndtsson et al., 2009).

The temperature reduction by GRs in buildings ranges between 4-6°C. Variable potential for related energy savings is between 9-50%. The average payback period is 16 years, but this depends on many factors including initial cost, maintenance, and assumed discount rate (Alim et al., 2022).

GRs can extend the life of a roof by as long as 20 years by reducing exposure of the roofing materials to sun and precipitation (CVC & TRCA, 2010). GRs can reduce the life cycle environmental impacts of a building by reducing energy consumption. Respecting general product life cycle, GRs are more environmentally friendly than conventional roofs. Potential profit is considerably higher than losses considering life cycle cost-benefit analysis (Xu et al., 2019).

Considerations

GRs are not effective for nutrient removal and may present increased risk over time due to nutrient leaching. Similarly, GRs show mixed performance regarding heavy metal filtration. While careful design and selection of media are recommended as solutions, it may be simpler to maintain water quality by routing runoff from GRs to another LID for treatment (Ahiablame et al., 2012).

In a LCA analysis for LID, GRs were the most expensive due to low accessibility locations and special engineering for building integrity (TRCA & UT, 2013).

Water Harvesting Systems

Benefits

Water harvesting could be an important component of urban SWM in the future (Fletcher et al., 2013). Rainwater harvesting systems used for irrigation can provide water balance benefits as water is infiltrated or evapotranspired following storage. Reducing runoff volumes can also help to reduce stream channel erosion, especially when used in series with other LID (CVC & TRCA, 2010). Simulations show that significant potential for runoff peak reduction exists, basically depending on the rainwater tank size and on the characteristics of the water demand of the property (Campisano & Modica, 2016). Water harvesting systems that supply daily (as opposed to seasonal) water demands are more efficient for stormwater runoff reduction (Fletcher et al., 2013). Rainwater harvesting can potentially reduce flooding effects up to 28% (Akter et al., 2020). Volumetric runoff reduction by cisterns varies from 23-90% depending on study location, but the general estimate to be used for initial screening is 40% (CVC & TRCA, 2010).

Water harvesting systems contribute to pollutant reduction by storing water and preventing runoff. If all of the water from a rain event is stored, the pollutant load going to receiving waters has been reduced to zero. The extent of water storage and pollution reduction depends on the relationship between post-storage water use and the holding capacity of tanks (CVC & TRCA, 2010).

Water harvesting systems are suitable for areas where past or current land use presents a risk or highly contaminated runoff (CVC & TRCA, 2010). These systems can also offer conservation of groundwater in areas that use groundwater resources (STEP, 2022h).

One study showed that RBs are the most cost-effective LID option (Yang et al., 2020). Water harvesting systems are one of the most affordable options for life cycle costs in the operation phase, with added cost savings considering the cost demand on potable water supply and downstream infrastructure and management of stormwater (TRCA & UT, 2013; STEP,2022h). Outdoor residential water use can make up 40% of domestic use of potable water during the summer months. Significant cost savings are therefore possible due to delayed expansion of municipal potable water treatment and distribution systems with increased population, lowered energy consumption for treating and pumping, and lowered residential water bills (CVC & TRCA, 2010).

Considerations

Detention storage of stormwater, including water harvesting systems, can affect flow regime and have both hydraulic and hydrologic consequences. Reducing peak flow through storage can result in increasing the duration of flow above a critical discharge (Burns et al., 2012). This can change based on how the water is used (I.e., for landscaping, which returns the water to the natural hydrologic cycle, or domestically, which sends it away for treatment as waste water, etc.).

The benefits of water harvesting systems depend on proper use. If the collected water is not being used, then the storage capacity is not available for future rain events and the effectiveness is negated. Furthermore, standing water presents a risk for mosquito proliferation (CVC & TRCA, 2010). Suggestions to mitigate these issues are offered in the Design and Maintenance Recommendations section.

Soakaways, Infiltration Trenches, and Infiltration Chambers

Benefits

Soakaways, ITs and chambers offer water balance and quality benefits through infiltration. Pollution removal occurs via sedimentation, filtering, and soil adsorption. Rate of pollutant removal depends on infiltration. For example, if 100% of the water from a rain event is infiltrated, then the pollutants leaving the site via runoff are zero. Volume reduction and associated erosion reduction depends on the infiltration rate of surrounding native soils. The runoff reduction rates are similar to perforated pipe systems and range between 60-95%. One study demonstrated 87% peak flow reduction during a two-year monitoring period (Roseen et al., 2009). The conservative reduction estimate used for option screening is 85% (CVC & TRCA, 2010). This shows significant potential for preventing downstream erosion.

In an eco-efficiency analysis, Abdeljaber et al. (2022) found that ITs were the most cost-efficient LID and that combinations of LID involving ITs were also the most cost efficient. Additionally, they found that ITs offered the greatest runoff reduction. TRCA & UT (2013) also found that they have some of the lowest life cycle costs for operation.

Considerations

The considerations or drawbacks of soakaways, trenches, and infiltration chambers are limited in the literature. General considerations for this LID are similar to other infiltration devices in terms of groundwater contamination, which is covered in the General Considerations for LID section above. Other risks are related to design specifications, which are discussed in the Design and Maintenance Recommendations section below.

Downspout Disconnection & Redirection

Runoff reduction and water quality improvement depends on soil type, slope, vegetative cover, and flow path length. Research for downspout disconnection is very limited. Runoff reduction ranges from 20-70% and the conservative estimate for screening is either 50% for permeable soils ranging from sand to loam or 25% for less permeable soils ranging from clay loam to clay (CVC & TRCA, 2010).

Risks related to downspout disconnection depend on specific site conditions such as soil permeability, slope, and proximity to a foundation or basement. These concerns are addressed in the Design and Maintenance Recommendations section below.

Ponds and Wetlands

Benefits

In general, wetlands, ponds, and retention basins are effective for pollutant removal (Fletcher et al., 2013). Heavy metals can be settled, filtered, and bio-assimilated by microorganisms (Walaszek et al., 2018). They may be significant sinks of both P and N by sedimentation, but resuspension may reintroduce nutrients to the water column (Griffiths & Mitsch, 2020). There are variations in physio-chemical parameters including temperature, dissolved oxygen, pH, and redox potential that are caused by seasonal changes and variations in wet or dry weather (Walaszek et al., 2018).

Compared to traditional stormwater ponds, constructed stormwater wetlands demonstrate a higher potential for C sequestration, vegetative diversity, and cultural, recreational, and educational opportunities (Moore & Hunt, 2012). CWs have been well studied for their ability to remove pollutants, attenuate peak flows, and deliver ecosystem services (Al-Rubaei et al., 2022).

Subsurface CWs have several advantages compared to surface wetlands. There is little risk of odors, exposure, or insect vectors. Direct contact with the rhizosphere improves performance for reducing organics and nutrients, similar to FTWs (Perdana et al., 2018). Vertical subsurface flow CWs have even been studied for their potential to treat domestic wastewater (Perdana et al., 2018). Horizontal subsurface flow CWs are a sustainable and proficient treatment and are low maintenance, simple, and have low operating costs (Sacco et al., 2021). Peak flow attenuation was shown to be between 97-100% in all seasons for a treatment train system consisting of a receiving water settlement pond followed by a vertical subsurface flow CW (Walaszek et al., 2018).

Sharma et al. (2021) reviewed the literature regarding the effectiveness and processes of FTW. FTW are an excellent way to enhance existing stormwater ponds or other water bodies treating or storing stormwater because they have flexible design and operation, they are environmentally friendly, and they do not increase demands on land use. They are not affected by water level changes and can be used in many scenarios, including existing SWMPs, lakes, canals, and riverine estuary developments that are highly polluted and require additional treatment. FTW can be used to remediate toxic heavy metals, nutrients, suspended solids, and other pollutants from wastewater. Biofilms found under FTW in the rhizome layer increase their pollutant removal potential.

Compared to grey infrastructure, wetlands have lower life cycle costs after the two-year mark (Xu et al., 2019). CWs have a long lifecycle potential and are predicted to last at least two decades with minimal maintenance while still maintaining effectiveness and performance standards if designed well and regularly inspected for major issues (Al-Rubaei et al., 2022).

Microplastics are an emerging environmental threat that has serious implications for wildlife and human health and stormwater is a dominant contributor of microplastics to the aquatic environment. Research is limited, but preliminary data suggests that bioretention and filtrations may remove 84-96%, wetlands 28-55%, and retention ponds 85-99% of microplastics (Stang et al., 2022). FTWs made from recycled PET bottles do not appear to increase microplastic concentrations (Ziajahromi et al., 2020). Wetland sediments can act as a sink for microplastics, especially car tire bits. However, the first flush effect can result in the release of these microplastics to surface waters (Ziajahromi et al., 2020).

Considerations

Retention systems have a limited ability to reduce overall runoff volumes because the only losses are due to evapotranspiration (Fletcher et al., 2013). Wetlands, ponds, and other types of detention storage can affect flow regime and have both hydraulic and hydrologic consequences. Reducing peak flow through storage can result in increasing the duration of flow above a critical discharge (Burns et al., 2012).

SWM ponds and wetlands have intentionally or incidentally provided habitat for wildlife, which may provide high-risk environments due to a lack of intentional planning and uncontrolled pollution from highway runoff. These circumstances may result in ecological traps, which display ecological indicators to wildlife that lead them away from more desirable habitats and toward hazardous ones that lower their fitness (Hale et al., 2019).

Related contaminants and persistent contaminants exceeding guidelines can bioaccumulate or have toxic effects (Marsalek et al., 2005), especially on frogs (Hale et al., 2019). CWs are particularly high in heavy metals, including zinc, aluminum, and iron (Yang et al., 2022). The ponds themselves may be used as treatment facilities, which conflicts with habitat needs (Marsalek et al., 2005). Constructed ponds and wetlands also have a higher incidence of invasive species, which present their own ecological hazards (Hale et al., 2019). Wetland sediments can act as a sink for microplastics, especially car tire bits. However, the first flush effect can result in the release of these microplastics to surface waters (Ziajahromi et al., 2020).

These deleterious effects may negate the positive benefits of CWs and ponds (Hale et al., 2019). Despite this, best practices including post-construction performance and monitoring for stormwater ponds and wetlands are lacking and outdated (Yang et al., 2022). Testing should be done to determine if an ecological trap exists, and then mitigated if that is the case (Hale et al., 2019). One way to avoid the ecological trap dilemma is to employ LID practices that are less likely to produce unintended hazards to wildlife and less likely to attract wildlife in general, such as bioretention gardens or water harvesting systems (Hale et al., 2019).

Water detained in CWs has been shown to be a consistent emitter of greenhouse gasses (D'Acunha & Johnson, 2019). There is not enough research to know how much of this may be offset by C uptake by vegetation.

Horizontal subsurface flow CWs specifically are very prone to clogging (Sacco et al., 2021).

FTWs are often used to improve pollutant and nutrient removal performance but may be ineffective if the percentage coverage is too low (Maxwell et al., 2020). Many studies have been conducted in laboratory and greenhouse experiments, showing promising results and notable effectiveness, but more long-term, full-scale field studies are needed (Sharma et al., 2021).

Pre-Treatment Technologies

Catch Basin Inserts

Catch basin inserts (CBI) do not require any additional land use because they are inserted into existing CBs. They are efficient for capturing gross pollutants, such as vegetation (Alam et al., 2018).

A study tested a CBI made of polypropylene geotextile and analyzed performance for biological oxygen demand, chemical oxygen demand, TSS, and phosphate with maximum improvements in water quality of 90%, 88%, 88% and 26% respectively. The heavy metals in influent and effluent water were found to be very low and below the guideline values. (Alam et al., 2018).

Aluminum-based drinking water treatment residuals (WTR), a byproduct from drinking water treatment, was combined with other common materials (sand and C material) in CBIs to remove total petroleum hydrocarbons (TPH), and dissolved Cu, Pb, and Zn. Median removal efficiencies were 81.2 and a slight increase in pH was observed. This low-tech, low-cost adsorbent media is effective in reducing metal and organic pollutants in stormwater (Na Nagara et al., 2021).

CB technologies such as oil and grit separators are considered conventional treatment methods. LID practices have comparable life cycle costs to an oil and grit separator option but are 35-77% more affordable when considering added stormwater treatment benefits (TRCA & UT, 2013).

Scientific literature assessing the effectiveness of CBIs is limited or outdated. Much of the current information about the latest technology in CBI comes from manufacturers of the products. The following is an incomplete list of products and is proprietary in nature:

- The CB Shield prevents sediment in the sump from being washed out. It can reduce scouring up to 92% and capture 50% TSS. Shields do not restrict flow, are easy to maintain, and fast to replace. This product is third party tested by Environmental Technology Verification (ETV) (CB Shield, 2022).
- LittaTrap™ is targeted to remove trash, debris, and plastic. EnviroPod also offers liners that can be used with LittaTrap to remove finer sediments. This product is third party tested by ETV and removes TSS to Canadian oil and grit separator standards (EnviroPod, 2022).

- SNOUT is a vented plastic composite hood that can be used with add-on accessories to improve performance. It targets debris and free oils, and heavy deposits sink to the bottom of the sump (BMP, 2022).
- StormSack is a geotextile insert that targets trash, sediments, and some oils. It is custom fitted to the storm drain and maintained with a vactor truck (no removal) (Echelon Environmental, 2022).
- Fabco Industries offers many CBIs, and FabPhos is of particular interest since it is a cartridge technology that targets phosophorus and other nutrients. It has been shown to reduce P up to 80%. On average, phosphate reduction is 64% and N compound reduction is 30% (Fabco Industries, 2022).
- Filtrexx Stormexx ® Advanced Blend Filter targets bacteria, heavy metals, nutrients, and hydrocarbons. Removal rates are as follows: Heavy metals (99%), Hydrocarbons (99%), soluble P (94%), ammonium N and TKN (41% and 22%), bacteria (71-93%), and TSS (90%) (Filtrexx, 2022).

Membrane Filters & Media Filters

Membrane and media filters are more commonly used as "stand alone" water quality treatment practices when space for surface practices is not available but may also be used downstream of LID facilities or treatment trains to enhance removal of sediment and other targeted pollutants (e.g., nutrients, metals) where warranted by receiving water sensitivity (STEP, 2022i).

Scientific literature assessing the effectiveness of membrane and media filters is limited. Much of the current information about the latest technology comes from manufacturers of the products. The following information is proprietary in nature.

- Jellyfish Stormwater Treatment by Contech is a compact, underground, in-line, piped structure that incorporates pre-treatment with membrane filtration. It targets the following with removal rates in brackets: trash (99%), TSS (89%), TP (59%), TN (51%), and Heavy metals (>50%). The Jellyfish uses one cylindrical unit, whereas the Stormfilter (below) uses multiple cartridges (Contech, 2022).
- Stormfilter by Contech is a large underground, in-line, piped system that uses multiple rechargeable, media-filled cartridges to target pollutants. It is popular worldwide, including in Canada and is fully customizable including Media options to target specific pollutants, cartridge sizing options, and various configurations (Contech, 2022a). Stormfilter with the PhosphoSorb media option removes the following with removal rates in brackets: TSS (89%), TP (82%), TN (50%), heavy metals (28-83%) (Contech, 2015).
- Jellyfish Filter by Imbrium a compact, light weight, underground, in-line, piped structure that uses membrane filtration. It targets the following with removal rates in brackets: trash (99%), TSS (89%), TP (77%), TN (51%), and Heavy metals (>50%) (Imbrium, 2022)
- Kraken Filter is a large underground, in-line, piped system that uses multiple rechargeable, media-filled cartridges to target pollutants. It uses a pre-treatment chamber to target trash, hydrocarbons, and sediments followed by a membrane filtration system chamber. It removes the following pollutants with removal rates in brackets: TSS (89%), trash (99%), P (72%), total metal (50%), hydrocarbons (90%) (Bio Clean, 2022)
- Filterra by Contech combines a landscaped concrete container with a filter media mixture. Water enters through a curb-inlet opening or pipe and is discharged through an underdrain system after passing through the treatment. It removes the following

pollutants with removal rates in brackets: TSS (86%), TP (70%), TN (34%), metals (>40%), hydrocarbons (87%) (Contech, 2022b)

- BayFilter is an underground, in-line, piped system that uses media cartridges. It uses a compound spiral media filter in a cartridge format. The spiral shape increases surface area and can be used alone or with multiple cartridges. It removes the following pollutants with removal rates in brackets: TSS (<85%), TP (>65%), metals (60%) (ADS, 2022)
- Up-Flo Filter an underground, in-line, piped system that combines sedimentation and screening with filter media. This product was developed with the US EPA and can be used on LEED construction projects. It targets the following pollutants with removal rates in brackets: TSS (80-98%), industrial materials, metals, nutrients, and very fine particles (Hydro International, 2022).

Filter Media

Sand filters offer water quality control, with no benefits to erosion or water quantity control (Ontario, 2003). Sand filters with varying designs and filter media may be used as part of an LID treatment train. The research for sand filters depends on the filter media it is comprised of or the treatment train it is a part of. Examples and specific studies are outlined below.

Iron enhanced sand filters (IESF) use engineered media mixed with iron. Iron is added to remove several dissolved constituents, including dissolved P, which is important for scenarios where nutrient removal is a priority. They may be used as part of a treatment train, alone, or as a retrofit. Iron enhanced filters have become common practice in Minnesota, USA (MPCA, 2022). If *E. coli* is also a concern, the substrate may be further amended to include biochar to target both *E. coli* and P (Matthiesen et al., 2018). IESF performed well to remove many of 123 tested contaminants of emerging concern, including pharmaceuticals, personal care products, pesticides, and many more (Fairbairn et al., 2018).

An organic filter is the same as the surface sand filter except it uses compost or peat to improve filtration of nutrients and trace metals. Bioretention filters are like surface filters but include open space and landscaping areas (Ontario, 2003). Blanket filters using bio-sorption activated media in the vadose zone of a stormwater retention basin perform well to remove N (Wen et al., 2020). A sand pre-filter combined with granulated activated C and peat or bark performed well to remove organic pollutants such as petroleum hydrocarbons, phthalates, and PAHs (Markiewicz et al., 2020). An innovative cost-efficient stormwater infiltration filter, made of gravel-peat mixture and geotextile, had very high heavy metal removal rates between 95-100% (Li et al., 2021)

Sand filters used in a treatment train with a CW demonstrated good results for reducing heavy metal loading in the wetland. Filter sand could also be reused as roadway backfill, which is an economical solution that avoids the landfill (Walaszek et al., 2018a). Sand filters did not perform as well as bioretention to remove microplastics in a treatment train with a buffer strip (Lange et al., 2022)

However, heavy metals trapped in filter sand may leach and be reintroduced to the interstitial water during later rainfall events (Walaszek et al., 2018a).

Design and Maintenance Recommendations

In general, LID solutions are location dependent and hydraulic and meteorological site conditions need to be taken into consideration for success, including soil type, plant selection, amount of sunlight, rainfall patterns, land use, etc. (Eckart et al., 2017).

The treatment train approach, combining LID solutions in series or parallel, is considered the best approach for effective SWM, working in conjunction with existing stormwater structures or conventional approaches when needed (CVC & TRCA, 2010). LID used in combination may provide more robust capabilities at the community and watershed levels. One study analyzed LID combinations for runoff control capacity. Yang et al. (2020) showed that the combination of the IT, PP, and RB displayed the best runoff control capacity. Another study showed that 50/50% and 25/25% RB and PP combinations resulted in 2-12% reduction for runoff, TN, and TP and 1-9% reduction for total stream flow and pollutant loads at the watershed level (Ahiablame et al., 2013). Shannak (2021) demonstrated that a combination of rain gardens and PPs produced the best results for urban aquatic environments within a watershed. Tirpak et al. (2021) showed that a parking lot retrofitted with a rain garden and PP provided significant runoff mitigation for both depths and peak flows. Eaton (2018) used a screening software approach to determine that for one primarily residential watershed, bioretention gardens provided the maximum runoff reduction, with further runoff reduction made possible by disconnecting impervious areas and using porous pavements in parking lots.

A simulation study for a site in London, Ontario found that IT or IT with GR were the most cost-efficient options for runoff reduction (Joksimovic & Alam, 2014). This study used guidance from the LID SWM Planning and Design Guide (CVC & TRCA, 2010) and the Assessment of Life Cycle Costs for LID SWM Practices (TRCA & UT, 2013).

The construction and maintenance phases of the LID life cycle generate the highest environmental burdens because of the raw materials required. The efficiency of raw materials should be optimized in the design phase (Xu et al., 2019).

For infiltration technology including swales, PPs, bioretention gardens, soakaways, and ITs and chambers, care should be taken to avoid groundwater contamination. To prevent contamination by salts and heavy metals, bioretention gardens should not receive runoff from high traffic areas where de-icing salts are applied or from pollution hot-spots (I.e., high-risk land use such as fueling stations, industrial sites, etc.). Low risk receiving areas such as roofs and low traffic zones can be prioritized instead. Additionally, pre-treatment options such as catch basin filters can be used prior to infiltration. These facilities also cannot be within 2 years travel time of a wellhead protection area if they receive runoff from parking lots or roads (CVC & TRCA, 2010).

For all LID with the potential to temporarily experience standing water, ponding after storm events should be limited to 24 hours to avoid mosquito propagation (CVC & TRCA, 2010).

Detailed information about design and maintenance of LID can be found in the LID SWM Planning and Design Guide (CVC & TRCA, 2010). The Sustainable Technology Evaluation Program (STEP) is an online resource that compliments that guide. On the STEP website (https://sustainabletechnologies.ca/) there are factsheets, wiki pages, web tools, and more available to support property owners, businesses, and municipalities with LID selection, design, and maintenance. The STEP Support Tools are available for the design, construction, monitoring, inspection, and operation and maintenance of SWM best practices. Website information about these and other supporting resources may be found in the “Other Reports and Resources” section below. The following sections offer supporting information to these resources and new information from the scientific body of literature. section below. The following sections offer supporting information to these resources and new information from the scientific body of literature.

Swales

The abilities of a swale depend on the channel slope design. Typical recommended practices are as follows. Slopes should be graded as close to zero as drainage will permit. Side-slopes should be no greater than 3:1 (h:v) (Schueler, 1987). Channels should be 2 meters wide (CVC & TRCA, 2010). Recommendations for slope range from 0-4%. STEP (2022a) and Duffy et al. (2016) recommend 1-5%, with check dams on slopes steeper than 3%. The CVC & TRCA (2010) LID SWM Guide recommends 0.5-6% slopes and echoes check dams for greater than 3%. Swales should receive 5-15% of the runoff from the contributing drainage area and ratios of impervious drainage to swale area range from 5:1 to 10:1 (CVC & TRCA, 2010).

Flow regimes are determined by vegetation height relative to water height, i.e., submerged or not submerged (Gavrić et al., 2019), indicating that vegetation should not be mowed too close to the ground. Sheet flow is ideal for inflow and swales may overlay any soil type (CVC & TRCA, 2010). Rocky check dams promote additional infiltration, but earthen check dams are not recommended because of the risk of erosion and sedimentation (Schueler, 1987).

Scotland’s Rural SuDS Guide (Duffy et al., 2016) recommends swales for draining roofs, yards, and areas draining into yards. Field swales are primarily used for water transfer between LID or from LID to a natural water body. This guide recommends check dams for steeper slopes. These recommendations describe swales as long, wide, shallow, less than 5% slope, with no sharp bends. Swales should be planted with a hardy, low maintenance grass seed mix of native species.

A great variety of vegetation can be used in humid zone systems such as roadside swales. Ekka and Hunt (2020) recommend grasses with non-clumping form, stiff blades, dense coverage, and some tolerance of standing water. Macrophytes should be tolerant to flooding conditions, high organic and inorganic loadings, and adapted to local weather conditions and diseases (Gomes et al., 2014). Plant presence in swales is key for metal pollutant stabilization (Leroy et al., 2017). Careful consideration (I.e., shading, vegetation type, gradient, etc.) should be made for growing conditions of swale vegetation and its establishment to ensure success (Mazer et al., 2001).

For swale maintenance, grass length should be 10-15cm (Ekka & Hunt, 2020). Any connecting pipes should be checked for debris and blocks, significant sediment build-up should be removed along swales, and repair of eroded or compromised grass (Duffy et al., 2016). Erosion can be prevented by minimizing longitudinal slope and incorporating check dams. Alternatively, permanent reinforcement matting may be used to withstand high velocity flows, or temporary matting for the vegetation establishment period (CVC & TRCA, 2010).

Special considerations are needed for swales at areas with high traffic volumes or stop-and-go spots such as stop signs, roundabouts, and crossings due to excess heavy metal deposition (Horstmeyer et al., 2016). Similarly, swales receiving runoff from zinc roofs should have surface soils tested and exchanged regularly to avoid groundwater contamination (Rommel et al., 2019).

Permeable Pavements

Generally, PPs can be used in the same contexts as traditional paved surfaces, with some exceptions. The slope of the permeable surface should be between 1-5%. Surrounding impervious areas should not have more than a 20% slope. In general, the impervious area treated should not exceed 1.2 times the area of PP which receives the runoff. The PP area should be down slope from buildings. A 4-meter setback is recommended, unless not receiving runoff from other surfaces, in which case no setback is required (CVC & TRCA, 2010).

Different types of surface patterns of permeable interlocking concrete pavement offer different advantages. Stretcher bond (classic brick) pattern showed superior results to other designs as it reduces surface runoff and spreads the water evenly under the permeable concrete block roadway. The 90◦ herringbone and 45◦ herringbone patterns are the best for increasing the durability of roads (Hashim et al., 2022).

Cleaning is recommended twice per year, with strategic considerations for periods of high sediment loading. For example, use of street cleaners after snow melt and before spring rains (Selbig & Buer, 2018). PPs can be snow ploughed with the blade raised to 25mm. Sand should not be applied to avoid clogging (CVC & TRCA, 2010).

As clogging is a major concern for PPs, the bedding layer and joint filler should consist of 2.5 mm clear stone or gravel rather than sand. Adjacent pervious areas should be stabilized with adequate vegetation. Small areas of clogging can be fixed by drilling small holes or by replacing the media between pavers (CVC & TRCA, 2010).

Grid pavers with aggregate should be poorly graded (3/8” to ¾” diameter), unable to be compacted, with 20-40% porosity, messy and unstable when used alone (Handlos, 2014). For grass pavers, a resilient species with deep roots works best, such as tall fescue. When purchasing pavers, percolation rate and frost-heave should be considered, and subgrade preparation may be required. Grid pavers are not designed to accept runoff from adjacent surfaces (University of Rhode Island, 2018).

Winter maintenance practices should be limited to ploughing, with de-icing salts applied sparingly (i.e., salt is not a preventative measure and no sand) (CVC, 2012). Snow ploughs require rollers to prevent catching paver edges. Seasonal inspections should look for gravel fill that needs replenishing or grass that needs reseeding. Grass should be maintained like a regular lawn (I.e., watering and mowing, and potentially fertilizing). Due to sunlight requirements, grass pavers are not appropriate for near-constant parking (University of Rhode Island, 2018).

Bioretention Gardens

Bioretention gardens are planted with perennial vegetation such as grasses, shrubs, sedges, rushes, and perennial stands. They are planted using a variety of mediums, including soil mixtures, sand, mulch, and organic matter (Ahiablame et al., 2012; Dietz & Clausen 2005; Dietz 2007; Davis 2008; Davis et al. 2009).

Cold climate modifications for bioretention gardens include extending the filter beds, an underdrain pipe below the frost line, an oversized underdrain, and salt-tolerant vegetation (CVC & TRCA, 2010).

Gardens should be set back at least 4 meters from building foundations. Planters close to buildings require an impermeable liner or for the foundation to be waterproofed. Open areas should be 10-20% of the contributing drainage area with slopes between 1-5% (CVC & TRCA, 2010).

To mitigate ammonification and nitrification effects and improve N capturing ability, Kim et al. (2003) created an anoxic zone by mixing newspaper with the sand layer in a bioretention cell. Newspaper is a good electron donor for denitrification resulting in 80% removal of nitrate. A saturated zone in bioretention systems can also improve N retention (Dietz & Clausen, 2006). Similarly, anoxic zones can promote nitrification and denitrification processes (Ergas et al., 2010). Aerobic nitrification and anoxic denitrification can be achieved with sulfur or wood chips (Ergas et al., 2010).

If bacteria contamination is a specific concern, significant retention of *E. coli* in bioretention cells was achieved with iron-oxide coated sand media (Zhang et al., 2010).

Hsieh and Davis (2005) demonstrated that bioretention cells with sand media have great pollutant removal capacity, but efficiency decreased over time due to limited biological activities sustained by the substrate.

To prevent damaging foot traffic from pedestrians, designers may consider strategically placed shrubs, curbs, or railings (CVC & TRCA, 2010).

Bioretention gardens should be maintained similarly to regular landscaping features; however they require little irrigation after plants are established, which occurs between 1-2 years. Regular pruning and weeding are needed, as well as general inspection of substrate and plant health (CVC & TRCA, 2010).

Green Roofs

Waterproofing is required for GRs, but a leak detection system and/or warranty provides security in the case of waterproofing failure. Vegetation health must be maintained. New GRs may require irrigation for the first year or two, after which time plants are established and maintenance requirements are significantly reduced (CVC & TRCA, 2010).

Structurally, the load bearing capacity of dead and live weights including soil, vegetation, accumulated water or snow, pedestrians, concrete pavers, etc. must be accounted for in the design phase (CVC & TRCA, 2010). GRs may be installed on slopes up to 10%. They should not receive water runoff from any other surface (CVC & TRCA, 2010).

Increased soil depth improves hydraulic performance (Dunnett et al., 2008) and can mitigate vegetation damage under heavy rain and winter frost (Boivin et al., 2001). Extensive GRs have been shown to be more economical than intensive GRs in long-term life cycle analysis (Xu et al., 2019).

GRs should be designed to accommodate the storm events that have the most significant impacts on the hydraulic infrastructure in the area. For this reason, the capabilities of any one GRare dependent on the design process used to create it (Eckart et al., 2017; US EPA, 2000).

Water Harvesting Systems

Year-round dual systems (indoor and outdoor use) must be built underground to protect from freezing and ice formation. Above ground systems must only be used seasonally. Dual systems must follow Ontario Building Code for plumbing. To prevent mosquito breeding and reproduction, inlets and overflow outlets should be screen protected. If screening is not sufficient, larvicide treatments may be added when the water is intended for irrigation only. For child safety, cisterns must have lockable covers or manhole entrances. Water demand should be estimated when selecting cistern size so that enough captured water is used between storms to avoid overflow (CVC & TRCA, 2010).

The vertical positioning of the tank will determine the volume of water that can be stored, and the amount of pumping required to move the water. Higher positioning results in reduced volume capacity but less pumping, and lower positioning results in greater volume capacity but more pumping. Depending on if the system is dual use or outdoor-only, a cistern on the roof or top floor may be the best way to create water pressure (CVC & TRCA, 2010).

Cisterns should be in native soils (not fill) and have at least a 3 meters setback from building foundations. Underground systems can be located below the frost line or insulated (CVC & TRCA, 2010).

Soakaways, Infiltration Trenches, and Infiltration Chambers

Soakaways, infiltration trenches and chambers should be set back at least 4 meters from building foundations and overflow outlets should go to pervious areas at least 2 meters from the building foundation. In winter months, these practices will continue to function if they are situated below the frost line (CVC & TRCA, 2010).

They should not be located on natural slopes greater than 15% and must be 1 meter or more above the seasonally high-water table. High permeability soils ranging from sand to loam are preferential for good infiltration. The drainage area to facility area ratio may be between 5:1 and 20:1, but 10:1 is the recommended maximum if the receiving area is a road or parking lot (CVC & TRCA, 2010).

Downspout Disconnection & Redirection

Discharge locations for downspout redirection should be at least 3 meters away from building foundations, unless topography is sufficiently sloped 1-5% away form the building. The flow path should be at least 5 meters. Compacted soils should be amended with compost to 30cm to increase infiltration. Ponding lasting longer than 24 hours is indicative of soil that should be amended. To prevent future compaction, areas should not receive excessive vehicular or foot traffic. Planting the area or installing a rain garden can discourage compaction (CVC & TRCA, 2010).

Wetlands and Ponds

Since wetlands and ponds are considered end-of-pipe solutions, they are not covered in the LID SWM Planning and Design Guide (CVC & TRCA, 2010). Instead, recommendations for several types of ponds and wetlands, including wet ponds, CWs, dry ponds, infiltration basins, and hybrid designs are included in the Ontario (2003) Stormwater Management Planning and Design Manual. UN-Habitat (2008) also produced a Constructed Wetlands Manual. These resources can be found in the Other Reports and Resources section below.

Because of the wide range of possibilities, from conventional stormwater ponds to engineered CWs, design considerations will depend on the goals and desired outcomes of the facility. Designing with the maximum ecological benefits in mind requires going above and beyond the minimum design requirements for stormwater ponds. To avoid the deleterious impacts of toxic accumulated pollutants, invasive species, and associated ecological trap mechanisms, wetlands can be strategically monitored and designed. For example, changing vegetation patterns to attract wildlife away from the most contaminated areas or to discourage use in some areas. Similar strategies can be used to encourage use of one wetland over another. Ideally, the benefits of a wetland or pond outweigh the costs in such a way that its presence in an urban environment is more beneficial than having no or few aquatic habitats in the area (Hale et al., 2019).

Water detained in CWs has been shown to be a consistent emitter of greenhouse gasses (D'Acunha & Johnson, 2019). One study showed that reducing permanently flooded areas and increasing shallow land areas could reduce GHG emissions while maintaining nutrient removal benefits. However, analysis of the microbial community is the determining factor when considering these questions (Bledsoe et al., 2020).

The seasonal and dry or wet weather variations that occur in SWMPs can be buffered by following the pond with a vertical subsurface flow CW, which acts as a filter (Walaszek et al., 2018).

FTWs can be augmented with contaminant-tolerant plant species, additives such as sulfur or iron to improve N remediation, addition of microorganisms to improve P removal, and regular harvesting of plant material to avoid reintroduction of nutrients and metals to the water. FTW combined with periodic aeration can greatly enhance pollutant removal abilities. The addition of C and sulfur can enhance N cycling. Certain bacterial strains can be used to enhance plant growth and biomass development and improve environmental stress tolerance (Sharma et al., 2021).

CWs require regular maintenance to control sediments, debris, and weeds (Al-Rubaei et al., 2022). While subsurface flow CWs may be prone to clogging, this can be avoided in vertical subsurface flow CWs through strategic timing of water inflow and outflow and the correct choice of filter media texture. The oxygen transfer rate through the bed must be high (Brix & Arias, 2005). The Danish guidelines for vertical flow CWs describe designs that maximize water treatment potential for this stormwater treatment method (Brix & Arias, 2005).

The biggest environmental impacts for CWs are transportation of materials and construction because of fossil fuel use. Wetlands and ponds that require a water pump use electricity, which is the biggest impact in this scenario, and compensation by vegetation is marginal compared to wetlands without pumps (Xu et al., 2019). For this reason, fossil fuel and electricity use should be considered and minimized to meaningfully reduce environmental impacts during the construction and maintenance phases.

Shallow water tables and impermeable soils can also often limit the use of LID strategies; however, Johnson and Sample (2017) developed a tool to assist with LID implementation in these kinds of areas and demonstrated that wet ponds and CWs were the most viable for this situation.

Pre-Treatment Technologies

Catch Basin Technologies

As catch basin technologies are primarily patented and proprietary in nature, the design, operation, and maintenance will be determined by the company that carries the product. In this case, the guidelines provided should be followed.

Design specifications for oil and grit separators are outlined in the Ontario (2003) SWM Planning and Design Manual.

Sand Filters

Sand filters are often used as part of a treatment train and can potentially be incorporated into decorative landscaping. Design and maintenance specifications for various sand and bioretention filters are outlined in the Ontario (2003) SWM Planning and Design Manual. The following are additional findings from literature.

No single filter media can remove all metals to the maximum extent, so a blend should be considered based on target pollutants. Calcite, zeolite, and iron filings are all high performers for heavy metal removal. Sand performs poorly in comparison (Reddy et al., 2014). A gravel peat filter made with a volumetric ratio of silica gravel, limestone gravel, and peat (ratio 5:10:3, respectively) is recommended as it maintained high heavy metal retention but had a lower clogging potential and was lower cost than the limestone gravel peat 5:1 mixture. (Li et al., 2021). Steel slag shows good potential to remove P and zeolite performs well to remove ammonia N (Chen, 2021). Layering sand, granulated activated C, bark, and peat will maximize effectiveness for removal of PHCs, phthalates, and PAHs (Markiewicz et al., 2020).

Other

One study concluded that soil amendment with polyacrylamide (PAM) and biochar could reduce P loss and increase the >2 mm water-stable soil aggregate under leaching conditions (Zhou et al., 2019). This strategy could be applied to agricultural fields to reduce nutrient loss and erosion caused by irrigation or LID technology such as swales or rain gardens.

LID Application in a Rural Context

While many farmers already participate in stewardship activities and sustainable management practices, municipalities play an important role in engaging the agricultural community and creating a GI strategy specific to the local context. Partnerships with conservation authorities, municipalities, and community groups can reduce costs for farmers, provide educational opportunities, and make successful rural LID projects possible (FGF & GIOC, 2017).

There are many benefits to the implementation of LID and GI in rural and agricultural lands. It can support farming production and provide ecological services, retain stormwater for use during droughts, and filter runoff, which improves water quality (FGF & GIOC, 2017).

Soil cultivation and manure, fertilizer, and pesticide application contribute to diffuse pollution from agricultural lands. As in urban environments, impermeable surfaces lead to rainfall runoff from farm roads, yards, and rooftops. Pollutants including sediment, nutrients, and pesticides may escape from agricultural land into ditches, which eventually connect with natural water bodies (Duffy et al., 2016).

Soil erosion is the biggest concern addressed by LID and has meaningful impacts on farming costs. Rural LIDs keep valuable soils on farmland, provide habitat and ecosystem services, and do not take valuable land out of production for the sake of building the LID (Duffy et al., 2016).

Rural LIDs reduce pollution by creating low-cost physical barriers to treat runoff and capture soil and pollutants. They prevent blockages in drains and ditches and can be used to return valuable, fertile soil back to growing fields (Duffy et al., 2016).

Clean Water Strategies for Agricultural Lands

There are many non-LID or LID-adjacent strategies that can be used to improve the water quality of receiving water bodies connected to agricultural lands. The following examples and more are covered by the Rideau Valley Clean Water Program (RVCWP, 2022) and currently have funding available within the Rideau Valley Watershed.

- Redirecting relatively clean water away from sources of contamination such as feed storage facilities or barnyards to avoid unnecessary contamination.
- Cover crops are vegetation planted to occupy agricultural land not covered by regular crop to control erosion, improve soil health, and reduce nutrient runoff.
- General erosion can be controlled through stabilization measures using riprap, vegetation, bioengineering, and bank seeding.
- Retiring unused land prevents further erosion and degradation of vulnerable bare fields, which can prevent erosion and sediment spills in nearby waters.
- Restricting livestock from natural waterbodies through fencing, livestock crossing infrastructure, and renaturalization prevents erosion and reduces nutrient inputs to the water.
- Proper manure storage prevents contaminant laden runoff from escaping lots.
- Precision farming through nutrient management plans combines strategic soil sampling and analysis, scheduling of fertilizer or manure application, and GPS to minimize nutrient loss and associated water contamination.
- Proper pesticide management, storage, and handling prevents spills and contamination of the surface and groundwater.

Additionally, stormwater may be harvested for use in irrigation (Fletcher et al., 2013). When optimized, agricultural LID can reduce irrigation requirements and improve the general water cycle in rural environments. Passive LID such as ITs and tillage practices to increase surface roughness, which increase infiltration rates, are most effective and efficient for agricultural water management compared to traditional irrigation or active LID focused on water detention and storage (Zubelzu et al., 2022).

Coordinated water quality management can be used to strategize the interaction between rural and urban water uses and their associated environmental impacts. Using catchment-based software (ex: CatchWat), regulating bodies can determine the best actions to take that can minimize effects on receiving waters. For example, reducing fertilizer application during wet periods and enhancing wastewater treatments at treatment plants during dry periods (Liu et al., 2022).

LID Suitable for Agricultural Lands

Several of the LID recommended for agricultural land have been outlined in previous sections, including swales, dry ponds, filter strips, and wet ponds. These practices can be used individually or in a treatment train depending on the context. Other LID well suited to an agricultural context are outlined in new sections below.

The farmstead and its buildings may send runoff to a swale, sediment trap, pond, or wetland. Swales and sediment traps should not hold runoff from pig and poultry buildings for more than a day to protect animal health (Duffy et al., 2016).

Field runoff may be sent to a sediment trap, pond, or wetland. Swales can be used to transfer runoff between them (Duffy et al., 2016).

Constructed Farm Wetlands

Constructed farm wetlands (CFW) are shallow, free surface flow constructed cells containing emergent vegetation. CFW may be used to treat lightly contaminated runoff from manure storage, a silage clamp, livestock handling areas, roof drainage, concrete areas, or machinery washings (Carty et al., 2008). A design manual was created for the environmental protection agencies of Northern Ireland and Scotland that provides extensive information about CFW construction, maintenance, and more and is included in the Other Reports and Resources section below.

Hedgerows, Buffer Strips, Windbreaks, and Shelter Belts

Hedgerows, buffer strips, windbreaks, and shelter belts all consist of rows of trees, shrubs and/or vines along roads, and between fields and residential lots. In the context of agricultural lands, hedgerows are planted strips that reduce soil erosion by providing a wind buffer. They're often used in combination with agricultural filter strips and ITs. Buffers and hedgerows can also provide habitat and may be a source of income if planted with something monetizable such as maple trees, fruit trees, or mushrooms (FGF & GIOC, 2017; RVCWP, 2022).

Riparian buffers are made of thick vegetation that slow runoff into streams, flood plains, wetlands, and lakes. They reduce erosion, sedimentation, and pollution into water bodies. The most effective buffer zones are made up of a healthy mix of vegetation such as grasses, shrubs, and trees (FGF & GIOC, 2017).

Sediment Trap

A sediment trap is a dry, vegetated basin that temporarily fills up during a rainfall event and traps sediments and pollutants. This is like a dry pond but exists for the purpose of trapping sediments as opposed to preventing erosion and controlling floods. A sediment trap helps reduce sediment loading in ponds and wetlands when constructed directly upstream. Sediment recovered here may be returned to fields (Duffy et al., 2016).

Tile Drainage Solutions

Agricultural tile drains are made of perforated plastic tubing buried 3-5 feet deep. The tiles pull excess water from the soil to improve oxygenation, prevent soil compaction, and improve yields. Usually tile drains filter to a larger main line that conveys water to a surface ditch or stream (Schilling, 2022)

Nutrient runoff from agricultural lands, including nutrient leaching from agricultural to tile drainage land, leads to diffuse pollution and can affect the conditions of receiving waterbodies (Pugliese et al., 2020). Subsurface drainage bypasses natural attenuation processes and provides a pathway to move contaminants from crop fields to ditches and streams (Hudson et al., 2018). Tile drainage control structures are designed to manage tile drainage outlets to reduce potential contaminant loading to receiving waters (RVCWP, 2022).

Tile drainage filter technology can also be a cost-effective way to mitigate P and N losses. Granular P filters typically use Al and Fe hydroxide or calcareous surface to retain dissolved P by sorption (Pugliese et al., 2020).

In the study by Pugliese et al. (2020) a filtration system consisting of a sediment settling pond and a filter using crushed seashells had a P removal efficiency of 62%. Hudson et al. (2018) tested a woodchip filter for N removal and found that results were affected by retention time and temperature, but that removal efficiency was above 90% up to 70% of the time.

Barriers to LID Implementation

Ontario was rated “highly LID-friendly" according to its regulations and guidelines in the context of Canadian provinces and territories (Ishaq et al., 2019). The incorporation of LID technology into stormwater best management practices will become standard practice (MECP, 2022) and has already been adopted by several major municipalities including Toronto (CVC & TRCA, 2010; STEP, 2022), Kitchener (Aquafor Beech Ltd. & Freeman Associates, 2015; Kitchener, 2021), Ottawa (City of Ottawa, 2019; City of Ottawa, 2022), and Hamilton (City of Hamilton, 2017).

Research Limitations

LID practices are micro-scale control measures that are focused on lot-level performance that will vary over space and time at the catchment or watershed scale. For this reason, more research is needed to better understand the real-world impacts of LID on larger scales (Ahiablame et al., 2012).

LID technology and GI have many competitive advantages over grey infrastructure, including environmental impact, cost, and performance both in water quality and quantity. However, GI cannot completely replace grey infrastructure due to the safety risks of extreme storm events. LID works best for smaller storms and does not perform well in large events. Green and grey infrastructure need to be balanced and optimized to work together in the most efficient way with maximum benefits, but more research is needed on the topic in order to achieve this (Xu et al., 2019).

Climate change will result in more irregular weather patterns, increased flooding, and more extreme storm events. In order to make LID more effective under climate change, strategic implementation based on regional climate conditions and storm patterns is important. However, necessary studies for treatment of pollutants based on climate conditions and effects of temperature on storm factors are rarely found. In the future, climate change impacts will be better studied with the development of climate prediction (Sohn et al., 2019).

Contaminants of emerging concern (CECs) are defined as “pollutants that are detected in water bodies, may cause ecological or human health issues, and typically are not monitored or regulated under current environmental laws” (Water Canada, 2022). In general, there is very little research on LID practices and removal of CECs (Ahiablame et al., 2012). This will become important in the future as the chemical intensification of society means that CECs are developed faster than they are studied or regulated and they already widely exist in our environments and are actively affecting the health of people and ecosystems (Water Canada, 2022).

Education and Awareness

Education and awareness are critically important elements in LID implementation and acceptance. A lack of education, understanding, and familiarity is one of the major barriers to homeowner's willingness to pay for LID in residential subdivisions (Bowman et al., 2012; Coleman et al., 2018; Darnthamrongkul & Mozingo, 2021; Gao et al., 2016; Gao et al., 2018; Ureta et al., 2021). Echoing these findings, a lack of education and outreach was also found to limit the effectiveness of regulatory initiatives for water management (Persaud et al., 2016). Policy makers and regulations should resolve the lack of knowledge and awareness through education, programs, and government incentives that can be used by developers, planners, municipal officials, engineers, and homeowners (Ahiablame et al., 2012).

For example, in a study about public perception of LID, even well-educated groups did not understand sustainable SWM and couldn't identify ecological or stormwater benefits of LID. However, public acceptance and appreciation of LID was positive regardless, especially when accompanied by interpretive signage teaching about both LID and SWM (Darnthamrongkul & Mozingo, 2021).

On a residential level, homeowners may also be hesitant to implement mitigation measures if the ecological urgency is not persuasive enough (Persaud et al., 2016). There is a common misconception that LID practices are not effective or not necessary and this is a significant barrier to public acceptance (Ureta et al., 2021; Coleman et al., 2018). However, only non-participants worry about things like effectiveness, maintenance, aesthetics, and insects. Residents already using LID practices do not have the same concerns (Gao et al., 2018).

A study on adoption of suburban RBs showed over a quarter of practices were discontinued within five years of their adoption (Gao et al., 2016).

Community Engagement

Community engagement and participation are important factors when employing a decentralized, source-control approach to sustainable SWM. Montalto et al. (2013) studied community engagement and LID adoption. This study demonstrated the importance of stakeholder engagement. Higher rates of success were found when relevant knowledge and perceptions were communicated to household decision-makers through social networks.

Another study by Brown et al. (2016) found that financial incentives and personal benefits, including financial savings on water bills, were the primary motivators, and the complexity of incentive program participation and distrust were the primary barriers.

Government and Private Sector

GI, including LID, is considered a "risky" land use for local governments compared to traditional development where the projects can be vetted, measured, and ranked by return-on-investment calculations, including benefits and burdens on local tax revenue. The performance and value must be communicated in traditional economic terms and GI needs to be incorporated into established zoning and land use functions as a standard (Chaffin et al., 2016).

Engineers, utility operators and managers, and public planning divisions may be risk averse and barriers such as unfamiliarity, lack of experienced local contractors, maintenance responsibility, and liability issues act as barriers. Within the watershed, distribution of responsibility and authority of water management may cause issues (Eckart et al., 2017). Studies on regional impacts of LID BMPs are few, which is important to policy makers (Xu et al., 2019).

Among stormwater professionals, the barriers ranked from highest to lowest priority are as follows (Lloyd et al., 2002):

- lack of an effective regulatory and operating environment
- limited quantitative data on long-term performance and best practices
- insufficient information on operation and maintenance and structural best practices, institutional fragmentation of responsibilities
- lacking culture and technical skills within local governments and water corporations
- lack of ability to factor externality costs into life cycle cost analysis
- lack of information of market acceptance of residential properties with LID
- poor construction management leading to reduced effectiveness.

As an example, government policies and public awareness are specifically noted as important to increase the GR adoption rate (Alim et al., 2022). This has been seen in Toronto with the GRbylaw discussed in the Green Infrastructure and LID Initiatives in Canada section.

Monitoring and Evaluation Limitations

There is a need to quantify environmental benefits and ecosystem services more clearly. However, there is a lack of data in various situations and insufficient data about LID effectiveness, especially long-term. Monitoring is often limited to regulatory requirements. Some data comes from demonstration sites but with lacking scientific oversight, which can impact data quality. Before and after studies would make sense regarding site hydrology, but parallel studies within the watershed are more common. Costs, benefits, and risks are difficult to identify accurately because of the described lack of data (Eckart et al., 2017).

Site-specific issues can add to the ambiguity of performance monitoring evaluation. In large watersheds, it’s difficult to determine the impact of LID measures on receiving waters. Studies may not be relevant across different areas with varying geological and meteorological characteristics. Optimizing the size of LID projects for the drainage area, determining proper spacing, and choosing optimal LID combinations for the project area may be difficult with limited information (Eckart et al., 2017).

Economic Limitations

Life cycle assessment (LCA) is a scientific, systematic tool used to assess environmental effects throughout the whole life cycle of a product, process, or practice (ISO 14040, 2006). Similarly, life cycle costing (LCC) is defined as a process of determining the sum of all expenses associated with a complete life cycle of a product system (Woodward, 1997). LCC is similar to LCA but does not include environmental assessment. LCC considers raw materials, labour, equipment, maintenance, operation, and energy consumption. LCA and LCC are motivating factors for governments considering sustainable development (Xu et al., 2019). LCA and LCC research for LIDs is limited and software for conducting analysis may be location specific. There are studies that have begun to evaluate LID by LCA and LCC that have been mentioned in earlier sections of this document. To assist, TALLY is an LCA model commonly used in the United States that can be used to evaluate LID options (Xu et al., 2019). It may be more accessible to use the tools available through the STEP program.

More generally, construction and maintenance of LID cause the greatest cost burden, but there are also significant economic benefits because of reduced peak flow and total runoff volume. There is little research about LID decommissioning costs at the end of the life cycle because most LID are still in operation (Xu et al., 2019).

Strategies to Advance LID Initiatives

Cultivating Motivation, Building Acceptance, and Creating Opportunities

Providing skills, knowledge, funds, and equipment is not enough to encourage pro-environmental behaviors. Promoting public involvement in watershed activities, increasing awareness about how LIDs work, and emphasizing the functional benefits of practices can be effective in motivating adoption (Gao et al., 2018). An approach that involves education and financial incentives can transform public response to increase adoption and participation in LID and sustainable SWM. Successful implementation of LID practices will require a multidisciplinary approach and coordination between government agencies, community groups, and the private sector (Eckart et al., 2017).

Compelling data communicated to residents is recommended to improve environmental stewardship (Persaud et al., 2016). Interpretive signs appear to be the preferable means for motivating stormwater education and producing positive public reactions to LID sites (Darnthamrongkul & Mozingo, 2021). For this reason, LID pilot projects and demonstrations are recommended as avenues for public education and outreach (Darnthamrongkul & Mozingo, 2021; Shin & McCann, 2018; Gao et al., 2016; Gao et al., 2018). Including informational signage on the LID installations themselves also helps to foster LID practice and maintenance by the property owner in the long term (Gao et al., 2016).

Demographically, women, people in suburbs, gardeners, and people with pro-environmental attitudes tend to be more accepting of LID (Shin & McCann, 2018; Gao et al., 2018; Gao et al., 2016). Water quality is the most motivating ecosystem service for support of LID practices (Ureta et al., 2021). Personal experience with stormwater drainage issues (for example, seepage and flooding) increases the likelihood that residents would adopt LID on their property (Coleman et al., 2018; Scarlett et al., 2021). Perceived individual benefit is a common motivator for LID like RBs and trees (Tanaka et al., 2022; Gao et al., 2016).

Economically, even small financial incentives are effective for adoption of LID technology on private residential property (Thurston et al., 2010; Liu et al., 2020). Residents support the idea of reducing stormwater fees in exchange for installing LID (Gao et al., 2018). Offering residents a variety of payment options improved willingness to pay (Tanaka et al., 2022). Interestingly, Reverse-auction has been demonstrated as effective for LID cost and public participation, especially for smaller municipalities lacking resources (Thurston et al., 2010).

Local landscape-scale planning is more likely to be successful with an assessment process that can advise the best approach and a detailed plan (Liu et al., 2020). Rain Ready Ottawa uses a similar system outlined in the “Case Studies and New Innovations” section below.

Contractors for LID projects will likely have more experience with landscaping purely for aesthetic purposes than for functional sustainable drainage design. For this reason, any involved contractors should be carefully managed and supervised. Final LID project construction must conform with approved, engineered designs or the ecosystem services promised may not function as intended (Chaffin et al., 2016). As an example, Rain Ready Ottawa uses contractors that have a specific training certification for LID projects that is discussed in Case Studies and New Innovations.

At the community level, if expectations of naturalness and neatness are met (Darnthamrongkul & Mozingo, 2021), residents support the use of LID in public spaces (Gao et al., 2018) and prefer subdivisions that include explicit environmental benefits over those that do not (Bowman et al., 2012). It should be noted that public opinion tends to prefer aesthetically pleasing projects regardless of functionality, so the aesthetic appeal of LID projects is an important player in public acceptance (Chaffin et al., 2016).

Social dimensions play an important role in the success of LID projects (Persaud et al., 2016). For example, residents who trust their neighbors are more likely to participate in sustainable SWM (Tanaka et al., 2022). Consistent use of relevant terminology should be used to create an image to engage stakeholders and society and to build recognition and understanding. For example, best management practices may sound like 'success' and water sensitive urban design could sound like 'care.' Outreach programs should make principles and objectives clear, while still cultivating inspiration through compelling language (Fletcher et al., 2014).

At the municipal level, an inclusive group of stakeholders should negotiate goals and objectives up front. With an incomplete commitment from all relevant stakeholders, the goals of a project can quickly change in a way that does not support the original vision. Adaptive management is the practice of implementing management actions as experiments with monitoring, evaluation, and adjustment as needed to manage ecosystem-based issues and projects. First, governments create the flexibility and legitimacy of adaptive management projects through agreed upon goals, governance structure, and transforming monitoring and feedback into policy. Second, collaboration with a diverse range of partners provides flexibility, organizational and administrative capacity that may be required for unexpected issues during the implementation of the adaptive management approach (Chaffin et al., 2016).

Funding for implementation and maintenance is required if LID is to be implemented using an adaptive management approach. Job training programs providing education on LID will require funding but will add to community socioeconomic benefits. For example, landscape-based LID like bioretention gardens require a specific type of maintenance that could be a specialized job skill.

Co-benefits of LID such as aesthetics, habitat creation, and quality of life improvements can garner support from funding organizations that typically deal with housing and human services. In this regard, it will be important to look for funding support beyond the typical avenues of environmental protection (Chaffin et al., 2016).

For the time being, a combination of green and grey infrastructure is the ideal approach to work toward environmental goals while still mitigating risks of flooding and property damage due to stormwater. However, through optimized engineering design, stormwater could be more purified in a more cost-effective way. Systematic optimization will happen at the municipal level by prioritizing clean domestic water supply and efficiency of water and energy use and connectivity, which will result in improved city livability (Liu et al., 2020).

The full potential benefits of LID practices in urban and suburban areas can be unlocked through a nexus of motivated and engaged citizens, confident support from municipal and regional agencies, effective source control management practices, and ongoing follow-up monitoring (Shuster et al., 2008).

The Government of Ontario

In Canada, provincial governments oversee the use of water, water development, and flow regulations, and legislate water supply and pollution control. The Canadian strategy to water management is the framework of watershed, ecosystem, social systems, and health well-being. Watershed governance takes these four principles and integrates them into eco-health and watershed-based integrated water resources management (Liu et al., 2020).

A comprehensive view of how LID is approached and regarded by the government of Ontario is available in a study by Ishaq et al. (2019). The regulatory frameworks in Ontario are very supportive to advancing LID projects in the province. The LID SWM Planning and Design Guide (CVC & TRCA, 2010) is fundamental reading that provides technical guidance and exists to cultivate understanding about stormwater issues between stakeholders. Ontario takes a landscape-based approach which allows land use and water management to be addressed together. These LID guidelines also recommend a treatment train approach, which incorporates grey and green infrastructure and encourages the use of LID.

The Stormwater Management Planning and Design Manual (2003) is another important document that provides guidance for urban and rural drainage in Ontario. It highlights the importance of the hydrologic cycle and ecosystem and encourages a treatment train approach to SWM. This guide has been updated to include both lot level and end-of-pipe controls. New LID practices introduced in this document include storage controls, wet swales, hybrid wet ponds/wetlands, perimeter sand filters, and bioretention filters (Ontario, 2003).

The LID SWM Planning and Design Guide (2010) created by the Credit Valley and Toronto and Region Conservation Authorities is intended to compliment the SWM Planning and Design Manual (2003). The 2003 document covers end-of-pipe, conventional practices and the LID SWM Guide focuses explicitly on LID practices for lot level and conveyance, echoes the treatment train approach from the 2003 guide, and encourages further exploration of innovative designs and solutions.

Building on these initiatives, the Government of Ontario is currently in the process of developing the Low Impact Development Stormwater Management Guidance Manual. In 2022, the draft document was released. While it does not contain any mandatory requirements, it aims to encourage the use of LID practices as they relate to planning, runoff volume control, groundwater considerations, criteria for model selection, climate change considerations, operation and maintenance, erosion and sediment control during construction. The guide provides extensive and comprehensive resources and information with the goal of protecting aquatic life, water quality, ground water, and ecosystems while reducing combined sewer problems, floods, and erosion, while building climate change resiliency. The manual is based on scientific research, literature, and field studies and concludes that innovative practices, designs, and technologies should be considered anytime these alternative solutions can meet stormwater goals (MECP, 2022).

Other Reports and Resources

In 2010, the Center for Neighborhood Technology published “The Value of Green Infrastructure,” which outlines the environmental, social, and economic benefits of GI including

GRs, tree planting, bioretention & infiltration, PP, and water harvesting (CNT, 2010). The benefits reviewed included several benefits beyond basic LID priorities, including stormwater runoff, energy use, atmospheric CO2, UHI effect, community livability, wildlife habitat, public education, and more. This guide provides a more holistic overview of several LID practices and is both comprehensive and user friendly.

For thorough and current international data about urban, rural, and stream recovery LID practices, visit the international BMP database (https://bmpdatabase.org/). This database stores information about performance, cost, and many other metrics.

Under the STEP program, the TRCA and University of Toronto (2013) have created several web tools (https://sustainabletechnologies.ca/tools/). One of note is the Life Cycle Cost Assessment of Low Impact Development Practices guide. It evaluated bioretention cells, PP, ITs and chambers, enhanced swales, rainwater harvesting and GRs. Costs for specific LID scenarios, examples, and costs for maintenance and rehabilitation are included. STEP also offers the LID Treatment Train Tool (https://sustainabletechnologies.ca/lid-ttt/), which can help designers to create optimal combinations.

Several other guides, handbooks, and information documents of interested are summarized in the table below.

LID Option	Description	Link
General LID Guidance	Low Impact Development Stormwater Management Planning and Design Guide (2010) by CVC and TRCA	https://sustainabletechnologies.ca/app/uploads/2013/01/LID-SWM-Guide-v1.0_2010_1_no-appendices.pdf
	STEP – Wiki Main Page	https://wiki.sustainabletechnologies.ca/wiki/Main_Page
	Reducing Stormwater Costs through Low Impact Development (LID) Strategies and Practices By US EPA	https://www.epa.gov/sites/production/files/2015-10/documents/2008_01_02_nps_lid_costs07uments_reducingstormwatercosts-2.pdf
	Low Impact Development Best Management Practices Design Guide (2014) by The City of Edmonton	https://www.edmonton.ca/sites/default/files/public-files/assets/PDF/LIDGuide.pdf?cb=1657118644
	LID Demonstration Project – New residential development project at the site of the former CFB Rockcliffe	http://webcast.ottawa.ca/plan/All_Image%20Referencing_OP%20Amendment%20Application_Image%20Reference_Rockcliffe%20-%20Low%20Impact%20Development%20Report%20-%20Part%204.PDF

	The Value of Green Infrastructure: A Guide to Recognizing Its Economic, Environmental and Social Benefits.	https://cnt.org/sites/default/files/publications/CNT_Value-of-Green-Infrastructure.pdf
	International BMP Database - thorough and current international data about urban, rural, and stream recovery LID practices	https://bmpdatabase.org/
	Assessment of Life Cycle Costs for Low Impact Development Practices	https://s3-ca-central-1.amazonaws.com/trcaca/app/uploads/2016/04/17182410/LID-LCC-final-2013.pdf
	STEP Support Tools for the design, construction, monitoring, inspection, and operation and maintenance of stormwater management best practices.	https://sustainabletechnologies.ca/tools/
	Grey to Green Road Right-of-Way Retrofit Guide by CVC & Partners	https://cdn.fs.guides.co/2fQa1LVPQCimcALM1S7a
Rain Gardens	STEP – Bioretention Options Summary	https://wiki.sustainabletechnologies.ca/wiki/Bioretention:_Variations
	STEP – Rain Gardens	https://wiki.sustainabletechnologies.ca/wiki/Rain_gardens
Swales	STEP – Swales	https://sustainabletechnologies.ca/home/urban-runoff-green-infrastructure/low-impact-development/swales-and-roadside-ditches/
Downspout Disconnection	STEP – Downspout Disconnection	https://wiki.sustainabletechnologies.ca/wiki/Downspout_disconnection
	Halton Downspout Disconnection Program	https://www.halton.ca/For-Residents/Water-and-Environment/Enhanced-Basement-Flooding-Prevention-Subsidy-Prog/Downspout-disconnection
Grid Pavers	Plastic Grid Pavers (2018) by University of Rhode Island	https://web.uri.edu/riss/files/factsheet_grid.compressed.pdf
Rain Barrels	STEP – Rainwater Harvesting	https://sustainabletechnologies.ca/home/urban-runoff-green-infrastructure/low-impact-development/rainwater-harvesting/

	Ontario Guidelines for Residential Rainwater Harvesting Systems: HANDBOOK (2010) by the Government of Ontario	http://www.arcsa-edu.org/Files/ONTARIO_RWH_HANDBOOK_2010.pdf
Catch Basin Technology	STEP – Pre-treatment Devices	https://wiki.sustainabletechnologies.ca/wiki/Pretreatment
Constructed Wetlands	Constructed Wetlands Manual by UN-Habitat	https://unhabitat.org/constructed-wetlands-manual
	Constructed Farm Wetlands Manual	https://www.sepa.org.uk/media/131412/constructed-farm-wetlands-manual.pdf
Rural Sustainable Drainage	Rural Sustainable Drainage Systems: A Practical Design and Build Guide for Scotland's Farmers and Landowners.	https://www.crew.ac.uk/publication/rural-sustainable-drainage-systems-practical-design-and-build-guide-scotlands-farmers
	A Green Infrastructure Guide for Small Cities, Towns and Rural Communities by Green Infrastructure Ontario Coalition and Friends of the Greenbelt Foundation	https://www.greenbelt.ca/report_green_infrastructure.

Case Studies and New Innovations

Case Studies

Dietz & Clausen (2008) compared the runoff volumes and nutrient concentrations of a traditional subdivision and a low-impact subdivision. Significant, logarithmic increases in stormwater runoff and N and P export were found as development occurred in the traditional subdivision. The increases in stormwater runoff and pollutant export were more than two orders of magnitude. TN and TP export after development was 10 and 1 kg/ha/yr, respectively, which was consistent with export from other urban/developed areas. In contrast, stormwater runoff and pollutant export from the low impact subdivision remained unchanged from pre-development levels. TN and TP export from the low impact subdivision were consistent with export values from forested watersheds (Dietz & Clausen, 2008).

J. F. Sabourin and Associates, Inc. (2008) assessed the performance of a grassed swale with perforated pipe (i.e., bioswale) in Nepean, ON after 20 years of operation. Peak flows and runoff volumes for the bioswale were 14-53% and 14-27% of those of the conventional system, respectively. The water quality of effluent flows was as good or better than that of the conventional system and TSS removal was 81-95%. Infiltration was optimal, there was no evidence of tree root damage or sediment accumulation, and underlying soils did not show evidence of nutrient or heavy metal accumulation. Vegetation quality and damage from winter snow removal were comparable for the bioswale and the conventional system, even though the conventional system had curbs and the bioswale did not.

Green Infrastructure and LID Initiatives in Canada

The City of Toronto has taken many initiatives to advance LID in Canada. They are the leading GR city in North America thanks to the Green Roof Bylaw that requires 20-60% GR area on new developments or additions over 2000m^2 (City of Toronto, 2022; Alim et al., 2022). Toronto also has a mandatory downspout disconnection policy. There are financial resources available for both programs (City of Toronto, 2022a).

Rain Ready Ottawa is a program run by the City of Ottawa that encourages and supports residents to reduce rainwater runoff on their property. The program offers general information, online courses, home assessments, and project rebates (City of Ottawa, 2022).

Many conservation authorities have clean water programs that focus on improving water quality. As mentioned above, the RVCA runs the Rideau Valley Clean Water Program (RVCWP, 2022). Other conservation authorities run similar programs with grants available for projects along the same lines. The Essex Region Conservation Authority (ERCA) conducts the Clean Water, Green Spaces program to address stormwater in rural and agricultural communities (ERCA, 2021). Lake Simcoe Conservation Authority (LSCA) runs a similar program offering funding for restoration projects on agricultural land. There is also funding available for community groups and schools to carry out tree planting, invasive species removal, citizen science projects, wildlife habitat enhancement, and other educational and environmental project initiatives (LSCA, 2016). Maitland Conservation offers a stream buffer planting program and runs the Huron Clean Water Project, which focuses on rural and agricultural projects but also offers community, stewardship, and special project grants (MaVCA, 2022). Some other conservation authorities who run similar rural clean water programs are South Nation Conservation Authority (SNCA, 2020), Toronto and Regional Conservation Authority (TRCA, 2022), and Mississippi Valley Conservation Authority (MVCA, 2022).

In lieu of or in addition to conservation authority clean water programs, Alternative Land Use Services (ALUS) is a Canadian charitable organization with an innovative community and farmer developed program that creates, enhances, and maintains ecosystem services on agricultural lands using nature-based solutions. Support is available to carry out projects such as wetland restoration, riparian buffer and windbreak planting, sustainable drainage systems, pollinator habitats, and more. If an ALUS program is not available in an area, there is an opportunity to initiate a new project (ALUS, 2022).

Delta, BC has been running the Adopt-a-Rain-Garden program for over 15 years. The program is a collaboration between the municipality, a volunteer group called the Cougar Creek Streamkeepers, the Delta School District, and other volunteers. One of the main issues with LID landscaping projects like rain gardens is the uncertainty around maintenance. The Adopt-a-Rain-Garden initiative addresses this issue and has been maintaining rain gardens across the city (Jones, 2020).

Green Infrastructure Ontario (GIO) is working with the Canadian federal government's plan to invest billions of dollars into GI over the next decade. GIO is focused on sustainable stormwater services, GRs, agriculture, urban forests, natural heritage, and parklands. The GIO website offers a Municipal Hub with GI resources specifically geared toward municipalities, including general resources, tool kits and guides, tools and calculators, guidelines, plans, and case studies (GIO, 2021).

RAIN Community Solutions is a nonprofit organization that supports municipalities with sustainable stormwater and low impact design projects. They offer community outreach and media, demonstration projects, neighborhood action planning, homeowner surveys, and market development (RAIN, 2022).

The Sustainable Neighborhood Action Program (SNAP) is a model for sustainable community development at the neighborhood level. SNAP projects include LID initiatives in a host of community economic, social, and health goals. Many communities have taken up SNAP initiatives in Canada as a means of addressing sustainable goals and priorities, with the TRCA leading the way (TRCA, 2022a).

New Innovations

Smart stormwater technology is the next wave of LID practice that uses internet connected devices to monitor, analyze, control, and optimize water flows in real time. This technology is currently underutilized due to inconsistent terminology and gaps in research. This tech is advantageous for larger municipalities with the resources to coordinate smart stormwater tech across catchment areas (Webber et al., 2022). As an example, a smart RB is outfitted with a water level monitoring device and a remotely controlled discharge value, which is paired with open-source software. This system can coordinate weather data, goals (I.e., preventing combined sewer overflows, reduction of drinking water, etc.), and control over the valve to optimize the use of the RB (Oberascher et al., 2021).

Similarly, LID optimization can be achieved through computer modelling tools. Commonly utilized tools include Stormwater Management Model (SWMM) and System for Urban Stormwater Treatment and Analysis Integration Model (SUSTAIN). Further models and methods are described in Eckart et al. (2017).

Huang et al. (2022) used a genetic algorithm (GA) and SWMM to evaluate life cycle cost-benefit for a highly urbanized area in China. While the results are specific to this geographical location, they proved that GA and SWMM are adequate tools for optimization in the long term (10 years) considering runoff reduction, LID area, and life cycle cost. A similar study by Eckart et al., (2018) used GA and SWMM to reduce peak flows, reduce total runoff, and maximize cost-benefit with different LID scenarios in Windsor, Ontario.

StormTreat System has been designed to capture and treat the first flush of runoff by being positioned high in the watershed and near the pollution sources. StormTreat incorporates sedimentation, filtration, and CWs into a modular, unitary 9.5-foot diameter structure. It is smaller compared to SWM ponds and wetlands and offers cost and space savings. Existing drainage infrastructure (I.e., CBs, etc.) is connected to tanks. The system intercepts first flush (first 2-3cm) but can be built to accommodate any size storm event (Horsley, 2000).

Walaszek et al. (2018a) tested a novel CW in a treatment train approach with a settling pond and sand filter. The efficiency of the settling pond was negatively affected by incoming flow during rain events. The sand filters showed good performance for heavy metals and other pollutants, but also showed a potential for leaching on subsequent rainfall events.

Anwar et al. (2020) tested a laboratory CBI with novel mix-medium of biochar and alum sludge was created to test nutrient removal. TSS removal was higher, over 90%, in course sediments over 150 micrometers. Phosphate removal was between 98-100%, ammonia removal was between 97-98%, and nitrite between 94-96%.

A new PP called evaporation-enhancing PP was developed as a potential method of UHI mitigation. This pavement is designed to manage stormwater in a region where the groundwater table is high. Therefore, a liner is needed for the PP to prevent infiltration from polluting groundwater. In the new pavement, capillary columns are installed in aggregate to lift runoff captured by the liner to the surface, which can promote evaporation and cool the pavement for a longer period The evaporation-enhancing PP was cooler than a conventional PP by as much as 9.4 °C during the experimental period. Moreover, the cooling effect of the former pavement could persist for more than seven days under the condition of no further rainfall (Liu at al., 2018)

Similarly, water retaining (WR) paver blocks do not infiltrate native soils. Instead, water is stored in the pores of permeable concrete and the sides and bottom are sealed with impermeable mortar (Qin et al., 2018). While typical PPs do not consistently reduce the UHI effect (Drake et al., 2013), WR paver blocks allow for more evaporation, which reduces UHI. Beyond the maximum water holding capacity, these systems will behave as impermeable pavements (Qin et al., 2018).

High-conductivity permeable concrete was prepared by adding steel fibers into traditional permeable concrete. High-conductivity permeable concrete is an effective method to alleviate UHI effect in dry and wet conditions (Chen et al., 2019)

Conclusion

In a review by Liu et al. (2020), GI for watershed management was discussed in respect to establishment, implementation, challenges, and strategies. LID is recommended as a benchmark practice and a part of protective policies for watershed management. Maintenance of healthy ecological processes in habitats should be a priority. This could include GI such as LID, ecological buffers, corridors, and habitats, and simulating natural environments in urban areas. Public awareness and participation should be prioritized and encouraged through education, incentives, and community. Watersheds should be managed by collaborative integration of resources across all environmental sectors. Lastly, water security and risk management should undergo assessment, contingency planning, monitoring, and early warning capability.

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