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Effectiveness of Low Impact Development Practices: Literature Review and Suggestions for Future Research

Laurent M. Ahiablame · Bernard A. Engel · Indrajeet Chaubey

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Abstract Low impact development (LID) is a land development strategy for managing stormwater at the source with decentralized micro-scale control measures. Since the emergence of LID practices, they have been successfully used to manage stormwater runoff, improve water quality, and protect the environment. However, discussions still surround the effectiveness of many of these practices, resulting in a reluctance to widely adopt them. This paper highlights evidence in the literature regarding the beneficial uses of LID practices. A discussion of how LID practices are represented in hydrologic/water quality models is also provided using illustrative examples of three computational models developed with algorithms and modules to support widespread adoption of LID practices. Finally, the paper suggests directions for future research opportunities.

Keywords Modeling · Diffuse pollution · Urban water planning · Environmental impact · Runoff · Water quality

1 Introduction

Increasing disturbance of natural landscapes due to urban expansion affects water resources and water quality (USEPA 2001). Alteration of natural hydrological systems by urbanization is generally translated by increased runoff rate and volume, decreased infiltration, decreased groundwater recharge and baseflow, and deterioration of water quality in streams, rivers, and shallow groundwater (Harbor 1994; Moscrip and Montgomery 1997; USGS 1999). These impacts along with adverse socio-economic outcomes of urbanization have led to the necessity for more intelligent and smart planning of urban growth such as smart growth, water sensitivity planning, low impact development planning, and other alternative ways to reduce negative impacts of urbanization on natural resources (USEPA 2000a; Coffman 2002; Moglen et al. 2003).

L. M. Ahiablame (✉) · B. A. Engel · I. Chaubey
Department of Agricultural and Biological Engineering,
Purdue University,
225 South University Street,
West Lafayette, IN 47907-2093, USA
e-mail: lamah@purdue.edu

B. A. Engel
e-mail: engelb@purdue.edu

I. Chaubey
e-mail: ichaubey@purdue.edu

I. Chaubey
Department of Earth and Atmospheric Sciences,
Purdue University,
225 South University Street,
West Lafayette, IN 47907-2093, USA

I. Chaubey
Division of Environmental and Ecological Engineering,
Purdue University,
225 South University Street,
West Lafayette, IN 47907-2093, USA

In recent years, low impact development (LID), an innovative approach of land development, has gained popularity (Coffman 2002). The underlying basic principle of LID is to maintain post-development hydrology of a site close to the natural condition present before development occurs (USEPA 2000a; Coffman 2002). Pioneered in the early 1990s in Prince George's County, Maryland (Coffman 2002), LID seeks to decrease the need for paving, curb, gutter, pipe systems, and inlet structures through the use of water features that could reduce the extent of hydrologic/water quality effects of impervious surfaces with reduced infrastructure construction and maintenance costs (HUD 2003).

Previous studies demonstrated the beneficial uses of LID practices at the watershed scale in comparison to watersheds developed without any consideration to LID planning (Selbig and Bannerman 2008; Bedan and Clausen 2009; Wang et al. 2010; Zimmerman et al. 2010). The benefits of LID practices at micro-scales (lot level) have also been shown in numerous studies (e.g., Hunt and Lord 2006; Davis 2008; Fassman and Blackbourn 2010; Gregoire and Clausen 2011). However, debates still surround many of these practices and many aspects pertaining to their benefits, indicating that knowledge gaps exist in regard to the effectiveness and application of LID practices. To this effect, a synthesis of the current literature is needed to support continuing in-depth research so that LID practices can be widely adopted and utilized as an established approach for stormwater management.

The objectives of this paper were to (1) highlight evidence of hydrologic/water quality benefits of LID practices through field and experimental studies, (2) describe how LID practices are represented in computational models developed for LID modeling, and (3) suggest opportunities for research and development of decision support tools incorporating LID practices. We acknowledge that the existing literature on each of the LID practices could be a sole topic of a standalone literature review (e.g., Scholz and Grabowiecki 2007; Davis et al. 2009; Roy-Poirier et al. 2010; Berndtsson 2010; Rowe 2011). We also acknowledge that novel studies with updated information will be published during the review process of this document and may not be herein reported. However, the discussion presented in this paper illustrates the range of advancements in the science of LID. This paper was not intended to provide an exhaustive review of the entire body of LID studies or simulation models that have potential to evaluate LID practices, but serves as a quick reference to individuals interested in LID technologies.

2 Methodology

This paper reviewed the global literature by drawing from peer review articles, books, technical reports, conference proceedings, case studies, design guidelines, project summaries, fact sheets, government publications, and unpublished reports. Search of a number of key words that include low impact development, urban best management practices, urban planning, and water sensitive planning using ISI Web of Knowledge, the Purdue University Library database, Wiley, Agricola, PubMed, JSTOR, Open Access Journals, Online Journals, Google Scholar, among others, was utilized to find publications. Published articles were also screened for citations to identify earlier studies. More than 250 publications were deemed relevant and directly or indirectly used for this review. The selected publications were categorized by LID practice to facilitate management and presentation of the information. This review focused on the most commonly utilized structural LID practices (e.g., bioretention, permeable pavement, green roof, and swale systems), which promote at least one of the following: runoff reduction, infiltration, evapotranspiration, and water quality improvement. Each practice is briefly defined and its performance discussed as reported in the literature. Three computer models are presented to discuss how LID practices are represented in hydrologic/water quality models. Many studies were reported in tables to show percent reduction in runoff and pollutant loads with the use of LID practices. Even though the percent removal (or efficiency ratio) metric has been shown to have limitations to adequately evaluate the performance of best management practices (BMPs), including LID practices (Huber 2006; McNett et al. 2011), it provides a general idea of findings from various geographic locations.

3 LID Overview

LID is a green approach for stormwater management that seeks to mimic the natural hydrology of a site using decentralized micro-scale control measures (Coffman 2002; HUD 2003) by achieving water balance

(Davis 2005). LID adheres to the following principles among others (PGCo 1999a; DoD 2004):

- Integrate stormwater management strategies in the early stage of site planning and design;
- Manage stormwater as close to the source as possible with distributed micro-scale practices;
- Promote environmentally sensitive design;
- Promote natural water features and natural hydrologic functions to create a hydrologic multifunctional landscape;
- Focus on prevention rather than mitigation and remediation;
- Reduce costs for the construction and maintenance of stormwater infrastructure;
- Empower communities for environmental protection through public education and participation.

The main goals of LID principles and practices include runoff reduction (peak and volume), infiltration increase, groundwater recharge, stream protection, and water quality enhancement through pollutant removal mechanics such as filtration, chemical sorption, and biological processes (Hunt et al. 2010). Following LID goals and principles, a large number of techniques are generally classified as LID practices. Hunt and Szpir (2006) and Hunt et al. (2010) published examples of structural and nonstructural practices that promote these main goals. Structural practices consist of bioretention, infiltration wells/trenches, stormwater wetlands, wet ponds, level spreaders, permeable pavements, swales, green roofs, vegetated filter/buffer strips, sand filters, smaller culverts, and water harvesting systems (rain barrels/cisterns). Nonstructural practices include minimization of site disturbance, preservation of natural site features, reduction and disconnection of impervious surfaces (i.e., elimination of curbs and gutters), strategic grading, native vegetation utilization, soil amendment and aerification, and minimization of grass lawns. LID promotes processes such as infiltration, filtration, onsite storage and detention, evapotranspiration, absorption, adsorption, precipitation, biodegradation, phytoremediation, and percolation, among others, which reduce the need for a centralized best management practice (USEPA 2000a; CEI 2008; Davis et al. 2009).

Stormwater management, before increased application of LID techniques, primarily focused on the reduction of peak runoff discharge rate by removing water quickly from a site to avoid flooding (CEI 2003). The approach of peak reduction does not aim to reduce volume of runoff nor improve water quality at development sites; instead, runoff is collected and routed to a centralized municipal facility or the nearest receiving water body with management techniques such as curbs, gutters, roadways, and pipes (PGCo 1999a; DoD 2004; CEI 2008). The peak reduction approach is known for causing downstream water quality problems by transporting pollutants into the receiving waters (USEPA 2000a; CEI 2008). This approach, often referred to as conventional development (CD), is still prominent in urban settlements where distributed stormwater control measures (LID practices) are not implemented or difficult to implement. The CD is also known as end-of-pipe practice, centralized approach, regional approach, or traditional approach. Examples of CD techniques include centralized stormwater management ponds, conveyance piping systems, pond/curb inlet structures, constructed concrete roadside ditches, and curb and gutter infrastructure.

While LID practices seek to keep water onsite as much as possible and protect water quality using landscape natural features, CD techniques intend to route water offsite as fast as possible through structural stormwater conveyance systems (PGCo 1999a, b; DoD 2004; Davis 2005; CEI 2008). CD methods support processes such as transport, collection, retention, discharge, and treatment with centralized end-of-pipe techniques at the outlet of drainage areas (USEPA 2000a). Although some CD techniques may incorporate conservation design to efficiently minimize onsite flooding and improve water quality with detention facilities (DoD 2004), they do not promote infiltration, groundwater recharge, and water quality improvement at the source with the same scope as LID strategies (USEPA 2000a).

Implementation of LID principles is a shift (of the stormwater practice) towards volume-based hydrology (VBH), a stormwater control approach that focuses on management of stormwater volumes (Reese 2009). The VBH is founded on the premise that reduction of stormwater volume will automatically result in solving other related problems such as pollutant loading, water velocity, peak flow rate, erosion, and sedimentation (Reese 2009). Management of runoff volume can be attained through managing stormwater at the source with distributed techniques (Debo and Reese 2002). The use of micro-scale distributed technologies to treat stormwater is growing in popularity worldwide. Low impact planning/LID is a term frequently used in Canada and the USA (Coffman 2002; Zimmer et al. 2007). Similar practices are described under the name of Water Sensitive Urban Design (WSUD) in Australia and Sustainable Drainage Systems (SUDS) in the UK (Lloyd 2001; Scholz and Grabowiecki 2007; Pezzaniti et al. 2009).

4 Evaluation of LID Practices: Field and Laboratory Studies

4.1 Bioretention/Rain Garden

Bioretention (or rain garden) systems are generally depressional areas designed to attenuate and treat stormwater runoff (USEPA 1999a; PGCo 2007). They are suitable for residential and commercial settings (Dietz 2007), but can also be used for agricultural water quality improvement (Ergas et al. 2010). Because bioretention systems behave similarly to natural and nonurban watersheds (DeBusk et al. 2011), they 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). Reduction of runoff volume and peak flow rate using bioretention systems is relatively well documented (e.g., Dietz 2007; Davis 2008; Line and Hunt 2009; Davis et al. 2009; Roy-Poirier et al. 2010; Chapman and Horner 2010; DeBusk and Wynn 2011), with a range of 40 % to 97 % (Table 1). For example, bioretention cells were shown to reduce average peak flows by at least 45 % during a series of rainfall events in Maryland and North Carolina (Davis 2008; Hunt et al. 2008). In a recent field study, a retrofit bioretention cell was shown to reduce by 97 % and 99 % flow volumes and rates from a parking lot (DeBusk and Wynn 2011). The reduction of runoff volumes and rates depends on the magnitude of rainfall events. During small events, bioretention facilities can readily capture the entire inflow volume (Davis 2008). Processes as infiltration and evapotranspiration play an important role in runoff retention. Chapman and Horner (2010) showed that 48 % to 74 % of runoff that flows through bioretention systems escaped in the form of infiltration and evaporation, and 20 % to 50 % through exfiltration and evapotranspiration (Li et al. 2009).

A large number of studies have credited bioretention as a best management practice capable of reducing 0 % to 99 % of sediment and nutrient losses (e.g., Davis et al. 2006; Hunt et al. 2006; Dietz 2007; Line and Hunt 2009; Roy-Poirier et al. 2010; Table 1). Luell et al. (2011) monitored bioretention cells during 13 months and 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 and Hunt 2009), between 70 % and 85 % of phosphorus (P), and 55 % to 65 % of total Kjeldahl nitrogen (TKN) using bioretention facilities (Davis et al. 2006). This efficiency is relatively well documented for most nutrients, except for nitrates (NO_3–N) for which a reduction of less than 20 % is reported (Davis et al. 2006). To improve NO_3–N reduction with bioretention, 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 NO_3–N. Other researchers have found that a saturated zone in bioretention systems can also improve N retention. For example, Dietz and Clausen (2006) created a saturated zone in a bioretention facility capable of storing 2.54 cm of runoff to demonstrate efficient removal of NO_2–N + NO_3–N, NH_4^+–N, and TN. Hsieh et al. (2007a) and Ergas et al. (2010) have also improved N removing capacity of bioretention systems by creating anoxic zones in the bioretention media to promote nitrification/denitrification processes. Aerobic nitrification and anoxic denitrification can be achieved with sulfur or wood chips (Ergas et al. 2010).

Average metal reduction in bioretention varies between 30 % and 99 % (Table 1). For example, bioretention pilot-plants were used to remove nearly 100 % of lead (Pb), copper (Cu), and zinc (Zn) (Davis et al. 2003; Li and Davis 2009; Chapman and Horner 2010). Prototypes of bioretention monitored in laboratory settings resulted in 88 % to 97 % reduction in soil media, and 0.5 % to 3.3 % in plant species for Zn, Cu, Pb, and cadmium (Cd) from simulated runoff events (Sun and Davis 2007). In bioretention cells with low metal retention capacity (especially in sandy soil media), the performance of the system can be improved by adding fly ash to the media (Zhang et al. 2008).

Table 1 Summary of percent runoff reduction and pollutant removal by bioretention systems

Study	Location	Runoff	TSS	P/TP	NO_3–N	NH_4–N	TKN	TN	Cu	Pb	Zn	FC[a]	O/G[b]
Davis et al. (2001)	Lab experiment, USA	–	–	60–80	24	60–80	60–80	–	>90	>90	>90	–	–
Davis et al. (2003)	Lab experiment, USA	–	–	>65	>15	–	>52	>49	>43	>70	>64	–	–
Hsieh and Davis (2005)	Lab experiment, USA	–	–	4–99	1–43	2–49	–	–	–	66–98	–	–	>96
Glass and Bissouma (2005)	Washington, DC, USA	–	98	−3	–	−65	–	–	75	71	80	–	–
Sun and Davis (2007)	Lab experiment, USA	–	–	–	–	–	–	–	88–97	88–97	88–97	–	–
Davis et al. (2006)	Maryland, USA	–	–	70–85	<20	–	55–65	–	–	–	–	–	–
Dietz and Clausen (2006)	Connecticut, USA	–	–	–	67	82	26	51	–	–	–	–	–
Hong et al. (2006)	Lab experiment, USA	–	–	–	–	–	–	–	–	–	–	–	83–97
Hunt et al. (2006)	North Carolina, USA	–	–	–	13–75	–	–	–	99	81	98	–	–
Roseen et al. (2006)	New Hampshire, USA	–	96	–	27	–	–	–	–	–	99	–	–
Davis (2007)	Maryland, USA	–	47	76	83	–	–	–	57	83	62	–	–
Rusciano and Obropta (2007)	Lab experiment, USA	–	92	–	–	–	–	–	–	–	–	92	–
Hunt et al. (2008)	North Carolina, USA	–	60	31	–	73	44	32	54	31	77	71	–
Zhang et al. (2010)	Lab experiment, USA	–	–	–	–	–	–	–	–	–	–	>82	–
Chapman and Horner (2010)	Washington, USA	48–74	87–93	67–83	63–82	–	–	–	80–90	86–93	80–90	–	92–96
DeBusk and Wynn (2011)	Virginia, USA	97	99	99	–	–	–	99	–	–	–	–	–
Zhang et al. (2011)	Lab experiment, USA	–	–	–	–	–	–	–	–	–	–	72–97	–

[a] *FC* fecal coliform including *E. coli*

[b] *O/G* oil/grease

Average retention of bacteria in bioretention ranges from 70 % to 99 % (Table 1). In Maryland, significant retention of *Escherichia coli* in bioretention was achieved with iron-oxide coated sand media (Zhang et al. 2010). This study reported 17 % improvement in *E. coli* O157:H7 strain B6914 cells retention with the enhanced bioretention media. Beside the configuration of bioretention media, lifespan has also been shown to positively affect bacteria retention capacity of bioretention facilities, which increased from 72 % to 97 % for *E. coli* O157:H7 strain B6914 after 6 months (Zhang et al. 2011). In addition, exposure of bioretention facilities to sunlight has been shown to increase microbial removal (Hathaway et al. 2009).

The composition of bioretention media can play an important role in the performance of the system. For example, Hsieh and Davis (2005) demonstrated that bioretention cells with sand media have great pollutant removal capacity. The efficiency of the sand media, however, decreased over time due to limited biological activities sustained by the substrate (Hsieh and Davis 2005). Similarly, Hsieh et al. (2007b) showed that sandy media in bioretention might lose its P retention capacity in only 5 years under typical stormwater runoff events. Thus, Lucas and Greenway (2011) suggested that amendment of bioretention media with P sorption materials can enhance the ability of the system to reduce P loads.

Construction activities can also impact bioretention performance. A comparison study of two excavation techniques of bioretention cells (scoop and rake) found the rake technique is preferable over the scoop method for maximizing the performance of the system, especially under dry soil conditions (Brown and Hunt 2010). Beside design configurations, sizing, choice of vegetation, siting considerations, and maintenance also play important and beneficial roles in the performance of bioretention systems (Hunt and Lord 2006; Jones and Hunt 2009; Davis et al. 2009; Trowsdale and Simcock 2011; Brown and Hunt 2012).

4.2 Green Roof

A green roof is a building rooftop partially or completely covered with vegetation over high quality waterproof membranes to compensate for the vegetation that was removed when the building was constructed (Miller 1998; USEPA 2000b; Rowe 2011). Green roofs have been around for decades and have been used to control runoff volume, improve air and water quality, and promote conservation of energy (USEPA 2000b). Green roofs can be categorized as "extensive" or "intensive" based on the thickness of the roof layer and the level of maintenance needed (GRRP 2010; Bianchini and Hewage 2012). The former is generally planted with dense, low growing, drought-resistant vegetation, and generally suitable for single family and multi-family residential buildings, while the latter has the ability to support a diverse population of vegetation, and widely used for commercial buildings. Also known as garden roofs, intensive green roofs may have grasses, flowers, shrubs, trees, root barriers, and drainage and irrigation systems, to hold and route rain water, thus slowing the velocity of direct runoff. Research related to the performance of green roofs as a means to manage stormwater quantity and quality have been reported for a variety of climate conditions (e.g., Carter and Rasmussen 2005; VanWoert et al. 2005; Bengtsson et al. 2005; Dietz 2007; Forester 2007; Rowe 2011; Stovin et al. 2012).

Average rainfall retention by green roofs varies between 20 % and 100 % (e.g., DeNardo et al. 2005; VanWoert et al. 2005; Bengtsson et al. 2005; Dietz 2007; Hathaway et al. 2008; Bliss et al. 2009; Fioretti et al. 2010; Carpenter and Kaluvakolanu 2011; Table 2). This performance, however, has been shown to decrease with increase in rainfall amount (Carter and Rasmussen 2005; Moran et al. 2005). During a rainfall event, once the water holding capacity of the roof material is reached, the excess water is converted into runoff. Studies in the Georgia Piedmont revealed that the capacity of extensive roof gardens to retain rainfall declined from 90 % for a 12-mm event to 39 % for a 50-mm event (Carter and Rasmussen 2005). Other studies showed that the depth of green roof soil layer as well as the composition of vegetation greatly influenced the water retention and release from the system (Dunnett et al. 2008; Buccola and Spolek 2011). Increased green roof soil layer depth was found to improve the performance of the system (Dunnett et al. 2008). Increased roof media could also mitigate damage of roof plant communities that may occur under heavy rainfall events and winter frosts (Boivin et al. 2001).

Nutrient removal using green roofs presents some challenges. During a field study, Hathaway et al. (2008) found that green roofs retained 64 % of rainfall,

Table 2 Summary of percent runoff reduction by green roofs

Study	Location	Runoff reduction
Scholtz-Bart (2001)	Illinois, USA	65
Bass and Baskaran (2003)	Ottawa, Canada	23
Liu (2003)	Ottawa, Canada	54
DeNardo et al. (2005)	Pennsylvania, USA	40
VanWoert et al. (2005)	Michigan, USA	49-83
Hathaway et al. (2008)	North Carolina, USA	64
Bliss et al. (2009)	Pennsylvania, USA	70
Roehr and Kong (2010)	Vancouver and Kelowna, Canada	29–100
Roehr and Kong (2010)	Shanghai, China	55
Stovin (2010)	Sheffield, UK	34
Voyde et al. (2010)	Auckland, New Zealand	82
Gregoire and Clausen (2011)	Connecticut, USA	51
Carpenter and Kaluvakolanu (2011)	Michigan, USA	68

while no significant TP and TN were retained. Other studies have also reported high concentrations of TP, NO_3–N, and TN losses from green roofs under no fertilization conditions (Hutchinson et al. 2003; Monterusso et al. 2004; Moran et al. 2005). This suggests that the practice of fertilization on green roof material may accentuate the risk for water quality contamination due to prolonged leaching (Berndtsson et al. 2006; Emilsson et al. 2007). Aitkenhead-Peterson et al. (2011) recently reported that unplanted growth medium or unhealthy plant species on green roofs may cause NO_3–N to leach into runoff. Extensive green roofs have also been shown to release high concentrations of P (Berndtsson et al. 2009).

Similarly to nutrients, research on the ability of green roofs in removing metals from stormwater resulted in varying findings. Gregoire and Claussen (2011) monitored a green roof in Connecticut and found that green roof effectively reduced Zn and Pb. Contrarily, Alsup et al. (2010) reported that green roof materials such as Axis, Arklayte, coal bottom ash, Haydite, Lassenite, lava rock, and composted pine bark may act as sources for heavy metals in runoff. In Sweden, Berndtsson et al. (2006) showed that green roofs contributed moderate amounts of Cd, Cr, Cu, Fe, K, Mn, Pb, and Zn to runoff.

Even though green roofs have been shown to reduce runoff volumes, their use as a means for water quality improvement was not reported for all green roof projects. To minimize potential pollutant losses from them, Dietz (2007) recommended that precaution should be taken when installing green roofs. A careful selection of green roof media is critical for maximizing the performance of the system in locations where pollutant removal is the goal (Hathaway et al. 2008), as pollutant retention and release from the system strongly depends on the nature of the composition of green roof media and amount of rainfall (Vijayaraghavan et al. 2012). After installation, proper maintenance or corrective measures are needed to help reduce contamination of stormwater runoff from green roof media (Zobrist et al. 2000). For example, the combination of green roofs with other LID practices such as routing the runoff through rain gardens could be an alternative to maintain water quality.

4.3 Permeable Pavement

Permeable/porous pavements are designed to temporarily store surface runoff, allowing slow infiltration into the subsoil (USEPA 1999b). Permeable pavements include block pavers, plastic grid systems, porous asphalts, and porous concretes (Dietz 2007). Research on porous pavements have been shown to reduce runoff and associated pollutant loads in a variety of locations (Dietz 2007; Collins et al. 2008; Pezzaniti et al. 2009; Collins et al. 2010; Fassman and Blackbourn 2010; Tota-Maharaj and Scholz 2010; Beecham et al. 2012).

Average runoff reduction from porous pavements varies between 50 % and 93 % (Table 3). In a 2-year

Table 3 Summary of percent runoff and pollutant retention by permeable pavements

Study	Location	Runoff	TSS	P/TP	NO_3–N	NH_4–N	TKN	Cu	Pb	Zn	FC[a]
Legret et al. (1999)	Rezé, France	–	58	–	–	–	–	–	84	73	–
Pagotto et al. (2000)	Nantes, France	–	87	–	–	–	–	20	74	–	–
Rushton (2001)	Florida, USA	50	>75	>75	–	>75	>75	>75	>75	>75	–
Hunt et al. (2002)	North Carolina, USA	75	–	–	–	–	–	–	–	–	–
Dierkes et al. (1999)	Lab experiment, Germany	–	–	–	–	–	–	98	99	95	–
Fach and Geiger (2005)	Lab experiment, Germany	–	–	–	–	–	–	>85	>85	>85	–
Dreelin et al. (2006)	Georgia, USA	93	–	10	–	–	–	–	–	80	–
Pezzaniti et al. (2009)	Lab experiment, Australia	–	94	–	–	–	–	–	–	–	–
Tota-Maharaj and Scholz (2010)	Edinburgh, Scotland	–	–	78	–	85	–	–	–	–	98–99
Meyers et al. (2011)	Adelaide, Australia	–	–	–	–	–	–	94–99	94–99	94–99	–

[a] Fecal coliform including *E. coli*

monitoring study of a permeable parking lot in North Carolina, Hunt et al. (2002) demonstrated that 75 % of rainfall events were captured by the porous media, while the remaining 25 % produced runoff from the study site. Similarly, Collins et al. (2008) found that permeable interlocking concrete pavements and concrete grid pavers were able to retain up to 6 mm of rainfall with no runoff. Further experiments from the same region confirmed that not only can permeable pavements reduce runoff, but they can also eliminate runoff generation (Bean et al. 2007) even during the most intense rainfall events (Brattebo and Booth 2003). Fassman and Blackbourn (2010) used permeable pavements to demonstrate that pre-development hydrology can be achieved with such technologies. Their findings were consistent with findings reported by Dreelin et al. (2006) who used porous pavements to reduce 93 % of runoff on two parking lots. The researchers also proved that porous pavements can be used to control small storms (less than 2 cm) and retain "first flush" runoff during larger storm events on clay soils.

The removal of TSS and nutrients by permeable pavements has been reported in a number of studies with average reductions ranging from 0 % to 94 % (Table 3). Assessment of water quality benefits of porous pavements by Bean et al. (2007) at two study sites resulted in varying findings. Low concentrations of TP, NH_3–N, TKN, and TSS, and high levels of NO_3–N were reported for the first site; only low concentrations for NH_3–N were observed at the second site. The authors linked the presence of high NO_3–N concentrations in the two cases to aerobic conditions that may potentially support nitrification within the pavements. Other studies have also found increased NO_3–N concentrations in water from permeable pavements (James and Shahin 1998, Collins et al. 2010).

Average metal reduction by porous pavements has been reported to vary between 20 % and 99 % (Table 3). Fach and Geiger (2005) used four types of permeable concrete blocks to remove significant amounts of Cd, Cu, Pb, and Zn from artificial rainfall-runoff events. Myers et al. (2011) reported 94 % to 99 % reduction of Z, Cu, and Pb in water stored in permeable pavement after 144 h. Other researchers observed 80 % removal of Zn (Dreelin et al. 2006). Pagotto et al. (2000) also demonstrated water quality benefits of porous pavements for Cu and Pb reduction. Experiments conducted by Dierkes et al. (2002) substantiated the capacity of porous pavements to capture dissolved heavy metals from runoff with no danger to groundwater contamination. However, the authors noticed that metals can be quickly accumulated in the top layer of pavements (upper 2 cm), resulting in greater pollution risks during subsequent runoff events (Dierkes et al. 1999). Thus, proper maintenance as well as careful assessment of the location of the system are critical to achieve high performance (Bean et al. 2007; Kwiatkowski et al. 2007).

Permeable pavements have also been shown to be efficient attenuators for grease (e.g., motor oil) due to a variety of microbial activities that can occur within the system (Newman et al. 2002), and for bacteria such as *E. coli* and fecal Streptococci (Tota-Maharaj and Scholz 2010; Table 3). Although permeable pavements are primarily used to reduce runoff and improve water quality, they can also be used as stormwater harvesting and storage mechanisms for reuse to alleviate increasing water demand for the rapidly growing urban populations (Myers et al. 2011).

4.4 Swale Systems

Swales are shallow open channels with gentle side slopes, filled with erosion and flood resistant vegetation, designed to convey, control, and improve stormwater through infiltration, sedimentation, and filtration (USEPA 1999c; Kirby et al. 2005). Although swales are generally used to replace or supplement traditional curbs and gutters for stormwater conveyance in urban settings (Barrett et al. 1998), they can also be used for erosion control in agricultural environments (Kirby et al. 2005). Swales can efficiently operate under a variety of seasonal conditions (Fach et al. 2011). Swale systems include infiltration swales, bioswales, biofilters, grassed swales, or filter strips, and vary from grassed channels to dry swales and wet swales.

Swales are mainly used to slow runoff velocity and improve water quality. Average retention in swales varies between 14 % and 98 % for nutrients and TSS, and up to 93 % for metals (Table 4). Bäckström (2002) reported that swales can be used to achieve high removal efficiency of pollutants when the swale is filled with dense and fully developed vegetation. Swales have been shown to trap 99 % of TSS, TP, TKN, TN, and Fe at the field scale (Kercher et al. 1983; Bäckström 2002). Similar studies found that 25 % to 30 % (Yousef et al. 1987) and 61 % to 86 % of TP (Deletic and Fletcher 2006), and 7 % to 11 % (Yousef et al. 1987) and 46 % to 56 % of TN (Deletic and Fletcher 2006) can be trapped by grass swales. Lloyd et al. (2001) measured 74 % removal of TSS and 55 % of TP with grass swales. Bäckström (2002; 2003) showed that the high reduction of pollutant loads by swales could likely be the result of sedimentation processes, high infiltration rates, swale length, and increased water residence time in the swale.

Swales, however, have moderate removal ability for heavy metals, especially in dissolved form (Bäckström 2003). Yousef et al. (1987) explained that the reduction of metals in grass swales is driven by adsorption processes, which are primarily controlled by sediments, suggesting that fractions of pollutants in dissolved form would not be efficiently retained in grass swales (Bäckström 2003; Deletic and Fletcher 2006).

5 Evaluation of LID Practices: Simulation Modeling

5.1 Modeling LID Practices

Even though the literature provides extensive monitoring information discussing the beneficial uses of LID practices, monitoring efforts are constrained to limited periods and conditions due to high costs of monitoring conventions. Simulation modeling provides valuable insight to extrapolate this information to different spatial (field to watershed) and temporal (single event to long-term simulations) scales.

In recent years, a number of researchers have used a variety of modeling techniques to assess the effectiveness of urban BMPs and LID practices in stormwater management (e.g., Ackerman and Stein 2008; Elliot et al. 2009; Wild and Davis 2009; Wild and Davis 2009; Avellaneda et al. 2010; Palhegyi 2010; He and Davis 2011; Golroo and Tighe 2011). There are two broad ways to represent these practices within hydrologic and water quality models. The first approach, which can be characterized as process representation, seeks to model processes (e.g., infiltration, sedimentation, adsorption, evapotranspiration, settling, and transformation of pollutants) occurring within the BMPs or LID practices (Metcalf and Eddy 2003; Huber et al. 2006). The process of interest can either be explicitly assessed in a practice or a group of practices (to examine the collective impacts of several practices with respect to this process), or a series of processes could be evaluated in the practice. Huber et al. (2006) can be consulted for an illustrative list of these fundamental unit processes.

A typical example of process representation would consist of modeling infiltration, evapotranspiration, and pollutant uptake in a bioretention system. Data availability and processing can, however, be an issue for this approach due to the fact that modeling unit processes involves extensive computational and data requirements (Huber et al. 2006). This approach allows detailed modeling suitable for design, construction, and optimization of development scenarios.

The practice representation approach uses an aggregation method to represent the practice as a whole. This approach measures the effects of the practice on runoff and water quality by combining all complex processes that the practice can perform in one

Table 4 Summary of percent pollutant retention by grass swales

Study	Location	TSS	P/TP	TN	Pb	Zn
Barrett et al. (1998)	Texas, USA	85	31–61	31–61	–	68–93
Lloyd et al. (2001)	Melbourne, Australia	55–74	24–55	–	–	–
Yu et al. (2001)	Virgina, USA and Taipei, Taiwan	30–97	29–99	14–24	–	–
Bäckström (2002)	Lab experiment, Sweden	79–98	99	14–24	75	–
Deletic and Fletcher (2006)	Aberdeen and Brisbane, Australia	46–86	46	56	–	–

parameter (e.g., representing the effects of rain barrel, bioretention, vegetated roof, and porous pavement with curve number values; see Sample et al. 2001; Ahiablame et al. 2012). The drawback for this approach is that the parameter may not accurately quantify the performance of the practice of interest (due to simplifying assumptions made during the modeling exercise). Usually this approach is utilized to compare hydrologic impacts of development scenarios with or without calibration in order to highlight the beneficial uses of BMPs and LID practices for planning and decision making (prior to more detailed studies for practical implementation).

5.2 Representation of LID Practices with Hydrologic/Water Quality Models

Model selection for a project is generally driven by the problem that needs to be solved and the project goal (Engel et al. 2007). Many computer models have been developed and widely used to evaluate the impacts of land change and BMPs on water resources and water quality (NRC 2008). Elliot and Trowsdale (2007) and Bosley (2008) have extensively reviewed computational models that can be potentially utilized for LID modeling. Even though new models have been developed or enhancement of exiting models with new algorithms has been completed since these publications (the two studies mentioned above), they provide a good understanding of the fundamental capabilities of individual models to handle different temporal and spatial scales. These studies should be consulted for additional details. In the present paper, three computer models, developed with algorithms and modules suitable for simulation of LID practices, are presented to illustrate the two representation approaches discussed in “Modeling LID Practices”. Each of these models was developed with different levels of complexity and uses different approaches to evaluate LID practices.

5.2.1 Long-Term Hydrologic Impact Assessment–Low Impact Development (L-THIA-LID) Model Overview

L-THIA-LID (https://engineering.purdue.edu/mapserve/LTHIA7/lthianew/lidIntro.htm; Table 5) is a simple rainfall-runoff model designed to assist in decision making by planners and natural resource managers for water quality and water resources protection (Hunter et al. 2010; Engel and Ahiablame 2011). L-THIA-LID is an enhanced version of the L-THIA model (Engel 2001), which uses the NRCS CN and event mean concentration (EMC) methods to simulate runoff and NPS pollutant loads based on local daily rainfall, land use, and soil data (NRCS 1986; Baird et al. 1996; Table 5). The CN is used in an empirically based formula to determine how much of a given rainfall event becomes surface runoff. The L-THIA-LID currently supports a group of LID practices, including bioretention/rain garden, grass swale, open wooded space, porous pavement, permeable patio, rain barrel/cistern, and green roof. Both lot and watershed level simulations are based on modified CN values which describe the effects of these practices on hydrology and water quality. The use of the CN equation in L-THIA-LID is a simple alternative to more complicated hydrological models that require inputs of intensive datasets, often not available for most areas of interest or that would be difficult to obtain. The L-THIA-LID model can be used to simulate runoff and NPS pollutant load reduction associated with LID practices from a single lot to a watershed scale, allowing comparison between LID development and conventional development. This model is a quick screening and easy to use tool to

Table 5 Examples of computational models with algorithms and modules for LID modeling

Model	Time domain	Surface runoff/ infiltration	Flow routing	Groundwater flow	Snowmelt	Water quality	LID representation
SWMM	Single event Continuous	Manning Horton CN[b] Green-Ampt	Steady state KW[c] DW[d]	Two-zone (saturated–unsaturated) mass balance	As runoff	CSTR[f] EMC[g] Exponential function Power function Saturation function Rating curve First-order decay	Vertical layers Process-based
SUSTAIN	Continuous[a]	Manning Green-Ampt Holtan-Lopez	KW[c] Nonlinear reservoir routing	Modified two-zone mass balance (saturated–unsaturated, interactions)	Degree-day NWS[e]	CSTR[f] Exponential function Power function Saturation function Rating curve EMC[g] Storage routing First-order decay	Process-based Storage routing Distributed Aggregation Tiered analysis
L-THIA–LID	Single event Continuous	CN[b]	N/A	N/A	N/A	EMC[g]	CN[b]

[a] Even though SUSTAIN operates with time series data, it allows to visualize individual storm events and evaluate the performance of management practices (in simulation results)

[b] *CN* Curve Number

[c] *KW* Kinematic Wave

[d] *DW* Dynamic Wave

[e] *NWS* Anderson's (1973) National Weather Service equation

[f] *CSTR* Continuously Stirred Tank Reactor

[g] *EMC* Event Mean Concentration

assist decision making for planners and natural resource managers.

5.2.2 Storm Water Management Model (SWMM) Overview

SWMM (http://www.epa.gov/ednnrmrl/models/swmm; Table 5) was developed to simulate single event or long-term stormwater quantity and quality mainly from urban areas (Huber and Dickenson 1988). SWMM is moderately complex and a widely used model for planning, research, and design related to stormwater runoff (e.g., Park et al. 2008; Abi Aad et al. 2010; Shuster and Pappas 2011). The model estimates runoff based on a collection of subcatchment areas that receive rainfall and generate runoff and water quality constituents as influenced by evaporation and infiltration losses from the subcatchments (Table 5). The runoff is then routed through a conveyance system of pipes, channels, storage/treatment devices, pumps, orifices, weirs, and regulators. New modules/algorithms have recently been added to the model to exclusively support simulation of LID practices. SWMM LID models processes within LID practices represented as a combination of vertical layers (Table 5).

5.2.3 System for Urban Stormwater Treatment and Analysis INtegration (SUSTAIN) Model Overview

SUSTAIN (http://www.epa.gov/ednnrmrl/models/sustain/index.html; Table 5) is a complex multi spatial-scale model developed to assist decision making regarding selection and placement of BMPs and LID practices for runoff reduction and water quality protection in urban watersheds (USEPA 2009). SUSTAIN uses multiple techniques to estimate runoff and water quality constituents (Bicknell et al. 2001, Table 5). SUSTAIN currently supports the simulation of a variety of LID practices, which include bioretention, cistern, constructed wetland, dry pond, grassed swale, green roof, infiltration basin, infiltration trench, porous pavement, rain barrel, sand filter (non-surface and surface), vegetated filter strip, and wet pond (USEPA 2009). The model uses process-based representation approach (see “Modeling LID Practices”) to simulate storage, infiltration, filtration, evapotranspiration, and pollutant routing and removal, among others, within individual or aggregated LID practices. SUSTAIN can be used to explore the benefits of LID practices prior to implementation, identify management practices for practical implementation, and evaluate the performance of implemented practices.

6 Opportunities for Research

Even though much progress has been made in the science of LID to understanding the performance of these practices, there are still many aspects and challenges, from engineering principles to public policy making, that must be assessed and addressed in order to support widespread LID adoption. These needs are discussed hereafter in more detail. They include among others:

- Characterization of runoff and water quality from different urban land uses;
- Need for continued data collection for evaluation of LID systems over different spatial and temporal scales and climatic conditions;
- Need for assessing removal of emerging and difficult-to-measure contaminants by LID practices;
- Enhancement of metrics and modeling techniques for evaluating the performance of LID practices;
- Scaling of the performance of LID practices from lot scales to watershed and regional scales;
- Development of easy-to-use decision support tools incorporating LID practices; and
- Need for addressing “road blocks” to increase LID adoption.

6.1 Characterization of Runoff and Water Quality from Different Urban Land Uses

Sources of NPS pollution in urban watersheds include atmospheric deposition, traffic, metallic surfaces, galvanized products, lawn activities, and construction activities among others (Baird et al. 1996; Sansalone et al. 1998; Sansalone and Kim 2008; Ying and Sansalone, 2010a, b). During rainfall events, pollutants are washed off and transported in downstream waters, causing water quality deterioration (Grove et al. 2001; Schueler 1995). To maximize the performance of LID practices in reducing runoff and improving water quality, improved understanding of pollutant transport from urban land uses is needed. For example, Passeport and Hunt (2009) have characterized nutrient concentrations and loads from eight parking lots in North Carolina for total nitrogen, total Kjeldahl nitrogen, ammonia–nitrogen, nitrate–nitrogen, total phosphorus, and orthophosphate. This study provides a good understanding of factors that may influence inputs of nutrients from parking lots. Similar studies are needed to improve prediction accuracy of water quality models and design of LID practices.

6.2 Insufficient Data for LID Practice Performance

Although the performance of bioretention systems is relatively well understood (Davis et al. 2009), there is currently a lack of sufficient scientific data related to understanding the relationship between processes in bioretention systems and processes in natural ecosystems. DeBusk et al. (2011) reported that bioretention systems behave similarly to natural and nonurban watersheds, indicating that processes such as interflow, groundwater flow, first flush, or natural occurrence of different species of pollutants should be taken into account to enhance methods and simulation models for the evaluation of these systems. Measured data characterizing natural ecosystems will also help define base guidelines for the evaluation of LID practices. Scientific data for continuing in-depth understanding of the effectiveness of LID practices, such as swale systems, green roof, rain barrel/cistern, infiltration wetland, and porous pavement, at various temporal and spatial scales, as well as in different geographic regions are needed. Emphasis should be given to inputs, specific transformations and accumulations, and export of pollutants from the systems.

Beside nutrients and metals, pH, dissolved oxygen, and temperature are also common water quality parameters measured when assessing water quality. There are only few measured data that present the impact of LID practices on these parameters. Pollutant removal by plant uptake depends on the bioavailability of pollutants in the water column, which in turn may influence the pH of the water column. As an example, water coming from a green roof may have an elevated level of pollutants (Hathaway et al. 2008; Aitkenhead-Peterson et al. 2011), which could change downstream water pH and consequently may create harmful environments for stream communities.

It is generally recognized that dissolved oxygen is more abundant in rapid flowing water than in stagnant water. Dissolved oxygen in infiltration practices with stagnant water should be fully investigated. Similar to pH, the temperature of water leaving LID practices can influence downstream habitats. As water becomes warmer, dissolved oxygen holding capacity of water also decreases due to rapid saturation, causing microbial uptake of some pollutants to decrease. More scientific data are also needed to help understand the performance of LID practices with respect to the effect of temperature as shown by Hathaway et al. (2009).

There is also a crucial need to evaluate the performance of swales for runoff reduction and green roofs for pollutant mitigation. The composition of green roof vegetation play an important role in the performance of the system (Schroll et al. 2011), suggesting that seasonal variation should be taken into consideration when evaluating green roofs (Berndtsson 2010; Schroll et al. 2011).

The availability of data regarding pathogen trapping in LID practices is another challenge. Stormwater runoff may contain a wide variety of pathogens including bacteria, fungi, viruses, and protozoans such as *Cryptosporidium* and *Giardia* (USEPA 2004). These pathogens can easily affect human and fish health. The influence of LID practices on pathogens should continue to be investigated so that improved designs can be implemented.

Effort should also be given to field and experimental work to collect scientific data for investigating the effects of storm retention using LID techniques on flood damage reduction (especially for small storm events).

6.3 Removal of Emerging Contaminants by LID Practices

Even though emerging contaminants have drawn increasing attention, and innovative analytical methods have been developed to detect them, the ability to quantify with exactitude these difficult-to-measure contaminants is still at an embryonic state. There is currently no documentation pertaining to LID practices and emerging contaminants. Increasing the fundamental knowledge to determine the sources, the fate and transport of these newly recognized contaminants in urban settings is needed in defining not only how to quantify and regulate them but also to investigate the ability of LID practices for reducing them.

6.4 Performance Metrics and Modeling Techniques for LID Practices

There is currently a large number of performance measures used to evaluate LID practices based on influent and effluent concentrations (GeoSyntec et al. 2002). However, variations exist in the literature in regard to the appropriate metric to utilize in specific situations and for specific practices (Huber 2006). For instance, McNett et al. (2011) demonstrated that using only efficiency ratio (commonly described as percent removal) to measure the effectiveness of bioretention systems can be misleading. The percent removal metric relies heavily on the relative magnitude and intensity of single stormwater events, and do not provide any basis to evaluate the long-term performance of the practice and effluent quality with respect to recommended water quality standards (GeoSyntec et al. 2002; Huber 2006). New metrics should seek to describe the performance of the practice with respect to processes (e.g., infiltration, evapotranspiration), characterize threshold in performance level of the practice, describe the amount and quality of outflows from the practice, and quantify downstream impacts of the practice (Strecker et al. 2001; Huber 2006). These improved metrics are needed to improve and standardize evaluation of LID practices.

In recent years, there has been a growing interest in modeling LID practices (Elliot and Trowsdale 2007; Bosley 2008; NRC 2008). Model results are as important as monitoring studies, as they provide cost effective alternative insights to the performance of these practices for hydrologic and water quality benefits. Model results can also serve as guides for developing watershed planning and management strategies. However, most modeling efforts often focus on relative comparisons of LID effectiveness between scenarios. To improve confidence in model predictions, modeling approaches need to account for design considerations and guidelines to represent actual ground conditions.

Some hydrologic and water quality models represent the impacts of LID practices using one parameter such as the CN approach. While modeling LID practices using CN values provides valuable information to guide decision making, the use of currently available CN values may overestimate or underestimate credit given to LID practices in simulation scenarios. Following Sample et al. (2001) and Damodaram et al. (2010), improved CN values that would accurately account for the impacts of LID practices are critical for the enhancement of LID modeling with runoff CN. Moreover, the majority of modeling efforts are currently limited to reporting load reduction achievements; future modeling efforts should consider characterization of pollutant concentrations within the modeling framework.

Future research should also consider standardizing modeling techniques when evaluating and reporting the effectiveness of LID practices (e.g., Ahiablame et al. 2012). This will allow to reduce modeler's bias, provide consistency across studies and models, provide ground to assess decisions made in the modeling exercise, support replication of modeling efforts, improve acceptance of modeling results, and facilitate comparison, sharing, and distribution of research results to a wider community, thus promoting widespread adoption of LID practices. Engel et al. (2007) discussed the potential benefits of standard protocols for conducting modeling studies and should be consulted for more detail.

6.5 Scaling Up LID Practice Performance

LID practices are micro-scale control measures. The collective effects of these practices at large scales can be expected to vary spatially and temporarily. Many LID practices are evaluated at a single lot level. Most data pertaining to the performance of these practices are also reported through micro-scale monitoring efforts. These efforts, however, are limited to short-term evaluation of LID practices due to high monitoring costs. While micro-scale monitoring of LID practices is necessary and appropriate to understand hydrologic processes and their interactions among different LID practices, generalizing results from such scales is very difficult due to variability in the performance of LID practices induced by variability in topographic, soil, and weather conditions. Simulation modeling enables assessment of LID effectiveness at different spatial (field to watershed) and temporal (single event to long-term simulation) scales. Scaling of results from lot scales to larger scales (e.g., watershed, region) will be a key advancement to evaluate LID practices so that specific processes such as the transport and transformation of pollutants, interflow, first flush, and erosion can be incorporated in watershed models to accurately represent LID practices.

6.6 Need for Easy-To-Use Decision Support Tools

There is a need to develop decision support tools using current information technologies such as internet and GIS to facilitate wide adoption of LID practices. These tools are valuable for stakeholders and planners to quickly evaluate and summarize information about the impacts of LID practices on hydrology and water quality of a site. For example, the web-based L-THIA-LID has been developed to assist in planning and decision making using readily available and accessible data (precipitation, land use, and soil information) of the location of interest (Hunter et al. 2010; Engel and Ahiablame 2011). The tool requires only simple tasks such as establishing land use areas and hydrologic soil groups for input variables to estimate runoff and pollutant loads of present and projected land development scenarios. Analytical results are also summarized into simple and easily interpretable charts and tables.

6.7 Need for Addressing "Road Blocks" to Increase LID Practice Adoption

Widespread adoption of LID practices faces impediments not only in scientific research but also in regulation and policy making. There are currently ordinances and regulations which prevent using many LID practices in many municipalities. Zhang et al. (2012) investigated obstacles surrounding implementation of green roof systems in Hong Kong. The authors identified three major barriers that must be overcome to facilitate acceptance and adoption of extensive green roofs. These barriers include lack of promotion from government and social communities, lack of government incentive programs, and expensive maintenance costs. Research is needed to bring innovative strategies into public policy and regulations linking contractors, developers, planners, municipal officials, engineers, and home owners in order to address the lack of knowledge and increase awareness through education, programs, and government incentives regarding system wide LID benefits (environment, society, life cycle costs).

7 Conclusions

LID is a land planning and design approach for stormwater management at the source with micro-scale control measures. The LID approach differs from the CD approach which seeks to route water off-site as fast as possible. The term LID is generally used in Canada and the USA, while WSUD and SUDS are common in Australia and Europe, respectively, to describe similar planning and design principles. Based on the literature, LID practices show great potential for mitigating the effects of urbanization and land development on hydrology and water quality. The literature is relatively profuse with monitoring-based evaluation of bioretention compared to other structural LID practices discussed in this review.

Even though analysis of the performance of bioretention systems should continue to advance, more scientific data are needed for other LID practices such as green roof and swale systems. Specifically, attention should be given to microbial removal in these practices. Water quality improvement using green roof continues to generate varying findings, calling for more research. The literature suggests that all LID practices could perform efficiently as long as proper design, implementation, and maintenance are followed.

The computational models presented in this review have different levels of complexity and use different approaches to represent LID practices. SUSTAIN and SWMM can be used to accurately evaluate fundamental processes occurring within the practices. These models were developed for in-depth analysis and require expert skills beyond the capacity of the general public. The L-THIA-LID model aggregates fundamental processes occurring within the practice into one parameter to characterize the impacts of LID practices. These types of models are quick screening tools developed to summarize information about LID scenarios. They are not necessarily suitable for design or study of optimum solutions.

Several gaps expressed in the literature are reported in this review to build the foundation for future research opportunities. These recommendations include characterization of runoff and water quality from specific urban land uses; continued field and experimental data collection for evaluation of LID systems over different climatic conditions, geographic locations, and spatial and temporal scales; need for assessing retention of emerging and difficult-to-measure contaminants in LID practices; enhancement of evaluation metrics and modeling techniques for LID practices, scaling of LID practice performance to larger scales (than lot levels), development of easy-to-use decision support tools incorporating LID practices; and finding effective strategic solutions to overcome “road blocks” for widespread promotion and adoption of LID practices. It is hoped that this review will serve as a guide to encourage continuing research to improve our understanding of LID systems and reduce reluctance to build more sustainable and low impact urban communities.

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