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Green stormwater infrastructure with low impact development concept: a review of current research

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ABSTRACT

Green storm water infrastructure (GSI) or low impact development (LID) is an alternative land development approach for managing storm water close to the source that has been recommended instead of the traditional storm water design. The main purpose of LID is to reduce the impact of development on water-related problems through the use of GSI practices such as bioretention, green roofs, grass swales, and permeable pavements that infiltrate, evaporate, or harvest and use stormwater on the site where it falls. In recent years, more research has been carried out on GSI practices and the use of these practices has shown magnificent benefits in stormwater management. LID techniques have been successfully used to manage stormwater runoff, improve water quality, and protect environmental and hydrological aspects of the developed areas. Bioretention cells have been effectively used in retaining large volumes of runoff and capturing pollutants on site. Pervious pavements have been extremely effective and efficient at infiltrating stormwater on site and storing large quantities of rainwater. Sand ditches are a new water harvesting technique that is being used to significantly reduce runoff, soil loss and sediment loss and to increase infiltration. This paper highlights evidence in the literature regarding the beneficial uses of LID practices and encourages adopting these practices for environmental friendly construction and sustainable development in the world. In the end, some of recommendations for the implementation of LID practices to achieve multiple benefits are given.

Keywords: Green stormwater infrastructure; Grey stormwater infrastructure; Low impact development; Green roof; Bioretention; Grass swale; Permeable pavement

1.Introduction

For the last few decades, rapid urbanization and climate change around the globe has caused the disturbance of natural landscapes [1,10]. Original land cover of grass and forest is transforming into impervious surfaces such as building and roads [2–4]. This change in land use has resulted in increased velocity and volume of surface runoff, decreased the time of concentration [5], and affects the water quality [6,7]. These adverse impacts of urbanization have led to the necessity for new, smart, innovative planning approaches which include smart growth, water sensitive planning, green stormwater infrastructure planning, low impact development planning, and other ways to reduce negative effects of urbanization on natural hydrology and landscape [8–10].

Green stormwater infrastructures (GSI) or Low impact development (LID), a new, innovative stormwater management approach for the land management and development because it has ability to reduce runoff, soil loss and improve the water quality [5–7], and now it has become popular around the world [9]. The GSI concept was adopted many decades ago in USA, to mitigate the adverse effects of increasing urbanization and impervious surfaces [11]. The main purpose of GSI design is to

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preserve the natural features as well as pre-hydrology of the site. Traditional stormwater treatment systems, which mainly collect runoff through pipe networks and deliver it to remote treatment facilities, contrast with the application of LID which attempts to maintain the pre-development runoff conditions in an area. Pervious pavements, rain gardens, bioretention areas, and bio swales all reduce the "effective impervious area" of a watershed and try to maintain natural hydrology [12].

In the last few decades, different GSI practices have shown promising results and now many developed countries including the USA, Canada, Australia, Germany, Japan, Australia, and South Korea are adopting GSI technologies [8]. The benefits of LID practices at the micro-scale have also been analyzed in numerous studies (*e.g.* [13–16]). This study attempts to elaborate on the following; (1) review the benefits of GSI strategies through some field and experimental studies, (2) introduce and explain different GSI practices and (3) suggest opportunities for future research on LID practices. This paper explains the benefits of different GSI practices for the stormwater management. The global literature on GSI, sourced from multiple papers, books, technical reports, case studies, conference summaries, design guidelines, and projects' data, has been analyzed in this study. The information has been reported in different tables to show the reduction in runoff and water quality improvement associated with implementation of LID practices in different countries. To evaluate the performance of these best management practices (BMPs), the GSI practices percentage removal metric has been reported [17,18].

2. LID concept

Low impact development (LID) is a new, innovative approach for stormwater management that seeks to mitigate the adverse effects of urbanization by maintaining the pre-development natural hydrology of a site using decentralized, micro-scale control measures [9,19] by achieving water balance [20]. LID emphasizes the use of small scale, natural drainage features integrated throughout the urban area to slow, clean, infiltrate and capture the urban runoff and precipitation, thus reducing water pollution, replenishing local aquifers, and increasing water reuse.

The main principles of LID are as follows [11,21]:

- To manage the stormwater near to the source as much as possible with the help stormwater distribution approach
- To minimize the impacts of development and maximize ecological benefits
- To integrate stormwater management strategies in early stages of construction in a particular area
- To encourage the environment friendly development
- To promote the natural hydrologic features
- To reduce the construction and maintenance costs

The main objectives of employing LID practice includes the runoff reduction, increase the time of concentration, groundwater recharge, stream protection, increase the infiltration and the water quality improvement by the removal of different pollutants through the mechanisms such as filtration, infiltration and other biological processes [22]. Hunt et al. [22,23] published some examples of structural and non-structural practices that encouraged the main goals of LID. Structural practices include bioretention, stormwater wetlands, infiltration wells, level spreaders, permeable pavements, green roofs, grass / bio swales, vegetated filter, sand filters, smaller culverts, and water harvesting systems. Non-structural practices have the following purposes, *i.e.* minimization of site disturbance, preservation of natural site conditions and features, reduction and disconnection of the impervious surfaces, soil amendment, aerification, strategic grading, and minimization of grass lawns [22,23]. The main objective of GSI practices is to encourage the processes such as filtration, onsite storage and detention, infiltration, evapotranspiration, biodegradation precipitation, and percolation, among others, which reduce the need for centralized stormwater practices [8,17,24].

Fig. 1 shows how the urbanization affects our environment. Fig. 2 explains how urbanization affects the stormwater runoff in an area. This also shows the change in runoff before and after urbanization in an area. Post development rainfall runoff is greater in volume and peak flow with a lower baseflow, and reduced time to peak. A study of a 4047 m^2 paved parking lot indicated that it generates 16 times more runoff flow than a meadow of the same size and similar climate conditions [25]. Traditional stormwater management techniques mainly focused on the reduction of peak flow discharge rate from the site to avoid flooding [26]. The approach of peak runoff only collects runoff from different sources (e.g. pipes, gutters, curbs) and delivers it to remote locations for treatment or discharge; it neither reduces runoff volume, nor improves the water quality of an area [11,21,17]. This traditional approach also causes downstream water quality problems by transporting pollutants into surface waters [8,17]. This approach is known as conventional development (CD), and it is still prominent in various urban areas where LID interventions are not implemented already, or are hard to implement due to circumstances such as lack of knowledge about the LID practices. Conventional development (CD) is also known as end-of-pipe practice, a traditional or centralized approach which just transfers pollution to another site. Examples of traditional stormwater techniques include centralized stormwater management ponds, conveyance piping systems, curbs, and gutter infrastructure. However, the GSI technology is less expensive than the traditional stormwater approach in the case of new development [27–30].

The GSI approach is also mainly related to volume-based hydrology (VBH), a stormwater control technique that focuses on management of stormwater volume in an area [26]. The main function of VBH is reduction of stormwater volume which results in solutions to other water related problems (i.e., peak runoff reduction, peak runoff delay, pollutant removal, water velocity, and erosion) [31,32]. GSI technologies are very popular and being used around the world due to their numerous benefits. Best management practices (BMPs) emphasizes the sound, sustainable, and decentralized stormwater and rainwater management [33–35]. Low impact development (LID) is a term frequently used in Canada and USA [9,36]. Similar technologies under the different names are described such

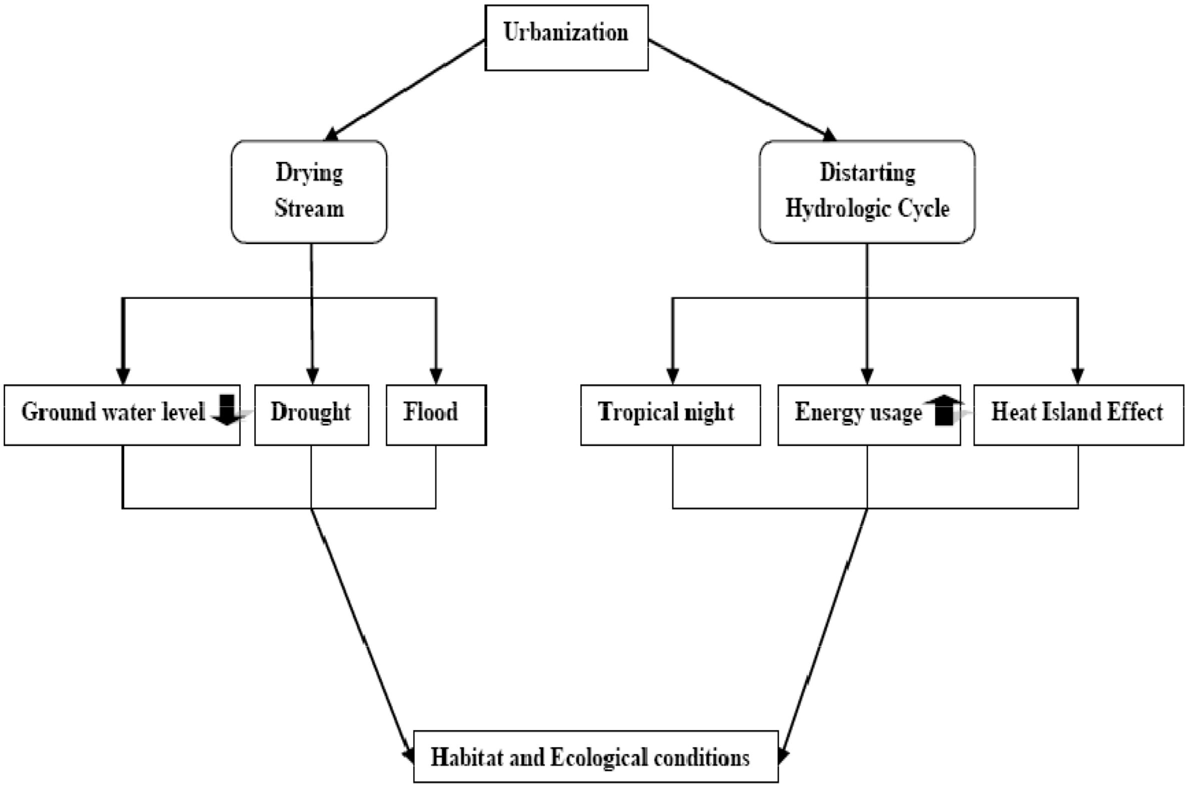

Fig. 1. Adverse effects of urbanization on the environment.

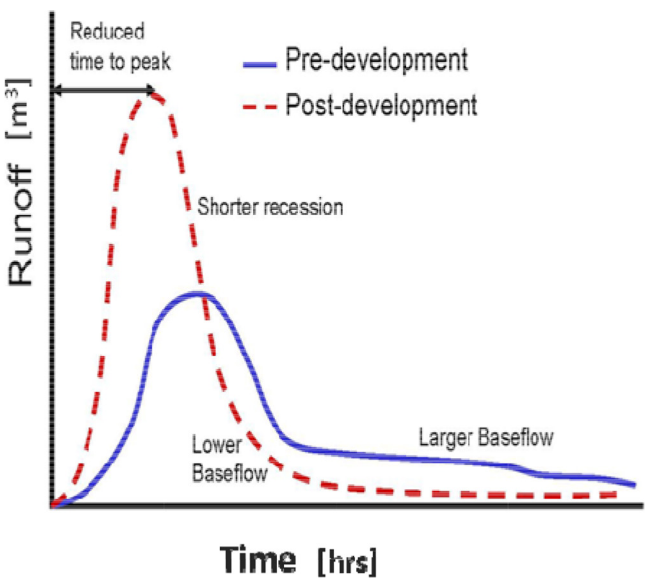

Fig. 2. Impact of urbanization on the hydrology at the catchment scale [25].

as Decentralized Urban Design (DUD) in Germany, Sustainable Urban Drainage System (SUDS) in UK, Water Sensitive Urban Design (WSUD) in Australia, Well-Balanced Hydrological System (WBHS) in Japan and EcoRich City (ERC) in South Korea [37–39]. The main objective of all above mentioned is the sustainable development by considering the distribution approach.

3. LID practices

3.1. Green roof for architecture

A green roof is a roof that consists of vegetation that grows on very special designed substrate soil for the stormwater runoff control. A green roof system is partially or completely covered with vegetation, laid over the waterproof membranes, and is also used to control rainfall runoff in an area [8,41,52,45,48]. The rainwater can collect in green roof and reuses it for different purposes (*e.g.* toilet flushing, irrigation purposes and washing) [8,40,52]. Green roofs are used for different purposes which include delaying the rainfall runoff, controlling runoff volume, improving air and water quality, increasing aesthetics, and reducing energy costs by Cooling mechanism [8]. These factors all help to avoid flash flooding in the urban areas.

The main purposes of the green roofs in the quantitative stormwater management are the reduction of outflow (volume retention) due to evapotranspiration and volume detain and store in green roof layers. For the stormwater management, it is interesting to study how green roods perform seasonally over the long period of time. Bengtsson [41] used the water balance approach to study green roof in Augustenborg, Sweden. From the results, it was found that annual outflow can be reduced approximately 64% due to evapotranspiration. Results from the Kohler et al. [42], evaporation from green roofs in Germany (5 and 12 cm depth) can reduce 60–80% runoff annually. Slope, depth of green roof and vegetation has great influence on the green roof runoff reduction performance [46,51]. Shafique et.al [52] investigated the performance of the green blue roof

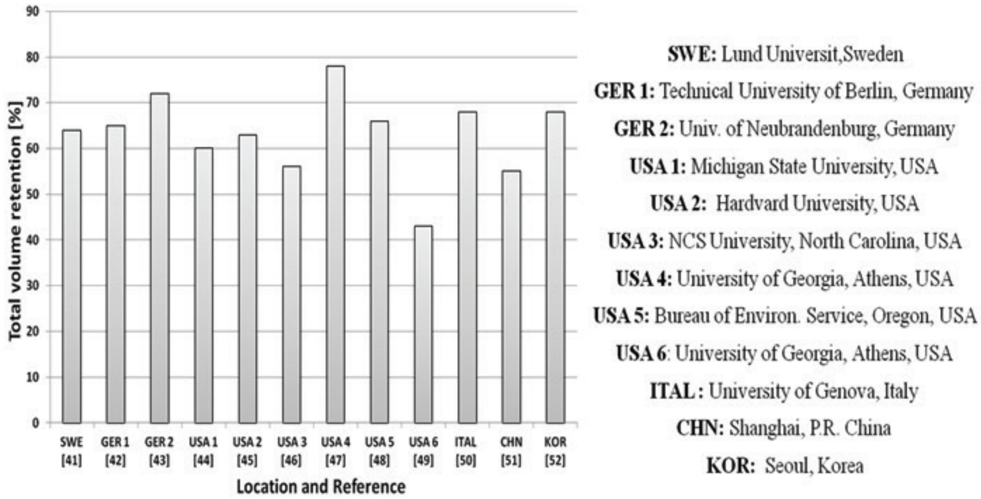

Fig. 3. Annual volume retention different green roof sites from a literature review.

at Seoul, Korea. From the result, the runoff retention was approximately 50% to 68% respectively. It may range from 40% to 80% of the total rainfall volume reduction (see Fig. 3) with the actual magnitude of retention being a function of the structure of the green roof under the different climatic conditions [43,47,48,50–52]. Fig. 3, below shows that the green roofs have ability to retain the large amount of runoff which can reduce the chances of flash flooding and other water related problems [41,51,52].

The important factors that can affect the effectiveness of the green roof are thickness of the media, type of plant cover, and the slope of the green roof. Many authors [45,51,43] explain that the slope of a green roof has a huge impact on the performance of the roof in stormwater management. Green roofs can be classified as "extensive" or "intensive" based on the thickness of the roof layers [53,54]. Extensive roofs are typically used for single family or residential buildings, mostly planted with dense, low growing, and drought-resistant vegetation. In contrast, intensive roofs have a higher diversity of vegetation and are mostly used in the commercial areas [48,51,52,54]. Intensive green roofs are also known as garden roofs, which may have grass, trees, and drainage systems that can hold a large amount of water and reduce the runoff rate which helps to avoid flash floods. A large body of research on the performance of green roofs for the stormwater quality and quantity has been well reported at different sites and under different climatic conditions (*e.g.* [55]). For example, Alsup et al. noted 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 [56]. In Sweden, from the different experiments, Berndtsson et al. reported that green roofs contribute moderate amounts of Cd, Cr, Cu, Fe, K, Mn, Pb, and Zn to runoff [57]. Some of the precaution in installing the green roof should be taken into consideration to minimize the potential pollutant losses [58]. The most important factor in green roof design in locations where pollutant removal is the major goal is careful selection of green roof media for maximizing the performance of the system [47,52], as pollutant retention and release from the system strongly depends on the nature of any green roof media, and the amount of rainfall in that area [51,59]. After installation, proper maintenance is needed to reduce contamination of rainfall runoff from green roof media [47,29,51]. For example, the combination of green roofs and blue roof could be an alternative to avoid flooding and the best utilization of the water in urban areas.

There are also two other types of roofs that are commonly being used in the urban areas.

3.1.1. Green-blue roofs and blue roofs

Green-blue roofs have almost the same mechanism as green roofs for stormwater management. A green-blue roof consists of the same layers as a green roof but there are some open spaces available for the storage of water in the roof. In green roofs water is mainly captured in the soil media, while in green-blue roofs there is another layer to store water in addition to soil media. In Seoul, Korea the green-blue roof design has been successfully applied and has shown promising results for stormwater management. The construction cost of green roofs and green-blue roofs is higher than for blue roofs but they also have more benefits as compared to blue roof systems.

Blue roofs are non-vegetated roofs that are used to detain rainwater on the rooftop. Weirs at roof drain inlets and along the roof can create temporary ponding and hence slow the release of stormwater from the roof which helps to reduce the peak rainfall runoff flow and speed in urban areas [60]. In this type of roof, a light colour water proofing layer is usually provided because it helps reduce the temperature of the building. And the water-resistant layer is used to avoid the leakage of water into the building. The cost of blue roofs is less than green roofs. Blue roofs are the best option as the retrofitting in urban areas because we can apply it easily with less time and cost in an urban area. On the other hand, green roof has more advantages than the blue roof, suitable to apply in new constriction to achieve multiple benefits. Green blue roof is a new modified form of green roofs that have ability to store the runoff into the storage as well in substrate layer [60]. In this way, large amount of runoff can retain to avoid the flash flooding problems in urban areas [60]. There is a need to design a system in which the stored water from a blue roof can be used for the irrigation of a green roof.

3.2. Bioretention and rain gardens for green areas

Bioretention is the one of the most widely used GSI practice across the globe. The main benefits of bioretention includes: (1) runoff control by infiltration and ground water recharge, (2) pollutant removal from water runoff, and (3) reduction of peak flow and protection from stream scouring [61,62]. Bioretention are depressed areas in the landscape designed to retain and treat stormwater runoff at the site and reduce peak flow into the sewer system [46,47]. The main process in rain gardens is infiltration that is used to recharge the groundwater. Bioretention system can maintain infiltration rates for several years [63,65,66]. In some stormwater management the reducing the pollutants is often a goal, in that case bioretention is a best practice for these purposes. Bioretention can be applied at a suitable place in the city such as residential areas, commercial buildings, and parks [58,63]. These are typically planted with perennials grass, shrubs, or trees. Reduction in runoff volume and peak flow rate using bioretention systems is relatively well described for several countries (*e.g.* [14,63,65,55,71]) with a range of 40–97% in Table 1.

When bioretention systems were applied at sites in Maryland and North Carolina, USA, the reduction of average peak flows by at least 45% were recorded during rainfall events [64]. Debusk and Wynn [66] constructed bioretention at Blacksburg, VA to analyze the runoff reduction. In a field study, when retrofit bioretention cells were applied at parking lots, runoff flow rates and volumes were reduced by 97% and 99% which indicated [66]. From the results, it is proved that the bioretention systems are useful system to reduce the runoff in an urban area. During the low volume rain events, infiltration and evapotranspiration are higher in rain garden that area without green infrastructure, this factor plays a very important role in runoff reduction [63]. Chapman and Horner showed that only 48–74% of runoff flows through bioretention systems into the sewer system with the remaining volume managed by infiltration and evaporation [76], and 20–50% through exfiltration and evapotranspiration processes [76].

Bioretention and rain garden systems have been applied in many counties for years and have manifested promising results in runoff reduction and water quality improvement. Numerous studies from across the globe have accredited bioretention as a best management practice capable of reducing sediments and nutrients loads from 0 to 99% [61–75] in Table 1. Many other researchers [62–64, 72–75] have applied the bioretention technology to retain TN, TP, and TSS, and it has been shown as a best practice to retain TN, TP, TSS and other heavy metals as shown in Table 1. Davis AP, 2008 [14] constructed two bioretention cells at Maryland, USA to measure the performance of this system. From the result, it is indicated that bioretention systems have ability to reduce TSS from 54% and 59% respectively [14]. Bioretention systems are capable to reduce the TSS and heavy metals from the runoff. Scientists have found that on average metals (Pb, Cu, Zn) reduction in bioretention varies between 30 and 99% in Table 1. Bioretention pilot-plants were used to remove almost 100% of lead (Pb), zinc (Zn), and copper (Cu) [62,64]. Prototype bioretention facilities monitored in the laboratory resulted in 88 to 97% of heavy metals captured in soil media and 0.5 to 3.3% of Zn, Cu, Pb, and cadmium (Cd) captured in different plant species from simulated runoff events [62]. A bioretention cell in an urban setting in North Carolina was studied from 2006 to 2007. Water quality samples were collected for different rain events and analyzed for some common heavy metals including Cu, Zn, and Pb. From the results, there were significant reductions in the concentrations of Cu upto 88–97%, Zn 88–97 %, and Pb 88–97% respectively [62]. This shows that bioretention systems are the best stormwater management practices to enhance the water quality in urban areas.

Table 1
Percentage runoff reduction and pollutant removal by bioretention systems

Reference	Experiment site	Runoff [%]	TSS [%]	TN [%]	TP [%]	Zn [%]	Pb [%]	Cu [%]
Sun X, Davis AP, 2007 [62]	Lab experiment, USA	–	–	–	–	88–97	88–97	88–97
Brown and Hunt, 2008 [63]	Rocky Mount, NC	90	92	80	72	–	–	–
Hunt et al., 2008 [64]	Charlotte, NC		60	32	31	60	32	77
Brown and Hunt, 2011 [65]	Rocky Mount, NC	95	58	58	–	–	–	–
Debusk and Wynn, 2011 [66]	Blacksburg, VA	97	99	99	99	–	–	–
Hathaway and Hunt, 2011 [67]	Wilmington, NC	–	100	–	–	–	–	–
Trowsdale and Simcock, 2011 [68]	New Zealand	–	90	–	–	–	–	–
Khan et al., 2012 [69]	Alberta, Canada	–	99	92	95	–	–	–
Chen, 2013 [70]	Lenexa, KS	–		56	–	–	–	–
Olszewski and Davis, 2013 [71]	Silver Spring, MD	79	–	–	–	–	–	–
Bakacs et al., 2013 [72]	New Jersey, USA	–	84–95	–	–	–	–	–
Geronimo et al., 2014 [73]	South Korea	–	–	49–55	85–86	–	–	–
Guo et al., 2014 [74]	Singapore	–	93.4	59.8	92.7	–	–	–
Houdeshel et al., 2015 [75]	Utah, USA	–	–	22	60	–	–	–

Bioretention systems have ability to remove the bacteria from the runoff and hence improve the water quality [79,80]. Some scientists [77,78] have also studied the retention of bacteria in rain gardens at different places in the USA. An average retention of bacteria in bioretention systems ranges from 70 to 99% in Table 1. In Maryland, USA, when iron-oxide coated sand media was used in bioretention cells a significant retention of *Escherichia coli* was observed, and retention of *E. coli* O157: H7 strain B6914 cells in the system showed 17% improvement [77,78]. Furthermore, the exposure of bioretention facilities to sunlight has shown an increase in microbial removal, which may play an important role in maximizing functionality of bioretention systems [80]. The composition of bioretention media plays an important role in the performance of the system. Construction activities can also have great effect on bioretention performance. The performance of bioretention cells used in sandy soil was not satisfactory. For this purpose, its performance can be improved by adding the fly ash in low retention capacity soil [79]. The comparison of two excavation techniques (scoop and rake) of bioretention cells was also studied. It was found that the rake technique is preferable over the scoop method due to increased performance of the system under dry soil conditions [81]. Factors such as design configurations, choice of vegetation sizing, siting considerations, and maintenance also play important and beneficial roles in the performance of bioretention systems (*e.g.* [64,65,72,74,77]).

There are some concerns that we should consider before implementing biorentention infrastructure in any area. These concerns can be described as follows:

3.2.1. Soils characteristics

Soil has a huge influence on the performance of LID practices, particularly for bioretention and permeable pavements. Before implementing LID the soil characteristics of a site should be studied well. Coarse grain soil with high infiltration rates has been shown to be the best and most suitable option for pervious pavements and bioretention cells, whereas soil with low infiltration rates has caused bioretention and pervious pavements to fail. However, researchers have shown that with proper design and installation, pervious pavements can be used with clay soils. Nowadays, the scientists are also trying to make best design practices by making better use of combinations of different infrastructures that can work under different site conditions. In Georgia, USA, a permeable pavement was installed over well-drained soil that contained a clayey subgrade [82]. In the subgrade, below a 10- inch thick layer of open graded gravel, and an underdrain system was installed. As it contained larger size media layer so there was only once runoff observed for 1.85 cm storm events [82]. In bioretention similar practices can be used to enhance GSI functionality. For example, in an area where the native soil may not have high infiltration capacity, a thicker reservoir of coarse aggregate beneath the pavement structure can be used to enhance the infiltration capacity [83]. These design practices enhance infiltration rates, store more water in the soil, and also increase the time of concentration that is necessary for stormwater management.

Over the last few years, different modifications in LID facilities have been successfully applied that have improved the functions of these facilities. For example, a horizontal terrace system equipped with drainage sand ditches was developed in Olszanka, Poland. This system uses two techniques for erosion control on steep slopes: increasing the infiltration into the soil and limiting the soil transformation [84]. A new technique, utilizing sand ditches for water harvesting, was developed in Jordan and the data was collected in field trials [85]. Total infiltration, total amount of runoff, sediment concentration, and sediment loss for the experimental plots were calculated after each storm during the winter season for the years of 2004 and 2005. Experimental results indicated that the sand-ditch technique significantly reduced runoff and sediment loss and increased soil moisture and infiltration as compared to control or compacted plots. The average rainfall runoff and sediment reduction in the sand-ditch plots were 46% and 61% compared to control plots. These results showed that the use of sand ditches is a better technique for rainwater harvesting than other systems using compacted soil [85].

3.2.2. Performance in winter

Winter performance is the ability of a system to perform in the winter; it demands huge attention when we want to apply bioretention cells or pervious pavements in a cold region. Many studies on pervious pavements and bioretention have been performed or are ongoing at different sites (*e.g.* New York, New Hampshire, Washington, Connecticut, and Ontario Canada). Information from manufacturers and researchers indicates that with proper installation and design, providing the proper base, the bioretention and pervious pavements systems will continue to infiltrate without any problem. During the winter season when there is snow fall in an area use of sodium chloride (NaCl) on road surfaces is a common practice to prevent ice formation. We should consider the following two factors related to the use of salt on the road salt for de-icing purposes: (1) its effect on nearby plants and (2) the amount of runoff that will be produced after melting ice in that area. Rain gardens should be designed in such a way that excess water can easily flow to another path to be drained without causing flooding in that area.

3.2.3. Selection of plants

A frequent concern with bioretention cells and green roofs that has drawn more attention recently is the selection of the plants for a particular climate. Green infrastructure practitioners around the world have used bioretention systems and green roofs mainly for runoff control, water quality improvement, and infiltration capacity. Most of the research on LID has been conducted in cold regions (e.g., USA, Canada, Sweden). Currently there is less data on LID in Asian countries where climate conditions are totally different. This lack of data has created challenges in selecting plants for the green roofs and biorentention facilities implemented in hot environments: (1) selection of plants for hot climate conditions, (2) identification of plants which can grow easily under different climatic conditions and can store plenty of water, and (3) types of plant that have higher evapotranspiration rates.

3.3. Grass swales or Bio swales for controlling stromwater runoff

Grass swales and bio swales are stable turf, parabolic, or trapezoidal open channels which are designed to convey runoff, control runoff, and improve stormwater through various processes. This type of system has gentle side slopes and is filled with erosion control material and flood resistant vegetation which infiltrate and filter stormwater [86,88]. This practice is generally used to reduce conventional curbs and gutters for stormwater conveyance in urban areas [88,91]. From multiple experiments, it was shown that swale systems can work efficiently under different climate conditions [90,88,92]. There are different types of infiltration swale systems that are being used which include grass swales, bio swales, bio filters, and filter strips. These systems can be used and adapted based on system requirements and desired conditions in urban areas.

The main purpose of swales is to minimize and delay runoff by infiltration of stormwater into the soil and enhancement of water quality by capturing different pollutants [87–89]. Several researchers [86,88–92] have worked on swale system performance in urban areas. Backstrom [84] suggested that when the swale is filled with dense and fully developed vegetation the swale system can achieve high removal efficiency, capturing up to 99% of different pollutants such TSS, TKN, TP, TN, and Fe in the field. He also explained that the high reduction of pollutant loads by swale systems depends on many factors including sedimentation processes, swale length, size of the grass, high infiltration rates, and increased particle time in the swale [91,93]. Zhao, Jinhui, et al. 2016 [93] analyzed the results from the grass swale that is located at the Jiangsu Province, China. Grass swale covered an area of 700 m^2. From the experiments, grass swale has ability to remove 83.5 ± 4.5, TSS and 81.3 ± 5.8 % for TP respectively. Grass swales are a best stormwater practice in urban areas as they have low construction and maintenance costs and can transform impervious areas into pervious areas. Swales are the most commonly used in the treatment of runoff from highways, residential roadways, and in and around of parking lots.

3.4. Pervious pavements for roads, sidewalks or parking lots

Pervious pavements are currently the most widely used LID infrastructure in most developed countries [94, 96,82,97,99,100]. Permeable or porous pavements are designed to temporarily store surface runoff, allowing slow infiltration into the subsoil [82,97]. There are different types of the permeable pavement systems which include porous asphalt, block pavers, porous concretes, and plastic grid systems [58]. Many researchers have studied porous pavements with results indicating that porous pavements reduce runoff and pollutant loads [82,94–101]. Average runoff reduction by porous pavements at varies from 50 to 93% in Table 2

Other scientists [82,97–99] have used pervious pavements in different areas, with results indicating successful reduction in rainfall runoff and elimination of the runoff generation in those areas (Table 2). Researchers have proven that porous pavements can be used to control small storms events more efficiently than other green stormwater practices, storm events usually less than 2 cm can easily in the pavements and also retain "first flush" runoff during larger storm events on clay soils [82]. Permeable pavements are also a very useful technique for removal of TSS, TKN, P, N and other heavy metals from runoff. Many authors [95, 99–102] indicate that the water quality of runoff from permeable pavements is much better than from asphalt pavements in the same urban area.

In Table 2, removal of TSS, TKN, and other nutrients has been noted with the significantly reduction. Bean et al. [103] explained that the water quality of runoff is different for permeable pavements at two different sites. Results showed that the TSS, TP, NH_3–N, and TKN concentrations were low at both sides, while the NO_3–N concentration was high at the first site and only a low level of NH_3–N was found at the second site area. Collins and James [103] found that high NO_3–N concentrations in the two cases were due to aerobic conditions that may possibly contribute to nitrification within the pavements. An increased NO_3–N concentration in water from the other permeable pavements sites was also found [104]. The amount of TSS, TKN, and other heavy metals in water depends on the number of factors. He et al. 2015 [102] constructed porous concrete pavements at the Alberta,

Table 2
Percentage of runoff reduction and pollutant retention by pervious pavements

Reference	Experiment site	Runoff [%]	TSS [%]	TN [%]	TP [%]	Zn [%]	Pb [%]	Cu [%]
Legret et al., 1996 [94]	Nantes, France	–	64	–	–	–	79	–
Dierkes et al., 1999 [95]	Lab experiment, Germany	–	–	–	–	98	99	95
Fach S and Geiger WF 2005 [96]	Lab experiment, Germany	–	–	–	–	> 75	> 75	> 75
Dreelin et al., 2006 [82]	GA, USA	93	–	–	–	–	–	–
Gilbert and Clausen 2008 [97]	CT, USA	72	–	–	–	–	–	–
Kadurupokune 2010 [98]	Melbourne, Australia	43–55	–	–	–	–	–	–
Fassman and Blackbourn 2010. [99]	Auckland, New Zealand	82	–	–	–	90	–	70
Myers et al., 2011 [100]	Adelaide, Australia	–	–	–	–	94.99	94.99	94.99
Mullaney et al., 2012 [101]	Dundee, Scotland	–	58	58	–	40–60	40–60	40–60
He, J. et al., 2015 [102]	Alberta, Canada	–	91–94.6	78–81	–	–	–	–

Canada. Different begging gravel layer from 100 mm to 500 mm and surface layers were used to investigate the TSS and TP removal. Different lab and filed experiments were done to investigate the effect of changing begging layer and surface layers on the performance of porous concrete. Results indicate that that the removal of TSS and TP removal by changing the surface layer were much lower than the begging layer. The maximum removal OF TSS and TP were found as 91–94.6 and 78 to 81 respectively [102]. In addition, the conceptual model was also developed to simulate the porous concrete pavements hydraulic and water quality performance [102]. For example, if the water enters the permeable system from non-permeable asphalt roads or from industrial areas then the amount of these pollutants will be higher. A careful consideration of all these factors should be considered before applying permeable pavement in an area.

A permeable pavement also helps in minimizing the amount of heavy metal in the water. In Table 2, the average metal reduction by using the permeable pavements has been reported from 22 to 90%. For these purposes, Fach and Geiger [96], Myers et al. [100] used different types of permeable pavements to remove significant amounts of heavy metals (i.e. Cd, Cu, Pb, and Zn) from simulation rainfall events. However, Geiger et al. found that pollutants in runoff accumulated in the upper layer of the permeable pavement and affected its performance [96]. Fassman and Blackbourn, 2011 [99] estimated the copper, Zn and TSS removal from the permeable modular concrete pavers. Result indicated that these concrete pavers removed 70% of copper, 90% of Zn and 825 of TSS as compared to road asphalt. Mullaney et al. 2012 [101] done experiments by using permeable interlocking concrete pavements (PICP). From the field experiments, PICP successfully reduced heavy metals from 40–60%. For the best performance and long-term benefits, a detailed study of the site and a suitable place for the application of permeable pavement is required [105]. From several experiments, it was found that performance of permeable pavements was very weak in places with heavy traffic and with different oil particles [105]. Nowadays, a better design for the permeable pavements is demanded which has enough strength while also avoiding the clogging problems that are typical of permeable pavement. The other types of pervious concrete are as follows:

3.4.1. Permeable plastic pavers

Plastic grids are an alternative pavement, consisting of a durable interlocking plastic grid filled with grass, gravel, and earth fill materials. These are very porous, promote quick rainwater infiltration, and are also suitable for locations which require natural drainage at the source. The installation of plastic grids varies according to the manufacturer, but the most important thing is the base preparation that is mainly responsible for infiltration. In Washington, USA, two plastic grid structures Grasspave® and Gravelpave® were successfully applied and enhanced the infiltration in that area [106,107]. It was found that their infiltration rates were so high that no surface runoff was observed from these two systems [106]. When compared with the asphalt pavements, the results showed that the plastic grids are a best practice for infiltration and enhancement of water quality in the urban area [106].

3.4.2. Pervious concrete and pervious asphalt pavements

Pervious concrete is also called porous concrete, permeable concrete, or no-fine concrete. It is a special type of concrete with a high porosity used for specific applications. This type of concrete has a special preparation mechanism in which no fine particles (i.e. sand and silt) are used. Skilled labour is required for the preparation of pervious concrete. Larger aggregate is used for this type of concrete to enhance the infiltration of water. It has been installed in many locations with results showing that this type of concrete is helps to prevent flooding and to restore the groundwater by infiltrating water in highly developed urban areas. In Florida, USA, when pervious concrete parking lots were combined with grass swales, the observed runoff was lower than the other an asphalt lots with swales, and cement lots with a swale [108]. Pollutant export load from pervious parking lots with a grass swale was reduced for NO_3–N, TSS, NH_3–N, and TN by 66%, 99%, 85%, and 42%, respectively, and metal load reductions were also more than 75% when compared to asphalt lots that without swale systems [108]. Pervious concrete is a structural LID best practice which is very helpful in reducing flooding and improving the water quality in an area. In Villanova University, United States, a large pervious concrete lot was installed [109]. In this pervious concrete pavement water from nearby concrete areas, rooftops, and grassed areas also contributed to runoff. In runoff, the concentrations of chloride from pedestrian areas and the concentrations of copper in roof runoff were found to be high, but with proper design and maintenance the water quality from pervious pavements can be improved [109]. Pervious pavements were also used in the parking lot of the University of Jordan campus. The old asphalt pavements were removed and the new pervious pavements applied on an area of 2746 m^2. The results indicated that the pervious concrete infiltrated a large amount of the rainwater and eliminated flooding conditions in that area. This new area can collect about 392 m^3 of stormwater which was very helpful in infiltrating the water and restoring ground water [110].

On the other hand, pervious asphalt is a variation on the typical hot mix asphalt (HMA). Pervious asphalt pavements have little or no fine aggregate particles in HMA used as wearing course over a standard asphalt layer. In 1977 scientists in Philadelphia, USA published the design for this type of asphalt pavements. This design has been used as a solid foundation for the design of porous pavements [107]. This mix is also known as open graded friction course (OGFC), and it has been used around the world because it can reduce noise and the risk of hydroplaning [108]. In the mix of the asphalt pavements, the OGFD material can be changed according to the requirements. Most of the research on asphalt pavements started with the United States Environmental Protection Agency (EPA) projects implemented since the 1970s [109]. Due to their tremendous benefits in stormwater management and sustainable development, the research has spread to different regions of the world such as France and Sweden [91,109]. For example, when Legret and Colandini [91] did experiments on asphalt pavement, they found that approximately 96.7% of the storm water volume infiltrated in the soil below the reservoir structure. While, in Sweden [110], when pervious asphalt road section with swales was used, the results found between 30 and 40% of rainfall ran off the site.

3.4.3. Clogging of permeable pavements

The most important factor that affects the performance of permeable pavements is clogging. When the fine pore spaces in the upper surface of permeable pavements fill with sediments or other debris they cause clogging which affects the hydrological performance of the permeable pavements. Clogging usually occurs within 2 cm of the surface of the pavement and reduces the infiltration rate and volume of the permeable pavements [115]. Regular maintenance is necessary to maintain the infiltration capacity of permeable pavements [114]. The clogging progression rates are mainly dependent upon factors which include location, site characteristics, and rain events. Research to find best design practices that can eliminate or reduce the rate of clogging in permeable pavements is ongoing. In Australia, scientists designed permeable interlocking concrete pavements (PICP) to delay the effects of clogging by making more efficient use of the bedding aggregate used in PICP systems. In this experiment, lateral drainage slots were cut into the underside of PICP blocks to allow more sediment to filter through which diminishes the clogging problem. Eight different slot designs were tried in the study to determine which designs made the most efficient use of the bedding aggregate to filter sediment. The study results indicated that the eight drainage slot designs deposited significantly more sediment (by weight) beneath the pavers than the control pavement. This research suggests that PICP systems with drainage slots cast into their bases would take much longer to clog than unmodified pavers [116]. Repair and maintance are necessay for the permebale pavemnts system to avoid clogging problems for the multiple long term benefits [115,116].

3.4.4. Groundwater pollution

Groundwater contamination is also an important concern in the stormwater management, where infiltration practices such as permeable pavements and bioretention are applied [117]. Research on this topic is well summarized by EPA projects [118]. In residential areas pollutants are found in low concentrations in stormwater, whereas pollutant concentrations are high in commercial areas and the areas near petrol stations. Potential implementation sites should be studied well before applying LID practices [117]. Pathogens may be found in high concentration in rainwater and sometimes cannot be stopped by soil layer, affecting the ground water [118]. Fecal coliform bacteria are well retained by different bioretention systems in the previously mentioned research [118]. However, field research on the removal of TSS, TP, NH_3–N, and TKN and heavy metals are well reported in the literature but field research on fecal coliform bacteria is lacking. Also, we should be concerned about concentrations of chloride in winter because the amount of chloride in water is larger during the winter season and it can easily travel to shallow groundwater posing threats to aquatic life [119]. As we know that LID promotes a distributed approach to treatment practices and it has the ability to treat bacteria, chloride, and heavy metals, these techniques should be applied in the cities to make them sustainable and environmental friendly.

4. Low impact development practices are the sustainable practices

The sustainability of any activity can be assessed by three interrelated categories of benefits: social, economic, and environmental [120]. These are also referred to as the triple bottom line (TBL). A GSI/LID practice follows the triple bottom line (TBL) and hence making our cities sustainable and resilient to climate change [124]. Low impact development LID/ Green stormwater Infrastructure (GSI) practices are the sustainable approaches that not only improve the water quality by managing the stormwater but also encourage redevelopment, provide recreational opportunities and help to achieve other social, economics, public health and environmental goals [121]. In urban areas GSI practices refers to those practices that control flood, by trees canopies, green areas and sensitive natural areas, such as parks and protected open spaces. However, several researchers [122–132] showed that the capacity of green infrastructure has capability to increase property values, neighborhood integration, and quality of life. GSI practices also play an important role in reducing urban vulnerability, enhancing quality of life, and urban ecology footprint. [124–132]. Providing equally-distributed ecosystem services and enhancing the water quality lead to make our cities safe, sustainable and resilient to climate change [125,128,130,131]. In Washington, DC has estimated that installation of green-roofs on most eligible buildings almost reduces 6–15% reduction in the number of CSOs into local rivers and total volume reduction to CSO approximately 26% [128]. In Washington, DC the value of the street trees is estimated about $10.7 million annually considering all benefits from trees. In Portland, USA the local government invested $8 million in green infrastructure to save $250 million in hard infrastructure costs [128]. Green stormwater Infrastructure (GSI) is very useful approach to retrieve the natural hydrology of an area and resilient to climate change. Molla [130] also explained the GSI economical, social, and environmental benefits and also shows how GSI practices tries to improve the environment of an area. Krause et al. 2010 [133] shows that the GSI practices protected the urban regions against floods and other negative effects of changing weather patterns. Because of this it can mintage the climate change effect and make the society safe and sustainable. GSI practices have ability to convert our grey infrastructure to green infrastructure which helps to make our cities safe, sustainable and resilient to climate change.

5. Comparison of benefits of Grey and Green stormwater infrastructure

Grey stormwater infrastructure majorly focuses on the flood protection rather than water quality enhancement [134]. Pipes and gutters usually used to collect surrounding water and throw to the far-off places [8,17]. In this approach, big water treatment plants used to improve that needs energy and costs [8,134]. On the other hand, green stormwater infrastructure (GSI) or Low impact development (LID) practices is the new approach that handle the stormwater near the source, mimic the natural hydrology and improves the environment of an area [5,7,11,135,136]. GSI provides many social, economic and environmental benefits [127,128,130,135]. GSI follows the triple bottom line approach and making the cities safe, sustainable and resilient to climate change. Benefits of green and grey stormwater infrastructure are given in the Table 3. GSI provides open green spaces, replenish the groundwater, improves the aesthetics; restore the wildlife habitat and recreational open spaces [130,135]. GSI are the best stormwater management practices (BMPs) to make city safe, sustainable and resilient to climate change.

6. Recommendations for Implementing the LID practices

LID technology is the use of various structural and non-structural practices to manage stormwater runoff near to the source. Common misperceptions about LID are that it cannot work well at sites with poorly draining soils or in cold and arid areas [138]. Some of the recommendations for the implementation of the LID practices are as follow [137, 138–141].

Table 3
Comparison of benefits Green stormwater infrastructure with Grey stormwater infrastructure

Category	Grey stormwater infrastructure	Green stormwater infrastructure (GSI)
Definition	Grey stormwater infrastructure is the system that use pipes/gutters for the stormwater management [8,17].	GSI is a new stomwater management approach uses different green infrastructure that not only works for the stormwater management that can allow for the same level of ecosystem services as non-disturbed, native settings, thus mimicking the efficiencies of ecosystems [134]. This system efficiently uses the land to make city sustainable.
Function	The main function of the Grey stormwater infrastructure is to collect the stormwater from an area and throw to the far-off places. To reuse the water big treatment plants used [8,17,134].	While green stormwater infrastructure green facilities such as green roofs, bioretention etc. used that control stormwater, infiltrate it into ground and store it to use for later purposes. The main function of GSI is to make city safe and resilient to climate change [135].
Benefits	Social benefits [134]: This system provides no social and recreational benefit.	Social benefits [2,3]: • Improves the quality of life and aesthetics • Improves the green spaces • As this system has more parks and green spaces etc. more people interact with each other that result in the improves health and social relation with each other
	Economic Benefits [135]: Grey stormwater infrastructure has less operation and maintenance costs than green stormwater infrastructure. However, the life cycle cost and construction costs higher than green stormwater infrastructure.	Economic Benefits [134,236]: • Green stormwater infrastructure reduces the hard infrastructure construction costs. • Maintain the aging infrastructures and increase the land values of that area • Reduce the energy consumption costs and encourage the economic development • It reduces the costs of big water treatment plants thus increase the life cycle cost savings.
	Environmental benefits [135,136]: One of main concern about the grey stormwater infrastructure is that this system considers very limited or no environmental benefits. This system improves the flood protection. It tries to protect the drinking water source protection but sometimes overflow degrade the water quality. This system does not consider to restore the wildlife habitat.	Environmental benefits [134–136]: • Green stormwater infrastructure improves the air quality by reducing the carbon emission. • This system efficiently uses the land and protects the surrounding from flood. • Improves the watershed health as well as human health • Protect of restore the wildlife habitat • Reduces the chances of sewer overflow • It protects the drinking water source • This system meet the regulatory equipments for receiving water • Replenish the groundwater and protect the water underground • Green stormwater infrastructure provides the additional recreational spaces

- The function of green roofs, permeable pavements, and bioretention can be made more efficient by using sandy course media that provides better drainage in underlying soils, designing larger surface areas for extra surface storage, and using vegetation that can withstand cold weather.
- The site must be studied well before the application of GSI technology and information gathered should be used to determine a suitable combination of LID practices that should be applied.
- LID practices can be used by employing sustainable plants that can withstand the hot as well as cold temperature.
- The use of under drains in poorly drained or clayey soils can allow LID practices to be used and take advantage of these systems' filtering capability.
- Cost is also a major concern in engineering designs, therefore the community developers may believe that LID practices create extra costs for a construction project. This perception is a big barrier that can be tackled by giving information, knowledge, and training about the long-term benefits of LID practices to city and regional planners.
- Nowadays, the main issue that arises while applying the LID practices is the lack of cooperation and collaboration between engineers (Civil Engineers, Transportation Engineers, Water Engineers, Land Engineers and LID experts). This issue should be eliminated by cooperating and collaborating for applying LID practices for the safe and sustainable city.
- Another issue is the management of the LID facilities that can eliminate by co-operation and collaborating between the local government, stakeholders and local residents. They should decide who will take care the management of LID facilities after constructions.

7. Conclusions

GSI systems are different from the CD approach which seeks to route water off-site as fast as possible. Based on the literature, GSI practices have shown great potential for mitigating the effects of urbanization and land development on hydrology and water scarcity of an area. However, GSI 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 management practices. This paper has shown that LID practices are most effective for preserving the natural hydrologic function of a site, improving water quality, and retaining pollutants.

On the other hand, there are certain situations where it may not be appropriate to use LID practices that rely on infiltration processes. Areas with more contaminant loading such as recycling centres, gas stations, or brown field areas with high soil contamination may not be appropriate for infiltration because of the increased risks of contamination of the groundwater. However, it is very rare case that an entire site is composed of such limiting conditions. 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 research. Recommendations for LID implementation includes experimental data collection for evaluation of LID systems over different geographic locations, climatic conditions for the improvement of GSI techniques, and scaling of LID practice to larger scales. This review paper serves as quick review and an encouragement for the people to apply the LID practices.

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Conflict of Interest

The authors declare no conflict of interest.

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