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LOW IMPACT DEVELOPMENT PRACTICES: A REVIEW OF CURRENT RESEARCH AND RECOMMENDATIONS FOR FUTURE DIRECTIONS

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Abstract: A low impact development (LID) is an alternative land development approach for managing stormwater that has been recommended instead of the traditional stormwater design. The main purpose of LID is to reduce the impact of development on water related problems through the use of stormwater management practices that infiltrate, evaporate, or harvest and use stormwater on the site where it falls. In recent years, more research has been carried out on the individual practice of LID such as bioretention, pervious pavements, rain garden and grassed swales. Nowadays LID practices have been successfully used to manage stormwater runoff, improve water quality, protect the environmental and hydrological aspects of the developed areas. Bioretention cells have been effectively used in retaining large volumes of runoff and pollutants on site. Pervious pavements have been extremely effective practice in infiltrating stormwater runoff as early as possible as rain fall on site and store a large quantity of water. Nowadays, sand ditch a new water harvesting technique is used that significantly reduces runoff and sediment losses and increases infiltration and soil loss. This paper highlights evidence in the literature regarding the beneficial uses of LID practices and encourage to adopt these practices for environmental friendly construction and sustainable development in the world.

Keywords: low impact development, green roof, bioretention, pervious pavement

Introduction

The effects of the traditional development practices on the hydrological cycle have been well demonstrated. As the urbanization, impervious surfaces increase [1-3], which results in increase of surface runoff and its velocity, and decrease time of concentration [4], and effects the water quality [5, 6]. These impacts along with adverse socio-economic

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outcomes of urbanization have led to the necessity for smarter integrated planning of urban growth including smart growth, water sensitivity planning, low impact development planning, and other ways to reduce negative impacts of urbanization on natural resources [7-9].

In recent years, low impact development (LID), a new innovative approach to land management and development, has become popular [8]. LID concept was adopted in Maryland as a way to mitigate the negative effects of increasing urbanization and impervious surfaces [10]. The preservation of the pre-development hydrology is the main goal of LID technique. In contrast to the traditional stormwater design, the LID approach demands more careful and useful studied design.

The purpose of the design is to preserve the natural features of the site in an undisturbed condition, and where any disturbance is necessary, reduce the impact to the soils, vegetation, and aquatic systems on the site. In contrast to traditional stormwater treatment, which typically only mitigates peak flow rates, the use of LID system will also help to maintain the pre-development runoff volume. Rain gardens/bioretention areas, cluster layouts, grass swales, and pervious pavements all reduce the "effective impervious area" of a watershed, or the area that is directly connected to the stormwater system [11].

Initial research on different LID practices has shown positive results and now almost every developed country is adopting LID technologies [7]. The benefits of LID practices at micro-scales (lot level) have also been shown in innumerable studies (*eg* [12-15]). However, debates still surround many of these practices and benefits, indicating that there is limited practical knowledge of LID, so we need more research for effectiveness and application of LID practices on the broad scale. To this effect, a synthesis of the current literature is needed to support continuing more in-depth research, so that LID practices can be widely adopted as an established approach for stormwater management.

The main objectives of this paper are to (1) Highlight some evidence of hydrologic/water quality benefits of LID strategies through field and experimental studies, (2) Introduce, the importance and benefits of different LID practices and (3) Suggest opportunities for future research and development of decision support tools incorporating LID practices. New successes of LID technologies have been documented in this report, but other unexpected outcomes have also arisen. In addition, some questions are frequently raised in regards of the suitability of LID for all sites, groundwater contamination, and winter performance of LID practices. The main goal of this literature review is to present relevant research on the various LID practices, and to synthesize the results so that the current status and future research needs of LID investigations can be assessed and applied more on site. However, the discussion presented in this paper demonstrates the range of advancements in the science of LID. This paper is not intended to provide a comprehensive review of the entire body of LID studies or simulation models that have potential to evaluate the entire LID practices, but serves as a quick review of large benefits of LID technologies.

Methodology

This paper reviewed the global literature by drawing from different source like peer review, research papers, books, technical reports, case studies, conference proceedings, design guidelines, project summaries, government publications, and unpublished reports. Search of a different number of key words that include low impact development, urban planning, urban best management practices and water sensitive planning using ISI Web of Knowledge, Open Access Journals, Google Scholar, different online journals, among others, was used to find publications. This review paper was categorized by LID practice to facilitate wastewater management and presentation of the information about individual LID practices. This review mainly focused on the most commonly used different structural LID practices *ie* bioretention, green roof, permeable pavement, and swale systems, which are useful in stormwater management and promote at least one of the following: runoff reduction, infiltration, evapotranspiration, and water quality improvement. Each practice is briefly described and its performance discussed in the review article. There were three computer models presented to discuss how LID practices are represented in hydrologic/water quality models. Many other studies and information were reported in tables to show percent reduction in runoff and pollutant loads with the implementation of LID practices. Even though the percent removal (or efficiency ratio) metric has been reported to have limitations to adequately evaluate the performance of best management practices (BMPs), including LID practices [16, 17], it provides a general idea of findings from various geographic locations.

LID overview

Low impact development (LID) is a green approach for stormwater management that seeks to imitate the natural hydrology of a site using decentralized micro-scale control measures [8, 18] by achieving water balance [19]. LID emphasizes the use of small scale, natural drainage features integrated throughout the city to slow, clean, infiltrate and capture urban runoff and precipitation, thus reducing water pollution, replenishing local aquifers and increasing water reuse.

The main principles of LID are as follows [10, 20]:

- Integrate stormwater management strategies in the early stage of site planning and design
- Manage stormwater as close to the source as possible with the some distributed micro-scale practices
- Encourage and implement environmentally friendly design
- Promote natural hydrological feature to create a hydrologic multifunctional landscape
- Mainly focus on prevention rather than mitigation and remediation
- Reduce costs for the construction and maintenance
- Empower communities and societies for environmental protection through public education and participation

The main goals of LID practices and principles include runoff reduction (peak and volume), groundwater recharge, stream protection, increase infiltration and water quality assessment through the removal of different pollutants from the mechanism such as filtration, chemical sorption and other biological process [21]. Following LID goals and principles, there are large number of techniques generally classified as LID practices. Hunt et al [21, 22] published examples of structural and nonstructural practices that promote these main goals of LID. Structural practices include bioretention, infiltration wells/trenches, stormwater wetlands, level spreaders, permeable pavements, green roofs, swales, vegetated filter/buffer strips, sand filters, smaller culverts, and water harvesting systems (rain barrels/cisterns). Nonstructural practices consist of minimization of site disturbance, preservation of natural site conditions and feature, reduction and disconnection of impervious surfaces (*ie* elimination of curbs and gutters), native vegetation utilization, soil amendment and aerification, strategic grading, and minimization of grass lawns [21, 22]. LID encourages processes such as filtration, onsite storage and detention, infiltration, evapotranspiration, adsorption, biodegradation precipitation, and percolation, among others, which reduce the need for a centralized best management practice [7, 23, 24].

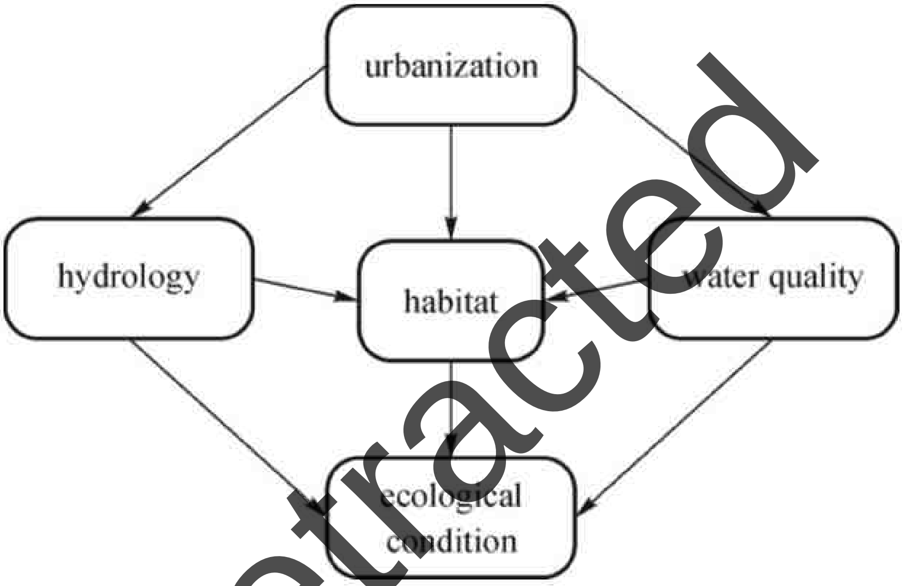

Fig. 1. Stressors of aquatic ecosystem degradation by urbanization

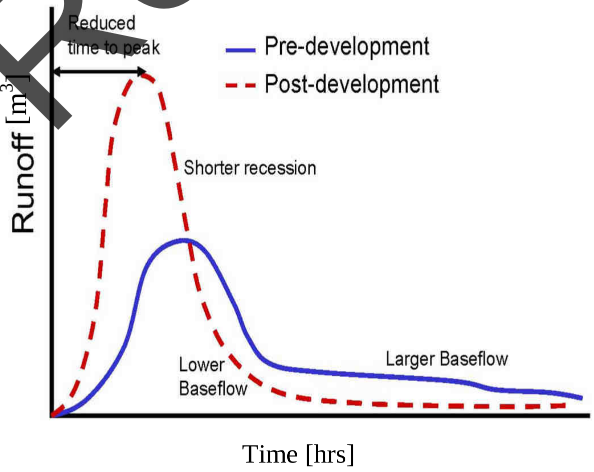

Fig. 2. Schematic illustration of the pertinent impacts of urbanization on hydrology at the catchment scale

Figure 1 showed how the urbanization degrade the aquatic ecosystem by different ways. We can solve all these problems by the use of LID system in the urban areas. As Figure 2, explains how urbanization affects the stormwater runoff in an area. This Figure also shows the change in runoff before and after urbanization in an area. Post development runoff is greater in volume and peak with a lower baseflow, and reduced time to peak. A study of a 4047 m^2 (1-ac) paved parking lot found that it generates 16 times more runoff than a meadow of the same size. However, we can reduce the runoff in urban area by the using LID practices, *ie* permeable pavements, bioretention and green roofs. Stormwater management, before the new increasing effective applications of LID techniques, mainly focused on the reduction of peak flow discharge rate from the site to avoid flooding [25]. The approach of peak runoff reduction does not aim to reduce volume of runoff, nor improve quality of water at sites. Instead, runoff is collected from the different nearest sites and routed to the nearest receiving water body with some management techniques such as gutters, curbs, roadways, and pipes [10, 20, 23]. This peak reduction approach is also known for causing some downstream water quality problems by transporting the different pollutants into the receiving waterbodies [7, 23]. This approach is often known as conventional development (CD), and it is still prominent in various urban settlements where distributed stormwater control measures (LID practices) are not implemented, or difficult to implement due to many reasons such as lack of knowledge and unawareness about LID practices results and achievements. The CD is also known as end-of-pipe practice, centralized approach or traditional approach. Examples of CD techniques include centralized stormwater management ponds, curb inlet structures, conveyance piping systems and gutter infrastructure.

LID practices try to keep water onsite as much as possible and protect water quality using natural features of the site, while CD techniques aim to route water offsite as fast as possible through structural stormwater conveyance systems [10, 19, 20, 23]. Implementation of LID principles is a shift (of the stormwater practice) towards volume-based hydrology (VBH), a stormwater control approach that mainly focuses on management of stormwater volumes [26]. The VBH is founded on the assumption that reduction of stormwater volume will automatically result in solving other water related problems including pollutant loading, peak flow rate, water velocity, erosion, and sedimentation [26]. Management of runoff volume can be achieved through managing stormwater at the source with distributed techniques [27]. The use of different micro-scale distributed technologies to treat stormwater is growing and popular worldwide. Low impact development (LID) is a term frequently used in Canada and the USA [8, 28]. Similar practices are also described under other names such as Water Sensitive Urban Design (WSUD) in Australia and Sustainable Drainage Systems (SUDS) in the UK [29-31].

LID practices

Bioretention/rain garden

Bioretention or rain garden areas are the depressed areas in the landscape designed to impaired and treat the stormwater runoff at the site and reduce peak flow [32, 33]. These can be applied in the residential and commercial settings, and are typically planted with the perennials, shrubs, or trees, and covered with shredded hardwood bark mulch. The benefits of the bioretention areas include decreased surface runoff, increased infiltration and pollutant treatment through a variety of processes [34]. Reduction of runoff volume and peak flow rate using bioretention systems is relatively well reported (*eg* [13, 24, 35-39]) with a range of 40 to 97% in Table 1 [40].

Table 1

Summary of percent runoff reduction and pollutant removal by bioretention systems [40]

Source	**Location**	**Runoff [%]**	**TSS [%]**	**P/TP [%]**	**NO_3-N [%]**	**NH_4-N [%]**	**TKN [%]**
Davis AP. [57]	Lab experiment, USA	–	–	60-80	24	60-80	60-80
Davis AP. [48]	Lab experiment, USA	–	–	> 65	> 15	–	>52
Hsieh CH, Davis AP. [58]	Lab experiment, USA	–	–	4-99	1-43	2-49	–
Glass C, Bissouma S. [59]	Washington, DC, USA	–	98	–3	–	–65	–
Sun X, Davis AP. [49]	Lab experiment, USA	–	–	–	–	–	–
Dietz ME, Clausen JC. [42]	Maryland, USA	–	–	70-85	< 20	–	55-65
Dietz ME, Clausen JC. [46]	Connecticut, USA	–	–	–	67	82	26
Hong E. [60]	Lab experiment, USA	–	–	–	–	–	–
Hunt WF. [43]	North Carolina, USA	–	–	–	13-75	–	–
Roseen R [61]	New Hampshire, USA	–	96	–	27	–	–
Davis AP. [62]	Maryland, USA	–	47	76	83	–	–
Rusciano GM. [63]	Lab experiment, USA	–	92	–	–	–	–
Hunt WF. [41]	North Carolina, USA	–	60	31	–	73	44
Zhang L. [51]	Lab experiment, USA	–	–	–	–	–	–
Chapman C, Horner RR. [38]	Washington, USA	48-74	87-93	67-83	63-82	–	–
DeBusk KM, Wynn TM. [39]	Virginia, USA	97	99	99	–	–	–
Zhang L. [52]	Lab experiment, USA	–	–	–	–	–	–

Source	**Location**	**TN [%]**	**Cu [%]**	**Pb [%]**	**Zn [%]**	**FC[a] [%]**	**O/G[b] [%]**
Davis AP. [57]	Lab experiment, USA	–	> 90	> 90	> 90	–	–
Davis AP. [48]	Lab experiment, USA	> 49	> 43	> 70	> 64	–	–
Hsieh CH, Davis AP. [58]	Lab experiment, USA	–	–	66-98	–	–	> 96
Glass C, Bissouma S. [59]	Washington, DC, USA	–	75	71	80	–	–
Sun X, Davis AP. [49]	Lab experiment, USA	–	88-97	88-97	88-97	–	–
Dietz ME, Clausen JC. [42]	Maryland, USA	–	–	–	–	–	–
Dietz ME, Clausen JC. [46]	Connecticut, USA	51	–	–	–	–	–
Hong E. [60]	Lab experiment, USA	–	–	–	–	–	83-97
Hunt WF. [43]	North Carolina, USA	–	99	81	98	–	–
Roseen R [61]	New Hampshire, USA	–	–	–	99	–	–
Davis AP. [62]	Maryland, USA	–	57	83	62	–	–
Rusciano GM. [63]	Lab experiment, USA	–	–	–	–	92	–
Hunt WF. [41]	North Carolina, USA	32	54	31	77	71	–
Zhang L. [51]	Lab experiment, USA	–	–	–	–	> 82	–
Chapman C, Horner RR.[38]	Washington, USA	–	80-90	86-93	80-90	–	92-96
DeBusk KM, Wynn TM.[39]	Virginia, USA	99	–	–	–	–	–
Zhang L. [52]	Lab experiment, USA	–	–	–	–	72-97	–

[a] FC fecal coliform including E. coli, [b] O/G oil/grease

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 [13, 41]. Nowadays, in a field study, a retrofit bioretention cell was shown to reduce by 97 and 99% flow volumes and rates from different parking lots [39]. The reduction of runoff volumes and rates mainly depends on the magnitude and duration of rainfall events. During small events, bioretention facilities can readily capture the entire inflow volume [13]. Processes such as infiltration and evapotranspiration play a very important role in runoff retention. Chapman and Horner showed that 48 to 74% of runoff that flows through bioretention systems escaped in the form of infiltration and evaporation [38], and 20 to 50% through exfiltration and evapotranspiration processes [36].

A large number of studies have accredited bioretention as the best management practice capable of reducing sediments and nutrients loss from 0 to 99% [35-37, 42, 43], as shown in Table 1 [40]. Luell et al monitored bioretention cells during time span like 13 months and found that 84 to 50% of TN and TSS, respectively, were retained by the bioretention systems [44]. Other studies reported up to 76% reduction for TSS [36], between 70 and 85% of phosphorus (P), and 55 to 65% of total Kjeldahl nitrogen (TKN) with the help of bioretention facilities [42].

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 [42]. To improve the issue of NO_3-N reduction with bioretention, Kim et al created an anoxic zone by mixing newspaper with the sand layer in a bioretention cell. Paper is a good electron donor for denitrification resulting in 80% removal of NO_3-N [45]. Other researchers have also found that a saturated zone in bioretention systems can also improve N retention. For example, Dietz and Clausen created a saturated zone in a bioretention facility capable of storing 2.54 cm of runoff to demonstrate the efficient removal of NO_2-N + NO_3-N, NH_4^+-N, and TN [46]. Aerobic nitrification and anoxic denitrification can be attained with sulfur or wood chips [47]. An average metal reduction in bioretention varies between 30 and 99% as written in Table 1 [40]. For that purpose, bioretention pilot-plants were used to remove nearly 100% of lead (Pb), zinc (Zn), and copper (Cu) [36, 38, 48]. Prototypes of bioretention monitored in laboratory settings resulted in 88 to 97% reduction in soil media, and 0.5 to 3.3% in different plant species for Zn, Cu, Pb, and cadmium (Cd) from simulated runoff events [49]. In bioretention cells with low metal retention capacity (especially in sandy soil media), the performance of the system has some problems and can be improved by adding fly ash to the media [50].

From previous experiments an average retention of bacteria in bioretention ranges from 70 to 99% as shown in Table 1 [40]. In Maryland, significant retention of *Escherichia coli* in bioretention was attained with iron-oxide coated sand media [51]. 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, lifetime has also been shown to positively affect bacteria retention capacity of bioretention facilities, which also increased from 72 to 97% for *E. coli* O157:H7 strain B6914 after 6 months [52].

Moreover, exposure of bioretention facilities to sunlight has been shown to increase microbial removal [53]. The composition of bioretention media can play an important role in the performance of the system. Construction activities can also have a great impact on bioretention performance. A comparison study of two excavation techniques of bioretention cells (scoop and rake) found the rake technique is more preferable over the scoop method for increasing the performance of the system, especially under dry soil conditions [54]. Apart from the design configurations, sizing, choice of vegetation, siting considerations, and maintenance also play important and beneficial roles in the performance of bioretention systems (*eg* [22, 24, 55, 56]).

Grass swales system

Swales are shallow open channels with gentle side slopes, filled with erosion and flood resistant vegetation, designed for different purposes, such as to convey, control, and improve stormwater through the different process (*eg* infiltration, sedimentation, and filtration) [64, 65]. Although swales are generally used to replace traditional curbs and gutters for stormwater conveyance in urban settings [66], they can also be used for erosion control in agricultural environments [65]. Swales can efficiently operate under a variety of seasonal conditions [67]. Swale systems include infiltration swales, bioswales, bio filters, grassed swales or filter strips and vary from grassed channels to dry swales and wet swales according to the desired conditions.

Swales are mainly used to minimize the runoff velocity and improve the water quality by block the different pollutants. Backstrom suggested [68] from the different experiments that swales can be used to achieve high removal efficiency of pollutants when the swale is filled with dense and fully developed vegetation. With the help of experiments, swales have been shown to trap up to 99% of TSS, TP, TKN, TN, and Fe at the field scale, showed that the high reduction of pollutant loads by swales in an area could likely be the result of sedimentation processes, swale length, high infiltration rates and increased water residence time in the swale [68, 69].

Green roofs

A green roof is a building rooftop partially or completely covered with vegetation, laid over high quality waterproof membranes, that is also used to reduce stromwater runoff, collect water and reuse it for different purposes (*eg* gardening, toilet flushing and washing) [7, 70]. Green roofs have been used to control runoff volume, improve air and water quality, and promote conservation of energy [7]. Green roofs can be categorized as “extensive” or “intensive” based on the thickness of the roof layer and the level of maintenance needed [71, 72]. The former is generally planted with dense, low growing, drought-resistant vegetation, and generally suitable for single family and multifamily 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, shrubs, trees, root barriers, and drainage and irrigation systems, to hold and route rain water, thus also slowing the velocity of direct runoff. Research related to the performance of green roofs as means to manage stormwater quantity and quality have been reported for a variety of climate conditions (*eg* [73, 74]). Alsup et al reported that green roof materials such as Axis, Arklayte, coal bottom ash, Haydite, lava rock, Lassenite, and composted pine bark may act as sources for heavy metals in runoff [75]. In Sweden, Berndtsson et al showed that green roofs contributed moderate amounts of Cd, Cr, Cu, Fe, K, Mn, Pb, and Zn to runoff [76]. To minimize potential pollutant losses from green roofs Dietz [35] recommended precautions that should be taken into when installing new type of 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 [77], as pollutant retention and release from the system strongly depends on the nature of the composition of any green roof media, and rainfall amount of that area [78]. After installation, proper maintenance or corrective measures are needed to help reduce contamination of stormwater runoff from green roof media [79]. 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.

Permeable pavements

Permeable/porous pavements are designed mainly to temporarily store surface runoff, allowing slow infiltration into the subsoil [80]. Permeable pavements include different system such as block pavers, plastic grid systems, porous asphalts, and porous concretes [35]. Researches on porous pavements have been shown to reduce runoff and associated pollutant loads in a variety of different sites [14, 35, 81-83, 96]. Average runoff reduction by using the porous pavements varies from 50 to 90% as shown in Table 2 [40].

Table 2

Summary of percent runoff and pollutant retention by permeable pavements [40]

Study	Location	Run Off [%]	TSS [%]	P/TP [%]	NO_3-N [%]	NH_4-N [%]	TKN [%]	Cu [%]	Pb [%]	Zn [%]	FC[a] [%]
Legret M, Colandini V. [93],	Reze, France	–	58	–	–	–	–	–	84	73	–
Pagotto C, Legret M, Le Cloirec P. [94]	Nantes, France	–	87	–	–	–	–	20	74	–	–
Rushton BT. [95]	Florida, USA	50	> 75	> 75	–	> 75	> 75	> 75	> 75	> 75	–
Hunt WF, Stephens S, Mayes D. [83]	North Carolina, USA	75	–	–	–	–	–	–	–	–	–
Dierkes C, Holte A, Geiger WF. [91]	Lab experiment, Germany	–	–	–	–	–	–	98	99	95	–
Fach S, Geiger WF. [88]	Lab experiment, Germany	–	–	–	–	–	–	> 85	> 85	> 85	–
Dreelin EA, Fowler L, Carroll CR. [86]	Georgia, USA	93	–	10	–	–	–	–	–	80	–
Pezzaniti D, Beecham S, Kandasamy J. [31]	Lab experiment, Australia	–	94	–	–	–	–	–	–	–	–
Tota-Maharaj K, Scholz M. [96]	Edinburgh, Scotland	–	–	78	–	85	–	–	–	–	98.99
Myers B, Beecham S, van Leeuwen JA. [89]	Adelaide, Australia	–	–	–	–	–	–	94.99	94.99	94.99	–

[a] Fecal coliform including *E. coli*

In a 2-year monitoring study of a permeable parking lot in North Carolina, Hunt et al explained that 75% of rainfall events were captured by the porous media, while the remaining 25% produced runoff from the study site [83]. Similarly, Collins et al [81] found that permeable interlocking concrete pavements and concrete grid pavers were able to retain up to 6 mm of rainfall with no runoff.

Further different experiments from the same region confirmed that not only permeable pavements can reduce runoff, but they can also eliminate runoff generation [84] even during the most intense rainfall events [85]. Fassman and Blackbourn used permeable pavements to explain that pre-development hydrology can be achieved with using such technologies [14]. Their findings were consistent with findings reported by Dreelin et al [86], 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 more frequent that are usually (less than 2 cm) and retain “first flush” runoff during larger storm events on clay soils.

The removal of TSS and other nutrients by permeable pavements has been reported in a number of studies with average reductions ranging from 0 to 94% as shown in Table 2 [40]. And also assessment of water quality benefits by using porous pavements at two study sites resulted in varying findings by Bean et al [84]. Low concentrations of TP, NH_3-N, TSS and TKN, and high levels of NO_3-N were reported for the first site; and only low concentrations for NH_3-N were observed at the second site. Collins and James [82] linked the presence of high NO_3-N concentrations in the two cases to aerobic conditions that may potentially help the nitrification within the pavements. Other studies have also found increased NO_3-N concentrations in water from different permeable pavements [82, 87].

Average metal reduction by porous pavements has been reported to vary between 20 and 99% in Table 2 [40]. Fach and Geiger [88] used four types of permeable concrete blocks to remove significant amounts of such metals *ie* Cd, Cu, Pb, and Zn from artificial rainfall-runoff events. Myers et al [89] reported 94 to 99% reduction of Zn, Cu, and Pb in water stored in permeable pavement after time duration of 144 h. Other researchers observed 80% removal of Zn [86]. Different experiments conducted by Dierkes et al [90] substantiated the capacity of porous pavements to capture dissolved heavy metals from the runoff so that those metals did not create groundwater contamination. However, Dierkes also 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 [91]. Thus, with proper maintenance, we also need careful assessment of the location of the system to achieve high performance [84].

Permeable pavements have also been shown to be efficient attenuators for grease (*eg* motor oil) due to a variety of microbial activities that can occur within the system [92]. Although permeable pavements are primarily used to reduce runoff and improve water quality, they can also be used for different purposes, like stormwater harvesting and storage mechanisms for reuse, to reduce increasing water demand in urbanized areas of the world [89].

Plastic grids

In recent years, several types of plastic grid structures are available. Design and installation techniques of plastic grids may vary slightly from the concrete blocks or grids, with the largest difference being the volume of fill material in the pavement structure. In contrast to concrete blocks which are mostly impervious, the plastic grid structure is mostly pervious. The large spaces are designed to be filled either with topsoil and planted with turf, or filled with a small diameter, sharp crushed stone. However, in plastic grids the installation specifications vary according to the manufacturer, but in general, the base preparation is critical to encourage rapid infiltration into the subgrade.

Two plastic grid structures, Grasspave® and Gravelpave® were studied in Renton, Washington [85, 97]. The only difference between the two installations was the change of infill material; topsoil and turf were used in the Grasspave®, and gravel in the Gravelpave® structure. As with the other products that were monitored at this site, virtually no surface runoff was reported from either of these two products [85]. The largest amount of stormwater runoff reported from the Grasspave® section, for a long-duration storm, where 121 mm of rain fell, and 4 mm of surface runoff observed [85]. The concentrations of copper and zinc in infiltrate water below all four pavement types were significantly lower ($p = 0.01$) than asphalt runoff concentrations [85]. In Georgia, runoff from a Grassy Paver™ plastic grid parking lot that was filled with sand and planted with grass was 93% less than runoff from an adjacent asphalt lot [86].

Pervious asphalt

Pervious or permeable asphalt, is a variation on the typical hot mix asphalt (HMA) that is commonly used as a road surface nowadays. In this type, the mix, which eliminate the fine portion of the aggregate typically included in HMA, was developed to be installed as a wearing course over a standard asphalt layer. The mix was termed as the open graded friction course (OGFC), and it has been used around the world since the 1970s because of its ability to dampen road noise and tire spray, and it also remove water from the road surface which reduces the risk of hydroplaning [98]. Modification has been made to the mix specs due to some structural issues. When stormwater infiltration is desired, the major design difference is that the OGFC material is typically put down over a coarse aggregate storage layer that is designed to rapidly infiltrate and store more water.

Research on pervious asphalt began with some EPA funded projects in the early 1970s [99]. After that, due to their more advantages research in Europe began in the 1990s. In France, a street section was repaved with this technique, and a 61-cm thick crushed stone reservoir was included below the pervious asphalt layers [93]. Legret and Colandini [93] reported that on average, approximately 96.7% of the storm water volume infiltrated in the soil below the reservoir structure. While, in Sweden, in a pervious asphalt road section with swales, between 30 and 40% of precipitation ran off the site [100].

Pervious concrete

Pervious concrete is basically a variation on the typical concrete mixture. In this mixture, fine sands are typically excluded, and the slurry is tamped or rolled in placed, rather than the traditional floating. This type of concrete requires a special preparation different from the traditional concrete, and a proper installation process of manufacturing requires experienced installers. It has been installed in many locations throughout the different countries around the world, however a little work done monitoring on pervious concrete installations has been performed.

A pervious concrete parking lot section with a combination of swale in Florida had a runoff coefficient value 0.20, which was lower value than the both these, the coefficients for an asphalt lot with a swale, and cement lot with a swale, which were 0.35 and 0.33 respectively [95]. It should be noted that the asphalt lot also contains a small “garden” area, which the Rushton suggested was responsible for the fairly low runoff coefficient from the asphalt lot [95]. Pollutant export load from the pervious lot with a grass swale was reduced for TSS, NO_3-N, NH_3-N, and TN by 91, 66, 85, and 42%, respectively, as compared to the asphalt lot without swale [95]. Metal load reductions (*ie* Cu, Fe, Pb, Mn, and Zn) were all greater than 75%. However, TP loads were only reduced slightly, by 3%, despite the large decrease in runoff volume, and some of the systems with grassed swales exported more TP than came in Rushton [95]. This phenomenon is also consistent with the TP export reported earlier from some bioretention systems [43, 46, 101].

A large pervious concrete lot is installed at Villanova University, United States. Although there were some problems with the installation of the materials, and some of sections had to be reinstalled [102], problems have been corrected, and the site has shown auspicious results. The site takes runoff from adjacent standard concrete areas, several rooftops, and grassed areas. The site has successfully captured and infiltrated runoff from different areas of all storms with 5 cm or less in size [103]. Water quality measurements were also taken at the site and concentrations of chloride were found to be higher during winter months, as deicers were applied to pedestrian areas at that site. In addition, concentrations of copper in roof runoff were fairly high [103]. However, the interesting fact is that neither chloride nor copper concentrations in groundwater below the pervious concrete were high enough to be of concern. Kwiatkowski et al concluded that with proper siting, an infiltration BMP such as the pervious concrete would not adversely impact on the groundwater [103].

Other concerns

Clogging of surfaces

A frequent concern with porous pavements that have more concern is the clogging of the surface over time. Rather than particles becoming lodged in the internal structure of the pavement, clogging of all types of pervious asphalt pavements seems to be confined to the surface 2 cm of the pavement [104]. The specifications for these types of products (*eg* pervious asphalt, pervious concrete) state that all the pavement surface should be cleaned out with vacuum suction on a specified time interval, so that the infiltration rate can be maintained without any problem. A better intensive vacuuming, high pressure washing, and suction removal of the remaining sludge are found to greatly improve the infiltration rate of a partially clogged pervious asphalt in France [93]. The maintenance recommendation for UNI-Ecostone® pavers is the removal and replacement of the different infill material in the pavements.

The frequency of replacement depends upon different factors, such as the local site conditions, and the loading of fine particles on to the pavement surface. Research on pervious pavement at different sites in North Carolina, Maryland, Virginia, and Delaware has shown that although the infiltration capacity of concrete block, concrete grid, and pervious concrete pavements may decrease if fine particles are loaded on to the surface, still they can infiltrate large quantities of water (comparable to grassed sandy loam), and the infiltration rate can be enhanced with replacement of the infill material [84]. On the other hand, in place of sand the Bean EZ et al recommend the use of crushed aggregate as an infill material to help encourage high infiltration rates at that places [84].

Winter performance

Another concern with pervious pavements that demands attention, just as with bioretention, is the ability of the system to perform in the winter. Numerous studies on pervious pavements in cold climates (*eg* Washington, New York, New Hampshire, Connecticut, and Ontario Canada) have been performed earlier or are also ongoing. Research findings support the claims of different manufacturers that with a proper base and proper installation, the system will continue to infiltrate through the winter without any problem, and the surface can be plowed, although some care should be exercised with sanding (to avoid clogging of the pores) and salting (to avoid potential groundwater contamination).

Soils

In addition to concerns about winter performance, fine grained soils with slow infiltration rates have been cited as a reason why a pervious pavement or bioretention cannot be used or failed at different sites. However, research has shown that with appropriate design and installation, pervious pavements can be used in clay soils. A previously cited example in Georgia that was installed over well-drained soils and used the clayey subgrade that could contain as much as 35-60% clay [86]. In the subgrade, an underdrain system was also installed below a 10-inch thick layer of open graded gravel there. Runoff from the underdrain they only observed one time, during a 1.85 cm precipitation event [86]. Just as with bioretention, in the areas where native soils may not have high infiltration rates, there can be installed thicker reservoir of coarse aggregate beneath the pavement structure and underdrain [105]. This process provides a larger water storage capacity, and a longer time for water to exfiltrate to the native soils before underdrain flow would begin.

A system of slope erosion control, consisting of horizontal terraces equipped with drainage ditches filled with sand, was developed in Olszanka, Poland. This system used two techniques for erosion control on steep slopes: limiting soil transformations and increasing the infiltration of surface water into the subsoil. This method showed clear increase in infiltration for terraces equipped with sand-filled drainage ditches under real climatic conditions: 11.69 and 13.6% increases for the base and upper parts of the slope, respectively [106]. A new technique, sand-ditch for water harvesting used in Jordan and it consisted of twelve field plots of 10 m × 2 m, that were constructed in two adjacent fields having silt loam soils but varied in soil depth, 0.75 and 2 m, and slope of 10 and 12%. Sand-ditch plots in which a ditch of 2-m long, 1 m wide and 0.8 m deep was constructed and two compacted plots and two plots covered with plastic mulch in addition to four control plots, 2 in each field. The total amount of runoff, total infiltration, sediment concentration and sediment loss for the experimental plots were calculated after each storm during the winter season 2004/2005. Experimental results showed that sand-ditch technique significantly reduced runoff and sediment loss and increased infiltration and soil moisture compared to control or compacted plots. The overall average runoff and sediment reductions in the sand-ditch plots were 46 and 61% compared to control plots. These results showed that sand ditch is a better technique for rainwater harvesting than other compacted soil [107].

Groundwater contamination

Due to the fact that stormwater runoff is known to contain a different variety of pollutants [108], concerns of groundwater contamination have also been raised where infiltration practices such as pervious paving or bioretention have been recommended or used. The results from a multiyear research projects sponsored by the US EPA on this topic have been summarized [109]. For residential and light commercial applications, the pollutants of concern are typically on some nutrients, petroleum residue from automobile traffic, pathogens, heavy metals and possibly pesticides. These pollutants are usually found in low concentrations in stormwater runoff, and are well retained by soils, therefore the contamination potential is also low or moderate [109].

Two exceptions to this general finding may exist: pathogens may be present in high concentrations in rainwater, and may not be well attenuated in the soil. Fecal coliform bacteria are well retained by bioretention column in the previously mentioned preliminary laboratory studies [110], however field research on bacteria and virus removal in bioretention and pervious paving systems is lacking in many aspects. Also, chloride may be present in stormwater, and concentrations may be high during winter months [111]. Chloride is also very itinerant in soil, and it can easily travel to shallow groundwater. Research is showing that concentrations of chloride have been increasing in local waterways in New England, and if it will not minimize and current trends continue, chloride levels in streams will reach dangerous levels, threatening aquatic life as well as human life [111]. The ability of LID systems to treat harmful bacteria, chloride, and heavy metals have to be investigated further.

It should be noted that LID promotes a distributed approach to treatment practices, rather than an “end of pipe” approach that was used in the traditional stormwater approach. If this strategy is adopted to, then the stormwater will have less chance to accumulate large masses of different pollutants in the stream. Therefore, the likelihood of having high concentrations of pollutants will be reduced if the distributed approach is used, and concentrations of different types of pollutants will largely be driven by the atmospheric deposition rates. Collecting and treating stormwater from heavy traffic areas or areas with high potential pollutant loads, while in the process of infiltrating “cleaner” runoff from buildings and low traffic areas, may provide a good margin of safety where groundwater contamination is a concern.

Conclusions

The LID system is different from the CD approach which seeks to route water off-site as fast as possible. Based on the literature, LID practices show great potential for mitigating the effects of urbanization and land development on hydrology and water scarcity of an area. However, LID is a relatively new suite of practices and is constantly developing. To date, the research on LID practices has not gone as far as the research on agricultural or traditional urban stormwater best management practices. The research in this paper has shown generally that LID practices are most effective for preserving the natural hydrologic function of a site, improving the water quality and retaining pollutants.

On the other hand, there are certain conditions where it may not be appropriate to use LID practice that relies on infiltration process. Areas with more contaminant loading such as recycling centres or gas stations, or brownfield areas with high soil contamination, may not be appropriate for infiltration, because of increased risks of contamination of the groundwater. Conditions such as steep slopes, shallow (< 3 ft) depth to bedrock or seasonal high water table are also cases where traditional pavement and stormwater management practices may be more appropriate. However, it is a very rare case that an entire site is composed of such limiting conditions. One common thread across green roofs, bioretention, and grass swales has been noted: export of phosphorus. This issue appears to be linked to high phosphorus levels in the media (for bioretention and green roofs), or possible fertilization of the planted areas. This can be a concern in such type of areas where underdrains or roof leaders are tied into a stormwater system; in these cases the excess loading of TP to surface waters may worsen an existing problem. Care should be taken to ensure that in cases where a drain is directly connected to the media, it does not contain high levels of phosphorus.

Mostly LID engineers are using models like RECARGA, Win-SLAMM, and P8 to design LID practices, although they may also use other models such as SWMM for hydraulic routing on a site. The Western Washington Hydrologic Model is an accurate model, easy to use, and provides credits for LID practices. We need to make different design tools and models of LID that can solve the different complicated water and environment related problems efficiently and effectively with a low cost. We also need to find best practices for rainwater harvesting and infiltration due to their numerous advantages in stormwater management.

Several gaps expressed in the literature are reported in this review to build the foundation for future research opportunities in LID. These recommendations include the characterization of runoff and water quality from specific urban land uses; continued various field and experimental data collection for evaluation of LID systems over different geographic locations, climatic conditions; need for assessing retention of emerging and difficult-to-measure contaminants in LID practices; improvement of evaluation metrics and modeling techniques for LID practices, scaling of LID practice performance to larger scales, development of easy-to-use decision support tools incorporating LID practices and collections of more important practical field data, and finding most effective strategic solutions to overcome “road blocks” for widespread promotion and adoption of LID practices in the whole world. It is hoped that this review will serve as a guide to understanding of importance of LID systems and to encourage the land developers for all over the world to use of LID in the societies due to their massive benefits.

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PRAKTYKA ROZWOJU SŁABO WPŁYWAJĄCEGO: PRZEGLĄD AKTUALNYCH BADAŃ I ZALECENIA DOTYCZĄCE PRZYSZŁYCH ICH KIERUNKÓW

Abstrakt: Zastosowanie praktyki rozwoju słabo wpływającego (LID) jest alternatywnym podejściem do zagospodarowania wód opadowych, które jest zalecane zamiast tradycyjnych projektów zarządzania wodą deszczową. Głównym celem LID jest zmniejszenie wpływu rozwoju na problemy związane z wodą poprzez stosowanie praktyk zarządzania wodą deszczową obejmujących filtrację, odparowanie lub zbieranie i lokalne wykorzystanie tych wód. W ostatnich latach większość badań przeprowadzonych w ramach indywidualnej praktyki LID dotyczyło bioretencji, przepuszczalnych nawierzchni, deszczowych ogrodów i trawiastych zagłębień terenu. Obecnie praktyki LID z powodzeniem są wykorzystywane do zarządzania spływami wody deszczowej, poprawy jakości tej wody, z zachowaniem wymogów ochrony środowiskowej i hydrologicznej. Komórki bioretencyjne zostały skutecznie wykorzystane w ograniczaniu dużych spływów, także zanieczyszczeń. Przepuszczalne chodniki były niezwykle skuteczne w praktyce szybkiej filtracji spływu i lokalnym przechowywaniu dużej ilości wody. Obecnie, nowo stosowaną techniką zbierania wody jest rów z piaskiem, który znacząco zmniejsza spływ i straty osadów oraz gleby, zwiększając filtrację. W artykule przedstawiono dane literaturowe dotyczące stosowania praktyk LID i ich pozytywnego wpływu na rozwój budownictwa przyjaznego dla środowiska i zrównoważonego rozwoju w świecie.

Słowa kluczowe: rozwój słabo wpływający, zielony dach, bioretencja, chodnik przepuszczalny