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Low Impact Development (LID) Practices: A Review on Recent Developments, Challenges and Prospects

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Abstract Low impact development (LID) practices are able to mitigate the detrimental effects of urbanization and climate change due to their salient design features. LID can restore the hydrology of urban areas to the pre-development functions by using distributed stormwater control and natural hydrological features. LID can help to achieve the goal of sustainable development as it promotes effective urban stormwater management. This review covers a comprehensive list of LID practices, namely bioretention cell, green roof, infiltration trench, permeable pavement, rain barrel or cistern, rooftop disconnection and vegetative swale. For each type of the LID, the recent advances covering the aspects of principles, design, performance, advantages and disadvantages and costs are systematically reviewed. Additionally, although LID has been quite broadly applied and demonstrated success in urban stormwater management in many countries, there are still some main challenges during the implementation such as clogging and water quality. Meanwhile, this review also highlights the great opportunities for further developments for LID practices to realize their wider practical application. Finally, future research directions are provided in order to give critical insights into potential future works to advance this field of research.

1 Introduction

The influence of human activities has greatly changed the appearance and function of the urban environment in the past few decades (Dhakal & Chevalier, 2015; Dillman et al., 2021; McMahon et al., 2018; Sanicola et al., 2018; Shafique & Kim, 2017). Urbanization has led to the expansion of cities and suburbs into many places that were once used for rural activities (Kim et al., 2017). It has been further reported that the urban sprawl and the fragmentation of natural resources have been formed due to the expansion of uncontrolled development. The growing rate of rapid development has resulted in many environmental issues in urban regions such as a speedy expansion of impermeable surfaces, increased stormwater runoff at the surface, changes in the soil conditions, decreased water and air quality and enlarged influence on the hydrological functions of the pavement (Ahiablame et al., 2012; Bichai & Ashbolt, 2017; Dhakal & Chevalier, 2015; Kim et al., 2017). Meanwhile, urbanization also facilitates human activities, which can

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directly affect the climate system of the earth through non-linear processes (Varotsos et al., 2013). According to the study of Efstathiou & Varotsos (2012), the global climate system and stormwater forecast can also be simulated by the application of detrended fluctuation analysis. The traditional development model in the city is defined as low sustainability development, which cannot meet the current requirements of sustainable urban development (Akther et al., 2018; Saha & Paterson, 2008). Research has found that these changes enhance the probability of natural disasters such as urban flooding events (Song et al., 2018). Flooding in urban areas has become more prevalent because of increased runoff quantity and impervious surface ratios (Akther et al., 2018; Conley et al., 2020; Sanicola et al., 2018; Trenouth & Van-der Linden, 2018). Meanwhile, the peak flow in urban will be higher, which improves the difficulty in governance during stormwater management. Water quality in urban rivers and groundwater has deteriorated sharply that attracts more attention as the country's economy increasing and society advances (Dhakal & Chevalier, 2015; Ishaq et al., 2020). The urban sprawl can raise the probability of flooding. Conversely, frequent floods will affect the economic growth of cities and further influence the development of urban. Therefore, many cities around the world are trying to limit their physical expansion while emphasizing the quality of economic growth (Kim et al., 2017). This is especially significant in environmental resources management; particularly, those resources are directly associated with the improvement of environmental quality in urban regions.

A more sustainable method is needed to address these challenges and balance the development of the urban environment. With a growing interest in urban regeneration, reconsidering urban water management and applying solutions can make cities more sustainable (Qiao et al., 2020; Sanicola et al., 2018; She et al., 2021). The application of stormwater management practices should monitor and control local water cycles (Kim et al., 2017). Low impact development (LID) practices as innovative approaches are emphasized, which aim to promote site penetration and restore ecosystem integrity in urbanized areas (Saadat & Malekmohammadi, 2020; Shafique & Kim, 2017). Prince George's County, Maryland, in 1997 first

pioneered this technology (Ahiablame et al., 2012). The traditional stormwater management system cannot completely realize these purposes because of itself conveyance of rainwater runoff away from point and non-point contamination sources (Sohn et al., 2019). LID practices combine land-use planning engineering and system design to create a cost-effective infrastructure management process (Kim et al., 2017; Zhao & Meng, 2020). These practice systems can support sustainable urban development in the long term. The basic principle of LID is to keep the hydrologic conditions after development close to the natural conditions before development (Ahiablame et al., 2012). LID practices seek to diminish stormwater runoff and improve water quality, meanwhile reduce cost in infrastructure construction, operation and maintenance (Akther et al., 2018; Dhakal & Chevalier, 2015; Fisher-Jeffes et al., 2016; Houle et al., 2013; Rodrigues et al., 2021). LID practices can reduce their impact on the surrounding environment through permeating and recharging rainwater into the underground (Sanicola et al., 2018; Shafique & Kim, 2017). The local rainwater control by using LID practices can be regarded as a resource rather than a constraint. LID practices are composed of several systems that are bioretention cell, rain garden, green roof, infiltration trench, continuous permeable pavement, rain barrel or cistern, rooftop disconnection and vegetative swale. Nevertheless, some of these practices might often occupy much land. Generally, highly urbanized regions are spatially constrained and advisable stormwater treatment approaches are best suited to urban areas without requiring further land occupation.

Stormwater management practices are also known as green infrastructure (GI), which summarizes a network of LID practices with the united objectives in the reduction of surface runoff and the improvement of water quality (Dietz, 2007; Ishaq et al., 2020; Kessler, 2011; Trajkovic et al., 2020). Additionally, stormwater management practices in early literature are also called best management practices (BMP) that involve structural or nonstructural controls to keep stormwater as pre-development quality (Kim et al., 2017). BMP includes not only technology but also methods and practices in water pollution prevention and runoff reduction as parts of its scope (Rodrigues

et al., 2021; Sun et al., 2014). The term LID practices consist of GI and BMP for research convenience in this study. Furthermore, LID practices in the USA and Japan are similar to sustainable urban drainage system (SUDS) in Europe and water-sensitive urban design (WSUD) in Australia (Sanicola et al., 2018). LID practices can be utilized to improve urban sprawl and land fragmentation while enhance the public comprehension of urban issues. Meanwhile, LID systems can apply tools and techniques to create a complex but efficient infrastructure throughout the site to control the source of the rainstorm (Kim et al., 2017). The design of LID practices should be an interconnected urban system, which makes the facilities function as ecologically and sustainably as possible (Shafique & Kim, 2017). These approaches can be implemented to create a sustainable living environment at the overall level, as they must contain environmental, economic and social aspects. LID practices are composed of three main functions that are collection, delivery and cleaning (Kim et al., 2017). Rainwater can wash away roofs and impermeable surfaces then might encounter contaminated regions and accumulate sediment. The rainwater with pollutants will infiltrate or flow into the groundwater or rivers of the city. LID practices can improve this rainwater flow process. The collection function means the reductions of stormwater runoff and the improvement of surrounding waterways (Shafique & Kim, 2017). The delivery function means directing stormwater runoff to other infrastructures that can absorb and store rainwater. Then, the water can be transferred to the pond where it is treated through a filtration system (Kim et al., 2017; Trenouth & Vander Linden, 2018). Retained rainwater can increase local water supplies and replenish groundwater aquifers in the meantime. Kim et al. (2017) explain that the cleaning function can filter and purify rainwater containing excessive contaminations and suspended solids to provide clean and healthy water. The major performances of LID practices are embodied in decreasing stormwater runoff, improving water quality and reducing construction and maintenance cost, which plays an important role in urban development and hydrology.

One main performance of LID practices is decreasing stormwater runoff. LID practices can reuse rainwater in urban by collection and infiltration, which

are the key points in urban hydrology because they approach the natural water cycle (Ahiablame et al., 2012; Kim et al., 2017; Shafique & Kim, 2017). The increase of impervious surfaces changed the hydrologic cycle of the subcathments (Eckart et al., 2017; Sohn et al., 2019). This results in the reduction of groundwater recharge, increased surface runoff, soil erosion and contaminations to aquifers (Dhakal & Chevalier, 2015; Earles et al., 2018; McMahon et al., 2018; Shaver & Puddephatt, 2008). The ecological degradation in urban regions has enhanced the social vulnerability to environmental variations such as property losses caused by flooding, inadequate groundwater supplies and increasing dietary pressures (Fisher-Jeffes et al., 2016; Sohn et al., 2019). Compared with the conventional stormwater management in the urban, LID practices have the ability to return runoff to the natural water cycle such as reducing total runoff, improving infiltration, decreasing peak flow and extending lag time (Ahiablame et al., 2013; Eckart et al., 2017; Son et al., 2017). Reduced rainwater on the surface can be collected by LID practices. Rainwater is a significant natural resource that is required for the ecosystems on the surface and subsurface (Dhakal & Chevalier, 2015). Rainwater that infiltrates into the ground can replenish the groundwater (Ahiablame et al., 2012). Rainwater and groundwater are two important sources for freshwater supply in the city, both of which provide water for rivers to maintain their base flow and river ecosystems. Additionally, development activities have compacted the subsurface soil, change soil structure and reduce soil infiltration capacity (Dhakal & Chevalier, 2015). It has been further reported that these activities subsequently change the path of rainwater falling on the land, leading to changes in the hydrological pattern of the landscape and increased velocity and flow of stormwater runoff. If urban development management is inappropriate, it can possibly cause flooding and other related issues such as river alteration and habitat vanishing (Thurston, 2006). Furthermore, urbanization is also harmful to water quality and freshwater ecosystems.

Improving water quality is also an important performance in LID practices. Global warming has caused significant changes in the frequency and pattern of storms due to raised greenhouse gases

concentrations in the atmosphere (Shafique & Kim, 2017; Wang et al., 2019b). Therefore, extreme storms could frequently happen under the global warming situation in the future. Urban rainwater degrades the level of aquatic life because the water environment is changed such as physical, chemical, thermal and sediment conditions (Dhakal & Chevalier, 2015). The ecosystems of urban streams and downstream freshwater can be affected by the loss of vegetation and alteration of land use (Kim et al., 2017). Most cities have a large amount of rainwater infrastructure, which consists of synthetic features such as embankments, drains and underground pipe networks (Trenouth & Vander Linden, 2018). According to combinational manners, these systems can be classified into two categories that are combined sewer systems (CSS) and separate sewer systems (SSS) (Dhakal & Chevalier, 2015). Rainwater might be polluted during the transportation of the system. Chemicals and pathogens in runoff constitute a serious and widespread public health problem (Ishaq et al., 2020). Fifty-four percent of the global world population lives in cities and continues growing (Leroy et al., 2016; Sanicola et al., 2018). The impact of changes in water quality on the environment and public health is noteworthy (Ishaq et al., 2020; Leroy et al., 2016). LID practices can address urban stormwater to satisfy the requirement of water quality for improving the utilization rate of water resource. These innovation technologies such as vegetative swales can adsorb suspended solids and metal pollutants because they are conducive to reduce flow velocities (Leroy et al., 2017).

LID approaches might lower the cost of urban stormwater management. Traditionally, there have been numerous resistance to the acceptance and adoption of LID design because they believe that some systems might require substantial construction and maintenance (Houle et al., 2013). Although the upfront costs of these systems are higher than traditional stormwater management systems, the long payback is cost-effective in the future (Trenouth & Vander Linden, 2018). As LID practices are beginning to implement, participants need more information, resources and guideline to estimate the total cost of LID practices including construction and maintenance costs. However, the implementation of LID techniques is not always easy because specific circumstances could affect the decision-making process (Kim et al., 2017). It is important that the necessary functionality is designed and installed with due regard in any applications of LID systems (Dietz, 2007). A LID practice with good performance relies on building material cost and infrastructure system complexity, which might generate additional expenses (Kim et al., 2017). Moreover, the costs affecting the project are related to construction costs, maintenance costs, design costs, licencing costs and land costs.

LID practices not only can achieve environmental benefits, but also economic and social benefits. Nevertheless, there are significant challenges that need to be addressed to enhance LID practices in the real world. Particularly, in order to ensure that the LID practices as conducted in countries with cold climates can be effectively applied to Asian countries, more efforts will be needed to improve the engineering design of the LID practices in the Asian countries. If LID practices can be retrofitted from the original traditional stormwater management system, it would be important to understand the impediments and challenges facing the technology. Additionally, the relevant guidance document in LID practices is insufficient, which might be obstacles during the design, construction and maintenance of the stormwater management systems.

The novelty of this review paper is that it provides a timely and comprehensive review which covers the recent developments of LID practices. In addition, this review paper elucidates the recent findings of cost for many different types of LID practices, which to the best of our knowledge have not been comprehensively covered in the literature. The main objective of this study is to realize a critical review of LID practices on recent developments, challenges and prospects. Seven types of LID practices are introduced in this review article, namely of bioretention cell, green roof, infiltration trench, permeable pavement, rain barrel or cistern, rooftop disconnection and vegetative swale. Each of LID practices is analysed from five aspects including principles, design, performance, advantages and disadvantages and costs according to the existing literature. Although these innovative technologies have become popular all

over the world, managers are still facing impediments during implementation. The discussion given in this study is aimed at providing opportunities and recommendations for further developments.

2 Overview of LID

LID is a green stormwater management approach that aims amongst others to achieve water balance by imitating the natural hydrology localized micro-scale control methods (Bhatt et al., 2019; Boguniewicz-Zabłocka & Capodaglio, 2020; Davis, 2005; Davis, 2008; Peng et al., 2020; Qin, 2020; Zhang et al., 2020b). Inherent amongst LID techniques is the augmentation of urban pervious surfaces to allow as much infiltration into the ground as possible, while enhancing water quality by using biological measures, chemical sorption and filtration (Hunt et al., 2010; Locatelli et al., 2017). Thus, by incorporating such techniques into built environments, their negative impacts on the natural hydrological process are countered and a water balance can be maintained (Lizárraga-Mendiola et al., 2017; Wang et al., 2019a; Zhang & Chui, 2018).

LID techniques may be either structural or nonstructural. Structural approaches to LID included green roofs, bioretention cells, permeable pavements, infiltration trenches, swales, buffer strips, rain barrels, wet ponds, stormwater wetlands, level spreaders, smaller culverts and sand filters (Hunt et al., 2010). Nonstructural approaches include the preservation of the natural site, the utilization of native vegetation and the minimization of impervious surfaces (Hunt et al., 2010).

3 Types of LID
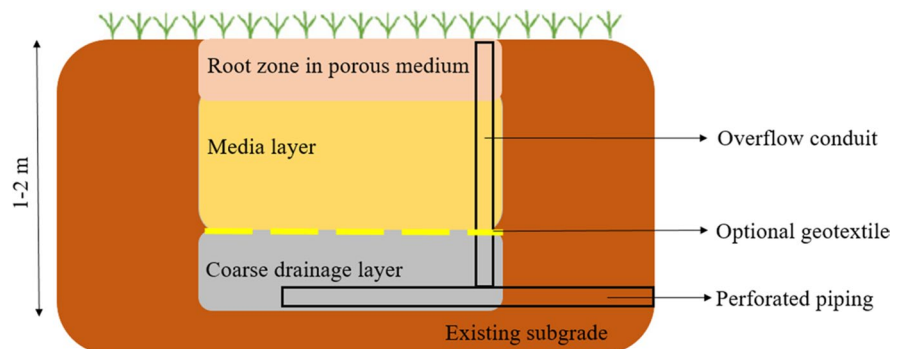
3.1 Bioretention Cell

3.1.1 Principles

The terms bioretention cell and rain garden are often used interchangeably when referring to stagnant landscape areas that are designed to attenuate and treat stormwater runoff (Ahiablame et al., 2012; Dietz, 2007; Guo et al., 2018; Mahmoud et al., 2019; Mangangka et al., 2015; Rodrigues et al., 2021). This approach to LID is gradually gaining prominence in the built environment as it can be used in commercial and residential settings (Guo et al., 2018; Zeng et al., 2020).

Bioretention cells operate by retaining captured stormwater for a period of time through their filter media thereby reducing runoff volumes (Liu & Fassman-Beck, 2017; Mangangka et al., 2015). The stormwater infiltration enhancement of bioretention cells primarily arises from their ability to delay stormwater runoff during periods of peak percolation (Davis et al., 2009; Johnson & Hunt, 2020). Additionally, the evapotranspiration by plants in bioretention cells contributes to a reduction in stormwater outflow (Winston et al., 2016b). Aside from their runoff mitigatory function, the permeable filler media of bioretention cells play an essential role in stormwater pollution reduction (Davis et al., 2009; Rycewicz-Borecki et al., 2017; Smyth et al., 2021; Zhang et al., 2020b).

3.1.2 Design

Bioretention systems consist of a surface ponding layer, vegetation, a soil layer, a storage layer, overflow

Fig. 1 The design of bioretention cell (adapted from Hager et al., 2019)

structures and an optional underdrain system as shown in Fig. 1, working in conjunction to manage stormwater runoff (Liu et al., 2014; Yang & Chui, 2018). A typical bioretention cell design consists of a vegetated surface layer above a porous soil media that is above a layer of gravel (Winston et al., 2016b). Though based on a similar standard, the design of individual bioretention cells tends to differ (Winston et al., 2016b). These variations can play a crucial role in the function of the system (Ahiablame et al., 2012). Besides the design of the bioretention system, the approach of its construction has been recorded to impact its performance (Brown & Hunt, 2010). Additionally, such other factors as location and maintenance can impact the performance of bioretention systems (Brown & Hunt, 2012).

Literature on bioretention system design has varying points of emphasis, but amongst the paramount factors highlighted are their hydrological effect and their pollution effect (Guo et al., 2018). From a hydrological point of view, the infiltration ability of bioretention cells is one crucial aspect. The bioretention cell's soil media, being the most essential parameter for runoff reduction, is recommended to be designed for infiltration rates of 25–50 mm/h (Liu et al., 2014). In addition to the soil media design, the vegetation type has been recorded to significantly influence the hydrological performance of bioretention cells. For the best hydrological performance, it has been recommended to prioritize taxonomically and structurally diverse planting for bioretention cells (Yuan et al., 2017). The hydrological design of bioretention cells should take into consideration the rainfall patterns of the target site as bioretention cells perform best and are most suited for longer span rainfalls with lower intensities (Sun et al., 2019; Wałęga et al., 2018; Yang & Chui, 2018). Researchers have found myriad approaches to improving the purity of stormwater discharged from bioretention cells. Kim et al. (2003) provide an anoxic zone by infusing the bioretention cell sand layer with newspaper resulting in an 80% reduction in nitrate-nitrogen (NO_3-N). Ergas et al. (2010) also reduce nitrogen output albeit by using sulphur or wood chips to create their anoxic zone. Dietz and Clausen (2006) show that nitrogen removal can further be improved by creating a saturated zone in bioretention cells. Lucas and Greenway (2011) recommend

the inclusion of P sorption materials to improve the phosphorus retention of bioretention cells.

3.1.3 Performance

Numerous field studies at varying locations have confirmed the stormwater runoff volume reduction ability of contemporary bioretention systems (Alikhani et al., 2020; Mahmoud et al., 2019; Yang & Chui, 2018). Over a series of rainfalls in Maryland, bioretention cells yielded flow peak reductions ranging from 44 to 63% (Davis, 2008). In the semi-arid climate of Mexico, it is found absorption rates between 2.25% and 5.37% of runoff volume for a bioretention system with sandy loam soil and succulent plants and herbaceous grasses (such as *Opuntia* spp. and *Agave* spp.) as shown in Table 1 (Lizárraga-Mendiola et al., 2017). In Xi'an (China), the effect of 28 large storm events on an experimental rain garden has been studied out of which only 5 resulted in an overflow (Tang et al., 2016b). They recorded overflow reduction rates within the range of 77% and 94% and highlighted the ability of rain gardens to significantly reduce the negative hydrological effect of the built environment. In another study over a longer span (March 2011-October 2017), it is found average runoff volume reduction rates of 60.0%, 97.8% and 96.3% for three separate rain gardens (Guo et al., 2018). On average, bioretention systems can control at least 60% of runoff (Zhang et al., 2019). This high hydrological performance of bioretention systems evident across the literature is however dependent on the magnitude of rainfall events (Davis, 2008). In addition, bioretention systems are most efficient in areas with small or medium rainfall events as opposed to areas with heavy rainfall events (Guo et al., 2018).

Besides their hydrological benefits, bioretention systems have been recorded to lessen the concentration of pollutants such as oil and grease, total suspended solids and heavy metals (Lee & Gil, 2020; Liu et al., 2014; Lopez-Ponnada et al., 2020). After monitoring bioretention systems for 13 months, it is found that 84% TN and 50% TSS are reserved by the bioretention systems (Luell et al., 2011). Bioretention systems have been recorded to retain an average of 70% to 99% of bacteria (Ahiablame et al., 2012). Other studies of bioretention systems have yielded 98% removal of copper, zinc and lead (Johnson & Hunt, 2016). Guo et al. have record pollutant

Table 1 Runoff reduction and pollutant removal of bioretention systems

References	Location	Media	Plant	Runoff	TSS	TN	TP	NO$_3$-N	NH$_4^+$-N
DeBusk and Wynn (2011)	Blacksburg, USA	Mulch, sand, leaf compost and soil	-	97%	Nearly 100%	99%	99%	-	-
Brown and Hunt (2012)	Nashville, USA	Sand and fines	-	89%	-	-	-	-	-
Randall and Bradford (2013)	Guelph, Canada	Base mix A (mainly composted wood/bark), sand mix and gravel	-	-	-	53.40%	75.50%	62.70%	-
Randall and Bradford (2013)	Guelph, Canada	Base mix A (mainly composted wood/bark), anoxic and gravel	-	-	-	8.79%	54.10%	99.30%	-
Randall and Bradford (2013)	Guelph, Canada	Base mix B (mainly food waste), Phoslock and gravel	-	-	-	-235%	33.90%	98%	-
Randall and Bradford (2013)	Guelph, Canada	Base mix A (mainly composted wood/bark), Al-WTR and gravel	-	-	-	23.10%	78.40%	24.50%	-
Randall and Bradford (2013)	Guelph, Canada	Base mix B (mainly food waste), Sorbitive and gravel	-	-	-	-67.30%	79.30%	-118%	-
Olszewski and Davis (2013)	Maryland, USA	Sand, silt and clay	-	79%	-	-	-	-	-
Li and Davis (2014)	Maryland, USA	Loamy sand	-	-	-	41%	-	45%	-
Liu et al. (2015)	Indiana, USA	-	-	26%	54%	34%	47%	-	-
Tang et al. (2016b)	Xi'an, China	-	-	77%–94%	-	-	-	-	-
Lizárraga-Mendiola et al. (2017)	Hidalgo, Mexico	Sandy loam soil	Herbaceous grasses and succulent plants (such as *Opuntia* spp. and *Agave* spp.)	94.63–97.75%	-	-	-	-	-
Gülbaz and Kazezyilmaz-Alhan (2017)	Istanbul, Turkey	Mulch, turf, vegetative soil, sand and gravel	-	23–85%	-	-	-	-	-
Guo et al. (2018)	Xi'an, China	Loess soil, coarse sand, silver sand and PVC perforated tube	-	60%	-18.60–100.0%	-119.30–85.06%	-467.40–48.89%	-583.50–58.65%	40.84–94.22%
Guo et al. (2018)	Xi'an, China	Loess soil	-	98%	-	-	-	-	-
Guo et al. (2018)	Xi'an, China	Loess soil, flapper, waterproof cloth and PVC perforated tube	-	96%	-121.35–85.23%	-18.80–75.76%	-46.40–101.10%	348.02–87.30%	14.60–153.80%
Xia et al. (2018)	-	-	-	-	-	52%	8%	-	-
Xiong et al. (2019)	-	Conventional mixed sand and soil media	-	-	-	-	-	-	-
Xiong et al. (2019)	-	Biochar-amended media	-	-	-	97%	57%	-	-
Xiong et al. (2019)	-	Iron-coated biochar (ICB)-amended media	-	-	-	93%	94%	-	98%

Table 1 (continued)

References	Location	Media	Plant	Runoff	TSS	TN	TP	NO_3-N	NH_4^+-N
Johnson and Hunt (2019)	North Carolina, USA	Filter soil	-	-	-	72%	79%	86%	-
Zhang et al. (2019)	Kyoto, Japan	Existing soil	*Cyclobalanopsis myrsinifolia* (Blume) Oerste, *Gardenia jasminoides* Ellis and *Eupatorium japonicum* Thunb	>60% runoff reduction	-	-	-	-	-
Rezaei et al. (2019)	Kuala Lumpur, Malaysia	-	-	23%	41%	29%	-	-	-
Guo et al. (2019)	Xi'an, China	Loess soil	-	97%	-	-	-	-	-
Zhang et al. (2020b)	Kyoto, Japan	Mulch, planting soil, engineered soil, sand and gravel	-	12.11–13.78%	15.50%	17.34%	19.07%	-	-
Alikhani et al. (2020)	Cincinnati, USA	Engineered soil, aggregate and native soil	-	50%	83%	25%	17%	-	-

reduction rates for bioretention system as being greater than 50%, but they also highlight the poor performance of NH_4^+-N over time (Guo et al., 2018). According to Johnson and Hunt, bioretention systems may sustain their treatment of nitrogen and phosphorus for about two decades if properly designed, built and maintained (Johnson & Hunt, 2019). Other studies have revealed a greater than 98% retention of oil and grease (Mahmoud et al., 2019). Xiong et al. simulate the performance of three types of media (1 = conventional mixed sand and soil media, 2 = biochar-amended media, 3 = iron-coated biochar (ICB)-amended media) (Xiong et al., 2019). Their analysis shows that the media composed of iron-coated biochar (ICB)-amended media as the best performer with removal rates of 94.6%, 98.3% and 93.70% for COD, ammonia and total phosphorus respectively. Though the results on individual pollutant reduction capabilities of bioretention cells may vary as a result of location and design configurations, the body of literature on bioretention points to overall pollutant reduction (Li & Davis, 2016).

3.1.4 Advantages and Disadvantages

Bioretention systems are beneficial due to their ability to decrease surface runoff, promote infiltration, increase groundwater recharge and reduce pollutant loads (Ahiablame et al., 2012; Davis, 2008; Dietz, 2007; Dietz & Clausen, 2006). Additionally, bioretention systems can be used in most settings of the built environment (Dietz, 2007), may require simple operation and management and provides ecological benefits such as the diversification and expansion of floral and faunal populations (Guo et al., 2018; Houdeshel et al., 2013).

From a microclimatic perspective, the greenery of bioretention systems contributes to cooling and increasing humidity during hot days thereby alleviating the effects of the urban heat island (Siwiec et al., 2018). This microclimatic benefit, coupled with the contribution of bioretention systems to aesthetic enhancement, further results in social benefit by enhancing the comfort of urban society (Liu et al., 2014; Siwiec et al., 2018).

3.1.5 Costs

The costs of bioretention systems largely vary since individual systems are heterogenous and may have a plethora of variations. Such variations may stem from factors including location, size, soil conditions, material type and soil types (Siwiec et al., 2018). The design lifespan of biorentention system is 40 years. Normally, the empirical lifespan is between 20 and 50 years due to weather or maintenance (Hua et al., 2020). Varying operational costs may also arise due to maintenance needs, which vary from system to system (Siwiec et al., 2018; Spraakman et al., 2020). The cost of biorentention can be estimated to reach 109–227 USD/m^2 (Hua et al., 2020). This cost only includes labour and material costs, which is used for construction. The land cost is not considered that depends on different implementation locations (Saadat & Malekmohammadi, 2020). Additionally, the annual operation and maintenance costs are about 6 USD/m^2 (Zeng et al., 2020).

3.2 Green roofs

3.2.1 Principles

Green roofs refer to building roofs that are completely or partially covered with a vegetation layer planted over a waterproofing membrane (Rowe, 2011). Green roofs, also known as living roofs, eco-roofs or vegetated rooftops, are gradually gaining ground as an alternative to impervious roof surfaces (Carson et al., 2013; Fan et al., 2020). Typically, green roofs are installed to compensate for the natural vegetation lost as a result of the building construction (Deska et al., 2020; Rowe, 2011).

Green roofs, as LID techniques, contribute significantly to the reduction of stormwater runoff through a combination of evapotranspiration by green roof vegetation and storage in the green roof media (Berndtsson et al., 2006; Dietz, 2007; Liu et al., 2021). During storm events, green roofs retain a portion of precipitation which gets buffered in the soil layer. A portion of this retained precipitation is drained, and another portion is retained based on the soil field capacity. The portion retained in the soil field is subsequently extracted by the plants of the green roof through evapotranspiration (Czemiel, 2010).

Typically, the hydrological performance of green roofs is measured based on their stormwater retention capacity or their stormwater retention rates. The stormwater retention capacity is estimated according to the maximum precipitation volume that is retained by the green roof, whereas the stormwater retention rates are the percentage of stormwater that is reserved by the green roof during a rainfall event (Akther et al., 2018). Both these performance determinants may be influenced by such factors as precipitation intensity, roof type, roof slope, media composition, media thickness, plant type and climatic conditions (Akther et al., 2018; Czemiel, 2010; Deska et al., 2020; Liu et al., 2019a; Palanisamy et al., 2020; Pęczkowski et al., 2018; Yao et al., 2020).

3.2.2 Design

Typically, green roofs are constructed by situating a drainage course, growing substrate and vegetation atop the waterproof membrane of a roof as shown in Fig. 2 (Carson et al., 2013). Green roofs are defined as intensive systems or extensive systems according to the thickness of the substrate layer (Ahiablame et al., 2012; Berndtsson et al., 2009; Carson et al., 2013; Czemiel, 2010; Ramos et al., 2017). Intensive green roofs typically consist of substrate layers that are greater than 15-cm depth, whereas extensive green roof substrates are less than 15 cm thick (Carson et al., 2013). Due to their thicker substrate layers, intensive green roof systems are able to support deeper rooting vegetation with plant growth up to the size of small trees (Carson et al., 2013; Castiglia & Wilkinson, 2016). Extensive green roofs on the other hand can only support short rooting vegetation (Carson et al., 2013; Castiglia & Wilkinson, 2016). This restriction nonetheless, the extensive system is the more frequently adopted option as they are cheaper, lighter, easier to instal and require less maintenance than intensive systems (Carson et al., 2013; Zhang et al., 2019).

Studies show that the thickness of the green roof soil layer greatly influences their ability to retain and discharge stormwater (Castiglia & Wilkinson, 2016; VanWoert et al., 2005; Yuan et al., 2017). Thus, intensive systems are deemed to perform significantly better than their extensive counterparts.

However, since most existing structures are not designed for substantial additional loads, the lighter weights of extensive systems enable them to cover larger areas when retrofitting existing roofs, thereby overcoming the higher efficiency of intensive systems (Castiglia & Wilkinson, 2016).

To enhance the stormwater performance of green roofs, it is recommended that substrate layers be well permeable so as to allow the channel of both water and air (Deska et al., 2020). This will allow enhancing stormwater infiltration, thereby reducing runoff and substrate erosion (Akther et al., 2018). Additionally, increased permeability will enhance plant root ventilation thereby preventing rotting (Young et al., 2014).

Plants are an essential component of green roofs and the plant composition of green roofs significantly influences their stormwater retention and discharge (Buccola & Spolek, 2011; Zhang et al., 2018). It has been suggested that when selecting plants for green roofs, designers should take into consideration the interaction of plants with the selected substrates as this influences stormwater retention (Zhang et al., 2018). The interaction of potential plant species with the microclimate of the green roof location should also be considered when selecting green roof vegetation as the selection of suitable plant species determines the success of green roof installations (Charalambous et al., 2019; Farrell et al., 2013). Additionally, since green roof retention increases as evapotranspiration increases, it is critical to design in such a way that evapotranspiration is enhanced (DiGiovanni et al., 2010). A typical way of attaining this is by selecting higher transpiring plants (Nardini et al., 2012).

Many other factors influence the stormwater retention of green roofs and should be considered in each

individual design (Liberalesso et al., 2020). The slope of the green roof for instance is an essential consideration as steeper slopes result in lower retention (Getter et al., 2007; VanWoert et al., 2005). Higher rainfall intensities have been recorded to result in lower retention (Vijayaraghavan et al., 2012; Villarreal, 2007). Weather conditions are essential as more antecedent dry days for instance can enhance water retention (Lee et al., 2015).

To minimize pollution, precaution should be taken in the design of green roof systems as pollution retention primarily depends on the green roof media composition (Dietz, 2007; Hathaway et al., 2008; Vijayaraghavan et al., 2012). It is important to select healthy plant species and plants that is no need for fertilization as doing contrary will increase the amounts of NO_3-N and TP respectively in outflow (Aitkenhead-Peterson et al., 2011; Dietz, 2007).

3.2.3 Performance

Favourable performance results have been observed across literature for green roofs over various climatic conditions (A'Saf et al., 2020; Ahiablame et al., 2012; Gao et al., 2021; Martin & Kaye, 2020). Rainfall retention in these studies ranges between 20 and 100% (Ahiablame et al., 2012). More recently, it has been revealed that average stormwater retention of 77% is achieved upon carrying out 16 tests on two fundamental mixtures carrying two plant species under natural rainfall (Charalambous et al., 2019). It is found a 77.2% stormwater retention for *Sedum lineare* planted on a 15-cm-thick substrate (Zhang et al., 2015). Carson et al. test the precipitation retention of two vegetation types and found retention rates of 47% and 61% for *Sedum mix* and *Sedum mix* with natives,

Fig. 2 The design of green roofs (adapted from Eckark et al., 2017 and Banting et al., 2005)
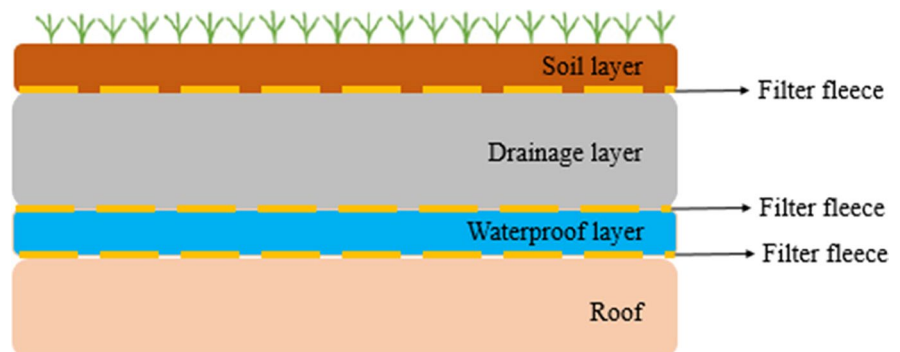
highlighting a significantly better retention performance for *Sedum mix* as shown in Table 2 (Carson et al., 2013; Charalambous et al., 2019). Additionally, they test the effect of media thickness on precipitation using the same vegetation type (*Sedum mix*) and find a 36% retention for a 3.2-cm-thick media and a 61% retention for a 10-cm-thick media.

The issue of green roof runoff pollution remains an issue of concern to stakeholders (Liu et al., 2019b). Liu et al. find average TSS concentrations of 37.73 mg/L and 12.08 mg/L for green roof runoff and conventional roof runoff respectively and average TN concentrations of 1.71 mg/L and 0.59 mg/L for green roof runoff and conventional roof runoff respectively (Liu et al., 2019b). This highlights a significantly high runoff pollution arising from the use of green roofs. Studies on pollution from green roofs however vary, with reports ranging from increased pollution to reduced pollution (Ahiablame et al., 2012). These differences can however be attributed to variations in the design which significantly affect green roof performance (Dietz, 2007; Hathaway et al., 2008).

3.2.4 Advantages and Disadvantages

Besides the ability to retain stormwater runoff, green roofs deliver additional advantages such as improving air quality, increasing biodiversity, saving energy, enhancing urban aesthetics, reducing urban heat island and enhancing urban cooling (Ahiablame et al., 2012; Charalambous et al., 2019; Cirkel et al., 2018; Deska et al., 2020; Dunnett et al., 2008; Rowe et al., 2014; Vijayaraghavan et al., 2012). Additionally, due to the abundance of vacant rooftops, green roof construction is not limited by the availability of space (Castiglia & Wilkinson, 2016).

As a LID tool, a disadvantage may arise since the stormwater runoff reduction efficiency of green roofs is relatively lower than that of large-storage rainwater harvesting systems (Charalambous et al., 2019). Moreover, green roofs occasionally contribute to stormwater pollution (Razzaghmanesh et al., 2014). This pollution can however be curbed by selecting suitable designs and construction materials for each green roof construction (Zhang et al., 2015).

3.2.5 Costs

Though green roofs are pricier than traditional alternatives, their benefits most often outweigh their construction premiums (Dietz, 2007). This economic viability is verified by an analysis report in Toronto (Canada), where large costs savings are estimated if conventional roofs were to be retrofitted with green roofs (Berndtsson et al., 2006). The initial investment of green roof takes into account the material and labour costs, which is also determined by different green roof classes such as extensive, semi-intensive and intensive types in the system. Moreover, the installation costs vary greatly in diverse countries. The average implementation cost of an extensive green roof is 112 USD/m^2 (Li et al., 2021; Manso et al., 2021). It has been further stated that the average implementation cost of 147 USD/m^2 is identified for semi-intensive systems, which is more expensive than extensive systems because plentiful plant species are usually used. The average implementation cost of intensive green roof is reaching 409 USD/m^2 as more materials are included such as small trees (Li et al., 2021; Manso et al., 2021). Furthermore, it is also important to understand the maintenance performance in the green roof system. The proper maintenance process could ensure the green roof system

Table 2 Precipitation retention by green roof

References	Location	Study period	Precipitation retention (%)	Vegetation type	Media thickness (cm)	Roof slope (%)
Carson et al. (2013)	New York City, USA	06/11–06/12	0.36	*Sedum mix*	3.2	2
Carson et al. (2013)	New York City, USA	06/11–06/12	0.61	*Sedum mix*	10	2
Carson et al. (2013)	New York City, USA	06/11–06/12	0.47	*Sedum mix & natives*	10	2
Zhang et al. (2015)	Chongqing, China	05/11–11/11	77.2	*Sedum Lineare*	15	-
Charalambous et al. (2019)	Nicosia, Cyprus	02/16–04/17	0.77	-	2.5	5

successful after the warranty period. The average annual maintenance costs can be estimated that are 4.84 USD/m^2, 8.78 USD/m^2 and 6.37 USD/m^2 in the extensive, semi-intensive and intensive systems, respectively (Li et al., 2021; Manso et al., 2021; Sherk et al., 2020). The economic value of green roofs is additionally emphasized in cities with costly stormwater treatment systems; where the 60–70% stormwater runoff mitigation provided by green roofs could provide significant fiscal relief (Dietz, 2007).

3.3 Infiltration Trench

3.3.1 Principles

The definition of infiltration trench is an underground trench that is packed with porous and permeable media to increase the capacity of underground infiltration and to control the urban stormwater (Conley et al., 2020; Hager et al., 2019). Infiltration trench might provide several purposes such as the reduction of urban runoff, the growth of groundwater volumes and the improvement of the water environment (Abdelkebir et al., 2021; Bonneau et al., 2017; Hager et al., 2019; Lucas, 2010; Newcomer et al., 2014). This measure can decrease the amount of surface runoff that is equal to 10% of rainfall (Joksimovic & Alam, 2014; Larson & Safferman, 2008). Generally, an infiltration trench is a linear structure. Moreover, the permeable material, involving gravel, sand, stone and filter fabric, can be designed to drain the surface water flow at a specific rate (Hager et al., 2019; Larson & Safferman, 2008). It has been reported that the groundwater would be recharged by the infiltration effect. The filter fabric can partly trap contaminants within the trench to retard the groundwater pollution. Furthermore, other materials such as ash possess a high adsorption capacity that might be utilized to increase the rate of infiltration and decrease the contaminant concentration of the infiltrated water (Hager et al., 2019). Infiltration trench as one of the structural management systems in stormwater runoff depends on filterable materials and subsurface soil to reduce the pollution impact, which is also an applicable solution for runoff in available spaces such as underground pipe (Conley et al., 2020; Freni et al., 2010). Additionally, optional geotextile materials can

be utilized in the infiltration trench system to lessen the risk of sediment-induced clogging during the entire construction (Hager et al., 2019).

Usually, infiltration trench is applicable in selected areas with a small and frequent storm because clogging problems are connected to the larger stormwater (Larson & Safferman, 2008; Lizárraga-Mendiola et al., 2017). It has been stated that bypass flow systems should be applied for great rainstorm events. The storm events cannot surpass the water storage of the infiltration system. Meanwhile, such events can boost the velocity of infiltration to improve the burden of filtering pollutants (Larson & Safferman, 2008). Therefore, this approach is not recommended to be used in seriously polluted regions. The effectiveness of pollution control in groundwater will be weakened. Furthermore, the trench should be checked to ensure they are well drained after each rainfall event at the beginning of few months (Larson & Safferman, 2008). The vital issue of a system that depends on penetration is whether the penetration rate remains constant over time (Hunt et al., 2010). The inspection well should be installed on the surface for observation. Regular checking is necessary to maintain the function of the infiltration trench. Semiannual inspections should keep in the whole trench life after the first few months (Hager et al., 2019; Larson & Safferman, 2008). Hydrops need to be paid attention to as it indicates filtration materials should be replaced. Clogged aggregate can diminish the infiltration efficiency along with time. Contaminants in a ditch can also have an effect on the rate of infiltration. Thus, trench fields should be changed over a long period of time to enhance the treatment effectiveness. The total equipment in the infiltration trench system needs to be checked at least twice a year for normal operation (Larson & Safferman, 2008). An infiltration trench is an efficient option to manage common rainfall events according to these principles. The principle is fundamental to the design, which can guide the trench plan. The specific design in infiltration trench practice plays a significant role to mitigate current stormwater problems in the urban city.

3.3.2 Design

The design of the infiltration trench is to gather the runoff on the ground, which can alleviate the current

flooding issues of the street in the city. Normally, the form of the infiltration trench is designed as a rectangular shape that is shown in Fig. 3 (Chahar et al., 2012; Lizárraga-Mendiola et al., 2017). The top of the trench is the infiltration surface (Bonneau et al., 2017). The dimensions of width and height in the infiltration trench can be determined according to the specific situation. The width of the infiltration trench is usually within a range of one to a few metres and the depth relies on the deepness of the frost line (Song et al., 2018). As long as the frost line is higher than the maximum effective depth of the trench, it can maintain the function throughout the whole winter. The runoff can be received from the impervious area that is the ground surface. The important part of the infiltration trench is the section that is filled with filtration material such as gravel and sand. The thickness of each material could be different according to the site condition. The filtration material can be fine gravel in 0.25 m and sand in 0.10 m from the top to bottom, respectively (Lizárraga-Mendiola et al., 2017). The screening results show that most materials are smaller than fine sand (< 125 μm) and are accounting for about 50% less than 63 μm, 34% less than 32 μm, 27% less than 14 μm and 16% less than 8 μm (Conley et al., 2020). Moreover, the perforated pipe is inside the porous and permeable materials and the optional geotextile material is around the perforated pipe (Bonneau et al., 2017; McBean et al., 2019). Additionally, the estimated movement of infiltrated stormwater should directly flow into the stream (Bonneau et al., 2017). All components of the system play an important role to develop the performance in regulating the streamflow of the city.

3.3.3 Performance

High groundwater table and low hydraulic conductivity in soil mainly affect the performance of the infiltration trench (Chahar et al., 2012; Lewellyn et al., 2015; Locatelli et al., 2015). The most intuitive parameter in performance is the infiltration capacity. Generally, there are two types of infiltration methods involving the infiltration trench and the infiltration pond (Heilweil et al., 2011). Two techniques are compared according to the infiltration capacity in the same soil condition. Heilweil and Watt (2011) present the result that the infiltration rate of the infiltration trench is greater than that of the infiltration pond. If the infiltration trench system is installed in the shallow groundwater region, the infiltration capacity is decreased by groundwater drainage (Locatelli et al., 2015). Therefore, the reduction of peak flow and annual stormwater runoff volume can be utilized to quantify the hydrological performance of a trench locating a shallow groundwater table. The dissipation capacity of the groundwater is associated with the groundwater table in a constant unsaturated depth (Locatelli et al., 2015). The original subterranean environment is disrupted by infrastructures such as underground pipes and deep tunnels. Thus, there is an interaction between groundwater movements and underground pipes, which is called urban karst (Bonneau et al., 2017). The dissipation capacity of the groundwater under this interaction will be enhanced when the groundwater table is deep (Bonneau et al., 2017; Locatelli et al., 2015). The impact factors include not only the groundwater table but also hydraulic conductivity.

Hydraulic conductivity can change the saturated state of the soil medium. Generally, the shape of the

Fig. 3 The design of infiltration trench (adapted from Hager et al., 2019)
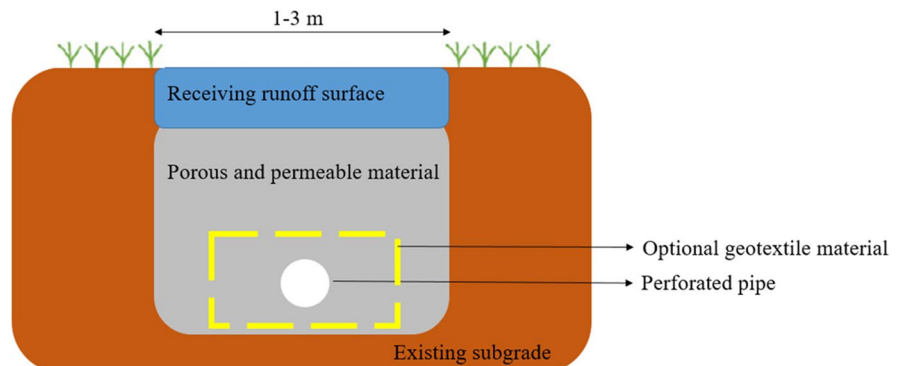
infiltration trench is long, moderately wide and shallow (Chahar et al., 2012; Lizárraga-Mendiola et al., 2017). The system collects runoff from neighbouring paved zones and makes water infiltrate into the underground aquifer (Bonneau et al., 2017). The coarse gravel as a filling material can provide storage, which commonly possesses higher hydraulic conductivity than the underground soil (Chahar et al., 2012). Therefore, the flow resistance in a trench is negligible and the perimeter of the trench can be regarded as the equipotential surface. The aquifer consists of multiple porous media and the hydraulic conductivity of the upper layer is less than that of the lower layer (Chahar et al., 2012; Locatelli et al., 2015). If the groundwater level of the aquifer is lower than the upper bottom, the wetting leading edge of the seepage water from the trench will advance in all directions; possibly saturating the lower permeable upper layer, but the seepage in the lower permeable layer will be unsaturated (Chahar et al., 2012). For instance, when the hydraulic conductivity in the trench is much lower than that of the underlying soil, the soil medium keeps unsaturated. In this case, the lower unsaturated layer will be a drainage layer for the upper saturated layer and ultimately replenish the aquifer. Therefore, if the value of soil hydraulic conductivity is 1×10^{-7} m/s or lower, the infiltration trench method needs to be altered to conduct average annual runoff diminutions of 16–70% (Locatelli et al., 2015). It has also been reported that the saturated thickness of an unconfined aquifer by reducing few metres can considerably diminish the hydrologic performance of the system. Additionally, the location of the groundwater table in an aquifer might be controlled horizontally or vertically by the river. Accordingly, the infiltration trench design should consider the groundwater conditions and hydraulic conductivity in soil, particularly in shallow groundwater regions. Other factors that affect the performance of infiltration trench might be stormwater quality, surrounding topography and maintenance practices (Conley et al., 2020; Petit-Boix et al., 2015).

3.3.4 Advantages and Disadvantages

The most widely known advantages of the infiltration trench involve recharging groundwater and reducing environmental pollutants (Chahar et al., 2012; Conley et al., 2020; Dabas et al., 2021; Lizárraga-Mendiola

et al., 2017; McBean et al., 2019). The infiltration system can provide the groundwater recharge function to mitigate the stormwater runoff phenomenon. Conversely, groundwater is excessively extracted and not replenished in the deep confined aquifers, which will result in land subsidence (McBean et al., 2019). McBean et al. (2019) further elucidate that there is also growing concern about the consequences of the sinking, which could exacerbate urban flooding, especially in coastal cities such as Shanghai and Guangzhou. It is essential to maintain the groundwater table at a safety level. Moreover, the study presents that the peak runoff decreases effectively with total infiltration increasing after the comparison of peak runoff, total runoff and total infiltration (Song et al., 2018). Therefore, the infiltration trench system should restore the natural hydrologic cycle in an urban area to support the functionality of groundwater recharge for the whole year rather than conflict with land using (McBean et al., 2019). Infiltration trench is the low impact development and green infrastructure practice, which can also attenuate contaminant delivery to groundwater (Conley et al., 2020). The trench is composed of gravel and sand. Meanwhile, physical filtration is performed by filtering out larger contaminants from the water. Many traditional pollutants such as heavy metals can also be captured by infiltration trench (Chahar et al., 2012; Hong et al., 2020). Thus, the quality of water in the catchment area could be improved. However, infiltration of rainwater staying in the detention and retention zones might raise the hazard of groundwater pollution, particularly in areas where the groundwater level is shallow and the geological condition is sandy, and pollutants may not obtain the opportunity for degradation or adsorption to the soil particles in order to reach saturation status (Chahar et al., 2012). If manufacturing industries are located in such areas and can discharge pollutions with high concentrations of resolvable toxicants, this must be taken into account to conduct and treat the urban stormwater flows (Larson & Safferman, 2008). Groundwater contamination might be effectively controlled through reasonable low impact development practice.

Although infiltration trench system is found to be efficient at restoring groundwater and mitigating groundwater contaminant, clogging and potential shortcuts can influence the performance in infiltration trench, which are important disadvantages in

stormwater management (Bonneau et al., 2017; Conley et al., 2020; Lewellyn et al., 2015). Infiltration trench is a structural approach that fits available spaces where underground pipes transport runoff; however, porous materials in trench system might be plugged with sediment to reduce permeability greatly (Conley et al., 2020; Heilweil & Watt, 2011; Tirpak et al., 2021). Lack of inspections and maintenances for the system can also cause clogging problems (Larson & Safferman, 2008). Replacement of the trench area will be needed if pore spaces are filled with clogged aggregate. Clogging rate can also affect the life of the trench system, which is diverse results according to local stormwater and site conditions (Conley et al., 2020). The maintenance needs of metropolises should be better informed, which could improve the ability in managing urban stormwater. Moreover, the performance in infiltration trench might be unpredictable due to the potential shortcuts (Bonneau et al., 2017; McBean et al., 2019). Bonneau et al. (2017) have elucidated that urban infrastructures change groundwater pathways and recharge volumes. It has been further reported that stormwater pipes of the infiltration trench system affect the horizontal movement of groundwater through crack and fissures. Potential shortcuts of stormwater in urban areas might lessen the efficiency of rainwater penetration as a groundwater replenishing approach. Additionally, the contribution of groundwater flow can also be reshaped through gravel trench networks because the hydraulic conductivity in the infiltration trench is generally more than that of native soil (Bonneau et al., 2017).

3.3.5 Costs

Severe weather is one of the biggest contributors to the rising cost of urban infrastructure management and maintenance (McBean et al., 2019). If the local government considers cost minimization in stormwater practices construction in the case of planning improvements and environmental protection, the infiltration trench system is the prior option (Chahar et al., 2012; dos Santos et al., 2021; Petit-Boix et al., 2015). The design lifespan of the infiltration trench is about 15–40 years (Hua et al., 2020; Lee et al., 2020). The construction cost of 97–149 USD/m^2 is estimated for infiltration trench systems, which is higher than that of bioretention cell systems (Hua et al., 2020). Meanwhile, the construction cost is about 40% greater than the conventional drainage system in urban areas

(Simpson & Roesner, 2018). The annual maintenance cost is 4.54 USD/m^2 (Lee et al., 2020). The stormwater source control plan is applied during the runoff management. The quantity and quality of rainwater might lead to the implementation of various substitutions for stormwater management. Infiltration trench is comparatively easy to build in unexploited areas and developed sites, which is commonly utilized to conduct stormwater runoff in inhabited, commercial, parking and open areas (Chahar et al., 2012; Rowe et al., 2021). Therefore, they can be installed beneath the sidewalk and pedestrian street to save additional space, which could indirectly diminish the construction cost.

3.4 Permeable Pavement

3.4.1 Principles

Permeable pavement is a porous infrastructure interface to allow collecting and infiltrating surface runoff as well as recharge groundwater (Ahiablame et al., 2013; Brunetti et al., 2016; Huang et al., 2016; Kuang et al., 2011). Generally, the permeable pavement structure involves a concrete paver and a filter layer (Brunetti et al., 2016; Drake et al., 2013). This method is widely used to solve the problem of increasing urban storm runoff and decreasing environmental pollution around the world (Brunetti et al., 2016; Chopra et al., 2010). Moreover, permeable pavement can be regarded as a sustainable infrastructure material to granting the infiltration and evaporation of stormwater runoff while functioning as a solution to boost hydrologic restoration and contamination control (Ahiablame et al., 2013; Kuang et al., 2011; Sansalone et al., 2012). The conservation of natural water balance and flow pathways is an important aim of integrated urban rainwater management, which might alleviate or avert the disturbance of natural procedures that have been proved to lead to harmful water systems (Drake et al., 2013). Many developers and local governments have been attracted by the continuous permeable pavement, as they would like to seek solutions to make cities sustainable (Ahiablame et al., 2013). The complexity of stormwater design and management in the city is associated with environmental, economic and social impacts (Drake et al., 2013). Furthermore, the stormwater management technology locally governs as much rainwater as possible at the source to simulate

pre-development site conditions, which means the negative impacts associated with urban rainwater should be minimized such as groundwater quality degradation and recharge losses (Brunetti et al., 2016; Drake et al., 2013; Fassman & Blackbourn, 2010; Ma et al., 2021). Therefore, permeable pavement can likely improve the capacity of locally managed rainwater relying on underground storage while recharging the groundwater under the condition of environmental safety.

Permeable pavement has been applied in numerous experimental programmes such as the realization of parking lots and pedestrian pathways in low-traffic areas (Chopra et al., 2010; Drake et al., 2013; Li et al., 2019; Palla & Gnecco, 2015; Papakos et al., 2010; Qin et al., 2013). Meanwhile, the permeable pavement structure can also be acted as a load-bearing infrastructure with a relatively smooth surface for low-speed movement of vehicles (Kuang et al., 2011; Chopra et al., 2010). Moreover, permeable pavement is also used as a highway overlay that is called a pervious layer or an open gradation friction layer (Drake et al., 2013). It has been further reported that the porous characteristic is the main design goal to diminish the traffic noise instead of the infiltration of the native soil in the application. The porous pavement system is a key technology to realize the LID plan in different aspects including addressing conventional large design storm flows and environmental pollutions under varying conditions, which are gaining popularity and successful practice in many countries (Chopra et al., 2010; Drake et al., 2013; Fassman & Blackbourn, 2010). Nevertheless, this technology has not been more widely utilized in Canada and the USA (Drake et al., 2013). It is an unusual phenomenon considering the prospective benefits of the continuous permeable pavement. Drake et al. (2013) explain that one reason is lack of awareness of the long-run environmental influence of runoff infiltration, particularly on the variation of groundwater resources under cold weather circumstances. It has been further interpreted that developers and engineers are demotivated to apply the technology that is without testing in longevity, sustainability and maintenance cost aspects. Additionally, the feature of the porous pavement system is not only filtration but also commensurate clogging (Chopra et al., 2010; Sansalone et al., 2012; Scott et al., 2022). The proper installation and regular checking might ensure the effectiveness

of function in a porous pavement system (Fassman & Blackbourn, 2010; Kamali et al., 2017). Inorganic and organic materials that block the pores of pervious concrete generally cannot react with the basic components of pervious concrete because strong chemical bond or cementation i inexistence (Drake et al., 2013). These clogged materials can be extracted to restore the permeability of permeable pavement by vacuum sweeping and pressure washing (Chopra et al., 2010; Huang et al., 2016). Therefore, providing design guidance and limitations of the permeable pavement are necessary.

3.4.2 Design

Pervious pavement is a best management practice that countenances water to permeate and can be transported by material matrix or open voids (Chopra et al., 2010). The structure of the porous pavement system consists of a permeable paving surface and one or more subsurface gravel lavers, which is demonstrated in Fig. 4 (Fassman & Blackbourn, 2010; Huang et al., 2016). Surface paving materials of permeable pavement are identified ten types that are porous aggregate, porous turf, plastic geocells, open-joined paving blocks or permeable interlocking concrete pavers, open-celled paving grids, porous concrete, porous asphalt, soft paving materials and decks and epoxy-bonded porous materials; subsurface gravel lavers are the functions of aggregate reservoirs (Dietz, 2007; Drake et al., 2013). Other portions of permeable pavement system design could likely be geotextiles, small aggregate filter and choker courses (Barrett et al., 2006; Drake et al., 2013). Each type of permeable pavement has diverse requirements in function, environment, aesthetic and cost. The most popular materials in a commercial application are permeable interlock concrete paver, permeable concrete and porous asphalt (Drake et al., 2013). Permeable interlock concrete paver is filled with open-grade aggregate by modular unit separation joints; permeable concrete and porous asphalt can be regarded as permeable concrete variants or asphalt variants in which the binder covers aggregate particles without padding the gaps between the particles (Kevern et al., 2010). Different boundary components depending on the site conditions can be designed to achieve full or partial infiltration. The permeability design of the pavement layer should be higher than the rainfall

intensity to ensure all the stormwater can probably infiltrate through the paving surface (Qin et al., 2013). If the filtration function is not required, an underground drain consisting of perforated pipes is placed near the bottom of the aggregate reservoir to gather and transfer seepage to the drainage system, whether or not further treatment (Drake et al., 2013). Rainwater that has been collected through the porous permeable pavement system in the underground drains is called exfiltration (Bean et al., 2007). Some carparks of permeable pavement are considered for vault storage, allowing conducting outflow and interception of leaks (Drake et al., 2013). Meanwhile, since the water level must rise to the bottom of the inverted arch to allow rainwater to drain out through these pipes, lifting the bottom drain above the catchment floor inverted arch will increase the degree of local overflow (Barrett et al., 2006). Furthermore, the design of a permeable pavement system also relies on the local soil and climate. Some sites with soil contamination may not be suitable to apply the permeable pavement system as it could increase the risk of groundwater pollution (Dietz, 2007). Deicing salts used for winder road in northern climates might lead to environmental issues because chloride in particular is predicted to traverse the pavement layer to boost the chloride ion concentration in groundwater (Drake et al., 2013; Huang et al., 2016).

3.4.3 Performance

The performances of permeable pavement can be presented in two aspects that include hydraulic conductivity and longevity. Local climate and geological condition such as shallow groundwater could have an effect on the performance of the porous pavement system (Zhang et al., 2020a). Additionally, the design differences of the system can also influence the functions particularly in boundary components that are types of underdrainage. The hydrologic performance of the permeable pavement is associated with outflow volume, peak flow, timing and frequency (Damodaram & Zechman, 2013; Drake et al., 2013; Fassman & Blackbourn, 2010; Li et al., 2020; Zahmatkesh et al., 2015). The key points of hydraulic performance are runoff attenuation, surface infiltration capacity and peak reduction (Huang et al., 2016). However, the most important hydraulic property of the porous pavement system is hydraulic conductivity, which is also the function of the pore-structure (Kuang et al., 2011). Kuang et al. (2011) further state that the total porosity can decide the value of hydraulic conductivity and has been developed to assess the pore diameter distribution in the porous media. Furthermore, pore diameter distribution is one of the most significant features of pervious pavement, which defines the hydraulic, infiltration and contamination treatment properties of the system (Chopra et al., 2010; Fassman & Blackbourn, 2010; Huang et al., 2016; Kamali et al., 2017). Hydraulic conductivity property should be combined with runoff data and historical rainfall volume to determine the performance of the porous pavement system, which also demonstrates that the infiltration-based practice is more efficient for small and frequently occurring stormwater (Damodaram et al., 2010; Fassman & Blackbourn, 2010; Kuang et al., 2011). Additionally, the variables of permeable pavements and rainwater can be completed by the hydrologic and

Fig. 4 The design of permeable pavement (adapted from Eckark et al., 2017, Hager et al., 2019, and Drake et al., 2013)
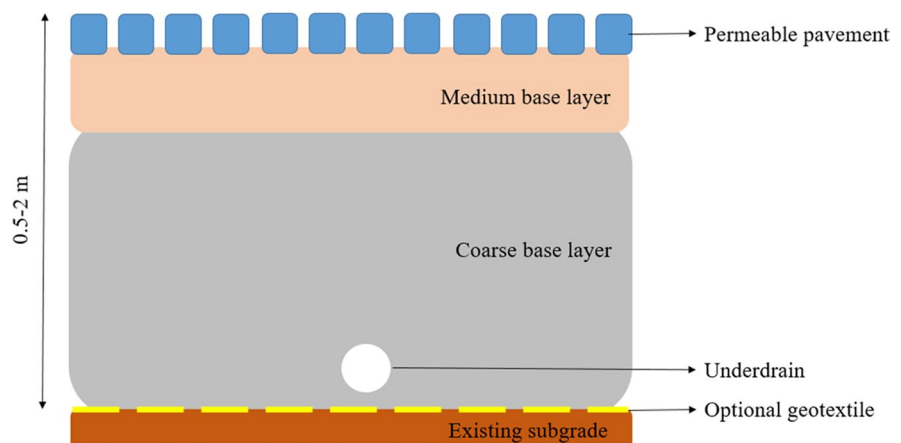
hydraulic simulation system (Damodaram & Zechman, 2013). Permeable pavement can also address the outflow that is treated by artificial sewage from the underdrain (Fassman & Blackbourn, 2010). Moreover, Fassman and Blackbourn (2010) further indicate that the performance of flow volume control under poor steep slope and subgrade soils situations should be acknowledged according to the ability to self-mitigate. Therefore, permeable pavement presents a better performance in mitigating urban waterlogging than rainwater harvesting in certain cases (Hu et al., 2017; Huang et al., 2016; Qin et al., 2013).

The longevity performance of the porous permeable system depends on the capability of the pavement to meet hydrology and water quality (Drake et al., 2013). Rutting and cracking might lead to structural failures, which will influence the permeability and pollutant removal capacity of the pavement. Finally, with the ageing of the pavement, it will not able to meet the essential hydrological and water quality requirements. Moreover, aesthetic and safety standards cannot be achieved for functional objectives. Clogging and maintenance are two major factors to affect the life span of the porous permeable system (Huang et al., 2016; Kamali et al., 2017). The filtration of fine particles could reduce the permeability of the pavement over time (Fassman & Blackbourn, 2010). However, the impact of clogging on permeability is invertible by regular maintenance (Drake et al., 2013). If the precipitation rates of stormwater are faster than the infiltrate rates, there will be water accumulation and surface runoff. Once the permeable pavement acts as an impermeable surface, the system loses its eco-friendly benefits containing peak flow reduction and the ability to remover rainwater contaminants. Therefore, it is important to maintain the surface and remove blockages before the hydrological and water quality performances of the pavement are significantly weakened. The effects of frost should also be considered during maintenance. The freeze–thaw cycle is the main reason for pavement damage in a cold climate (Roseen et al., 2012). The durability of the porous pavement system has been demonstrated and assessed by researchers (Drake et al., 2013; Huang et al., 2016). Roseen et al. (2012) claim that mixed designs and construction techniques can improve the longevity of the continuous permeable pavement. However, maintenance need is still necessary to enhance the day-to-day functionally to

avoid sediment and debris buildup (Chopra et al., 2010; Drake et al., 2013). The maintenance practice should address two functional objectives that are transportation and infiltration needs (Huang et al., 2016). Loss of hydraulic function due to lack of proper maintenance, it is widely believed that the porous pavement system has a short effective lifespan and cannot deliver reliable penetration (Drake et al., 2013). Therefore, performance failures due to unnecessary surface clogging might be understood as innate defects in permeable pavement products rather than as being related to inadequate maintenance.

3.4.4 Advantages and Disadvantages

The implementation of permeable pavement can lead to a reduction of storm runoff and contamination loads (Ahiablame et al., 2013; Chopra et al., 2010; Liu et al., 2015). Particularly in water quality in the environmental performance aspect, the porous pavement system has the potential ability to impact groundwater quality by treating stormwater (Drake et al., 2013). Pollutants enter the rain through a series of human activities and natural processes under dry weather. The suspended matter is deposited on sidewalks through vehicles and atmospheric deposition. Vehicle wear could leave heavy metal as trace and tire wear could also deposit hydrocarbons and polyaromatic hydrocarbons (PAHs) matters (Drake et al., 2013). Several pollutants such as total suspended solids, total nitrogen and heavy metals are captured by the filtration system through the paving surface and base filters (Alharbi et al., 2021; Huang et al., 2016). High nutrient levels in rainfall could lead to excessive eutrophication, which might result in a negative influence on the surface runoff system. Drake et al. (2013) indicate that the porous pavement system can provide appropriate conditions for hydrocarbons where they can be preserved on the paving surface or within the base filters for volatizing or degrading. A porous pavement system might dilute seasonal high contamination concentrations because it can change the timing, rate and flow of rainwater, but these outcomes have not been fully or rigorously assessed (Drake et al., 2013).

Clogging is the major disadvantage in the permeable pavement in terms of stormwater management (Fassman

& Blackbourn, 2010; Winston et al., 2016a). Compaction by traffic load is the main factor causing congestion, and pavements affected by higher traffic rate are more vulnerable to infiltration loss (Drake et al., 2013; Huang et al., 2016). Moreover, the open structure of the permeable pavement might slowly be clogged because of the continued entrapment of fine-graded soils and organic substances such as leaves and plant residue in the surface runoff (Chopra et al., 2010). The porous pavement system as a passive structure will gradually lose permeability and reduce the long-term performance due to clogging (Sansalone et al., 2008; Winston et al., 2016a). Consequently, some local authorities in the USA are reluctant to provide stormwater management subsidies for the construction of the permeable pavement (Chopra et al., 2010).

3.4.5 Costs

Cost information is necessary to increase the acceptability of the porous pavement system as a viable mainstream alternative to the conventional impervious pavement (Drake et al., 2013; Joksimovic & Alam, 2014; Peterson et al., 2021; Zeng et al., 2020). The empirical construction cost can be reached from 53 to 81 USD/m^2 (Hua et al., 2020; Wu et al., 2020). The annual maintenance cost in permeable pavement systems is about 0.91 USD/m^2 (Lee et al., 2020). Permeable pavement is the most cost-effective in reducing peak flow compared with bioretention and green roof (Chui et al., 2016). It has been further explained that one reason is porous pavements address the runoff from surrounding impermeable areas and the high permeability of pavements and reservoirs consents for continuous infiltration during heavy rains; another reason is a low cost of unit construction and operation management and its ultimate causes are relatively simple materials and operations, respectively. Moreover, permeable pavement as a dual system provides transport and stormwater management infrastructure. Drake et al. (2013) further report that cost comparisons must take into account the drainage infrastructure that has been substituted or diminished due to the penetration and storage provided by the porous pavement system. Additionally, the cost of permeable pavement does not vary with the area and depth but will be improved as design stormwater increases, which is similar to bioretention (Chui et al., 2016).

If monitoring and water scale management exist, the porous pavement system can likely produce the desired environmental results. Such a large study is needed to demonstrate the ability of the porous pavement system to achieve and sustain environmental benefits within large urban catchment areas. Thus, environmental benefits and costs are probably guaranteed to be maximized and minimized, respectively.

3.5 Rain Barrel or Cistern

3.5.1 Principles

Rain barrel is a container that collects water from urban rooftops during storm events to realize effective stormwater management and release the rainwater during dry periods for domestic water supplies (Blanco et al., 2009; Li et al., 2019; Papakos et al., 2010; Shuster et al., 2013; Walsh et al., 2014). Water is harvested and stored from rainwater harvesting systems, which can likely be utilized in residential applications in toilet flushing, drip irrigation and laundry washing (Ahiablame et al., 2013; Shuster et al., 2013). Rain barrel can also collect rainwater for non-potable applications such as landscaping, lawn sprinkling and recreational water (Liu et al., 2015; Papakos et al., 2010; Walsh et al., 2014). Rainwater includes water gathered from roofs. Stormwater runoff is from the mixture of driveway surfaces and road surfaces as well as roof surfaces. Rain barrel is conducive to the reduction of peak flow volume and water pollutions (Blanco et al., 2009; Liu et al., 2015). Rain barrel can be mostly placed in inconspicuous locations including the corner of the house backyards and parking areas (Papakos et al., 2010). Moreover, they can also be used for decorative designs. Rain barrel utilizes its unique capacity to supplement water demand by capturing stormwater, thereby decreasing water bills and providing rainwater for storage in areas with limited space, which can eventually enhance the capacity for water management (Blanco et al., 2009; Walsh et al., 2014).

The maintenance of the rain barrel system is minimal compared to that of an infrastructure-based water management facility (Shuster et al., 2013). Generally, maintenance activities of rain barrel are composed of storage tanks and gutters cleaning (Amin et al., 2013; Meera & Mansoor, 2006). Homeowners undertake

the onerous operation and maintenance, which is the significant factor to be considered during the residential rainwater harvesting program (Walsh et al., 2014). Due to the absence of a nationwide guiding principle on the design, installation and maintenance of the rain barrel or water quality principles related to this water resource, jurisdiction is usually controlled by local government health agencies (Farreny et al., 2011a; Shuster et al., 2013). Therefore, the maintenance of the rain barrel system might prevent them from accepting the system or lead to poor system performance for some homeowners. Moreover, Shuster et al. (2013) also report that many respondents mention maintenance issues in terms of the owner-user surveys. Additionally, regular roof cleaning is recommended in the rain barrel system. However, the report indicates that though the shortage of roof maintenance and cleanliness, water quality analysis results show the low pollutant loadings according to total suspended solids and total organic carbon (Farreny et al., 2011b).

3.5.2 Design

The most basic rain barrel setting includes a catchment surface such as a building roof, a rain gutter, a storage unit, a network of pipes connected to the catchment surface and the storage unit and a system for transferring overflow volumes (Shuster et al., 2013). The details of the rain barrel system are shown in Fig. 5. A filter system or first flush device might be included in some rain barrel systems, which is usually incorporated into the system to improve the quality of the collected water (De Kwaadsteniet et al., 2013; Hager et al., 2019; Mendez et al., 2011). It has been further reported that the first flush device is applied to transfer the initial runoff volume from the catchment surface to flush out the contaminants that have accumulated since the last available rainfall. The water quality is significantly increased through averting the first 38 L for 93 m^2 of watershed areas using the first flush device (Mendez et al., 2011). The quality of rainwater collected from pilot residential equipment in Ireland complies with local bathing water regulations even using the basic filters (O'Hogain et al., 2011). The size and shape of storage are varying according to different requirements. The most common residential water storage units include polyethylene barrels that are no greater than 300 L (Hager et al., 2019; Shuster et al., 2013). Domestic rainwater is stored in storage tanks, which can be built above or under the ground (Mwenge et al., 2007). Storage tanks usually consist of bricks, rammed earth, plastic sheets, stabilized soil and mortar jars to store small amounts of water; main materials in rain barrel system are used such as earthenware, polyethylene, concrete and iron to collect large quantities of water (De Kwaadsteniet et al., 2013).

3.5.3 Performance

Installation of the rain barrel is a good solution to reduce runoff volume and improve water quality in residential areas (Hager et al., 2019; Li et al., 2019; Liu et al., 2015). Moreover, rain cisterns can be used in commercial or industrial areas (Liu et al., 2015). Rain barrel has the unique ability to supplement water demand by capturing runoff, thereby providing rainwater for storage in areas with limited space (Walsh et al., 2014). Several barrels can be joined

Fig. 5 The design of rain barrel (adapted from Hager et al., 2019)
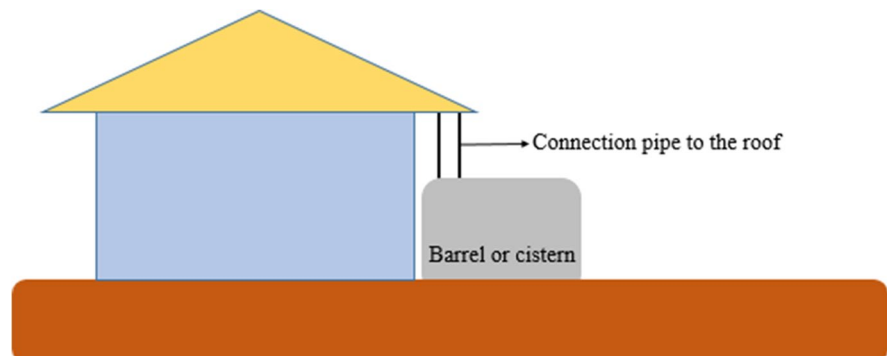
together to improve the storage capacity for infiltration and irrigation (Shuster et al., 2013). The primary performance of a larger rain barrel is to capture smaller and larger storms events for a longer period of using (Walsh et al., 2014). Additionally, the drainage time of the rain barrel system is also important because microorganism might grow with storage times increasing. Walsh et al. (2014) indicate that the enhancement of drainage duration could restrict the ability to obtain the subsequent runoff in the rain barrel system.

The quality of the harvested rainwater depends on roof slope, storage system material, land use practices and weather patterns (Farreny et al., 2011b; Gwenzi et al., 2015; Lee et al., 2012; Morales-Pinzón et al., 2015; Zhang et al., 2014). Roof materials play an important role in the quality of the collected water. Traditional roof materials consist of concrete tiles, metal and asphalt fibreglass shingles and alternative roofing materials include green roofs (Meera & Mansoor, 2006; Mendez et al., 2011). Rainwater collected from the roofing surface needs to be flushed, filtered and disinfected at least one time, which can ensure the water quality (Mendez et al., 2011). The water chemistry of rain barrel is slightly acidic, turbidity, and showing a wide range of conductivity (Shuster et al., 2013). Researchers find the relationship between the water quality and the selected variables such as pipe material and roof material (Morales-Pinzón et al., 2015). They find that the selected variables cannot affect the water applications in a non-potable aspect. The performance of the sloped smooth roofs in water quantity and quality is better than that of the rough flat roofs (Farreny et al., 2011b). The water of the rain barrel system is usually discharged in winter because of the freezing damage to the system (Hager et al., 2019; Shuster et al., 2013). Moreover, residential rain barrels are applicable for low contact using such as plant watering (Shuster et al., 2013).

3.5.4 Advantages and Disadvantages

The rain barrel system has many significant advantages that are low installation and maintenance costs, decreased burden on utility water supply, untreated water for non-potable purposes and lower water bills (Farreny et al., 2011a; Morales-Pinzón et al., 2015; Rahman et al., 2014). The application of collected water is useful during the sustainable housing analysis.

The major disadvantages of the rainwater collection system are storage constraints and water quality risks (De Kwaadsteniet et al., 2013; Ishaq et al., 2020). Most applications in rain barrel system are located in residential areas due to storage constraints (Walsh et al., 2014). A rainwater collection barrel can also be used as a breeding space for mosquitoes (De Kwaadsteniet et al., 2013). Mosquitoes are a vector of various diseases including malaria. De Kwaadsteniet et al. (2013) further claim that water-borne disease particularly tends to infect people who are elderly, young and compromised immune systems. Regional climatic conditions could also have an impact on the water flow dynamics of rain barrel systems (Hager et al., 2019).

3.5.5 Costs

Rain barrel system can be expected to deliver the most cost-effective option for the catchment in a residential area (Walsh et al., 2014). The most important considerations in deciding whether to instal the rain barrel system are financial costs and benefits, with issues of public acceptability and water quality taking the back seat (Tam et al., 2010). The construction cost of the rain barrel system is about 1.91 USD/m^2 (Li et al., 2021). The report further indicates that the maintenance cost is 1% of its construction cost. Therefore, it is predominantly significant to decide the economic viability of the rain barrel system. The small capital cost and the expected reduction in water runoff can promote the development of the rain barrel system (Farreny et al., 2011a). Collected rainwater can provide sufficient amounts of water at a small cost in residential buildings in many countries (Rahman et al., 2014). The system can also reduce the water bill, which can lower the cost of living for people (Hager et al., 2019). Furthermore, the result of the study suggests that the rain barrel system is best installed at the community level as it can realize economies of scale and should be implemented at the time of settlement construction (Walsh et al., 2014).

3.6 Rooftop Disconnection

3.6.1 Principles

Rooftop disconnection features roof downspouts that can drain into permeable landscape areas and vegetated surfaces rather than directly into rain pipes

(Sarminingsih et al., 2019). Vegetated surfaces include grass lawns and rain gardens (Hager et al., 2019). Moreover, it can also simulate a roof drain that is directly connected and overflows to the permeable area (Walsh et al., 2014). Rooftop disconnection can be applied in the residential roof so that the rainwater might be along the channels to water catchment areas.

3.6.2 Design

The rooftop disconnection system consists of roof surface and downspouts (Sarminingsih et al., 2019). The roof area is usually treated as an impermeable surface whose runoff is straight linked to the outlet of the subcatchments. Runoff flows through the infiltration area of the subcatchment area, where it has the occasion to seep down into the soil. Fig. 6 demonstrates a typical layout of a simulated rooftop disconnection. Runoff of the roof surface is gathered in the side gullies, downpipes and channel systems of the guide pipes.

3.6.3 Performance

Rooftop disconnection is one type of LID practices that can decrease runoff and pollution significantly (Sarminingsih et al., 2019; Walsh et al., 2014). There is a distance between drainage pipes and roof rainwater. Sarminingsih et al. (2019) report that rooftop disconnection is applicable for all lands, especially housing. The collected water can be directed to the pervious surface, which can be presented as the routing of residential rooftop runoff to lawns. The aim

of stormwater management is to minimize flooding. With respect to existing infrastructures, rooftop disconnection as a passive drainage-based practice might be helpful to realize the stormwater management goal in long-term loads (Walsh et al., 2014). Moreover, contaminations from the housing roof could also be piped into the catchment area.

3.6.4 Advantages and Disadvantages

There is not enough research literature on rooftop disconnection at present. One advantage of rooftop disconnection is easy to instal in the residential zones (Hager et al., 2019; Sarminingsih et al., 2019). Moreover, roof disconnection can accomplish stormwater management aims such as increased infiltration, mitigation of sewer overflow and reduced runoff (Hager et al., 2019). The scale and range of rooftop disconnection application are not sufficient so that the effectiveness of runoff reduction is inconspicuous in the urban area (Walsh et al., 2014).

3.6.5 Costs

The cost-effectiveness of rooftop disconnection will influence the development of the system. It is widely believed that simple operation and maintenance can efficaciously reduce the cost of rooftop disconnection practice (Hager et al., 2019; Walsh et al., 2014). It has been further indicated that a greater reduction in total runoff volume with cost-effectiveness growth under wet years is found due to the rooftop disconnection system from the annual analysis.

Fig. 6 The design of rooftop disconnection (adapted from Hager et al., 2019)
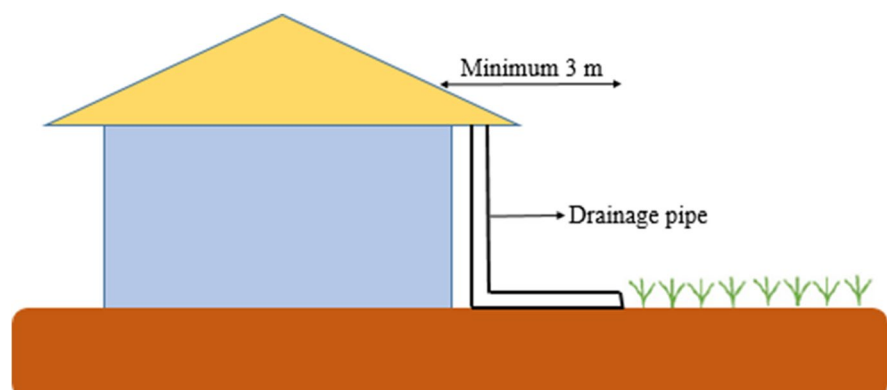
3.7 Vegetative Swale

3.7.1 Principles

Vegetative swale is also called bioswale, which is the linear depression that displays as a drainage channel with sloping sides to capture, transportation and filter stormwater runoff (Hager et al., 2019; Jamil & Davis, 2009). Vegetative swale as a stormwater management method is a popular strategy in urban village, park, green land, industrial land and roads (Wu et al., 2020). Moreover, it is also one of the most basic and simple construction LID practice to substitute conventional curbs and gutters drainage systems (Lucke et al., 2014). Vegetative swale is a landscape surface trench with dual runoff control function in the drainage system, which means it not only reduces the peak rainfall-runoff by storing, but also eliminates total suspended solids from rainfall-runoff (dos Santos et al., 2019; Jeon et al., 2017; Peng et al., 2019). Total suspended solids are common high concentration pollutants in urban runoff (Jamil & Davis, 2009; Peng et al., 2019). Furthermore, the discharge of total suspended solid is significant because the turbidity of water will be growth when the concentration of total suspended solid is increasing. Increased turbidity prevents sunlight from penetrating into the water, which can influence the photosynthesis of plants. Accordingly, the cleaning removal efficiency of surface accumulation pollutants in vegetative swale can have an impact on the total suspended solids load of runoff (Peng et al., 2019). A vegetative swale can be used in linear applications with complex stormwater management impediment (Hager et al., 2019; Jamil & Davis, 2009). Additionally, a vegetative swale can also be installed near the roadways, parking, sidewalks, irrigated urban landscapes and bridge decks to diminish the contamination load during transportation (Leroy et al., 2016; Winston et al., 2010). Sustainable drainage systems such as localized vegetated system have usually emerged for conducting urban stormwater near the source (Fletcher et al., 2015). These methods can be conducive to reinstate the hydrologic balance of the area before development, improve the water environment and enhance the biodiversity and urban landscape (Flanagan et al., 2018). Meanwhile, the reduction of the stormwater processes can be achieved by boosting the evapotranspiration and infiltration as these approaches are similar to the natural state (Luan et al., 2017). Rainwater contamination in medium-traffic areas is minimal, and the application of vegetative swale seems justified in conducting runoff through infiltration and evapotranspiration without polluting disproportionately groundwater and soil (Leroy et al., 2016).

3.7.2 Design

Vegetative swale is designed as a LID practice without perforated pipes at the base, which is shown in Fig. 7. The effluent seepage cannot be transported through the drainage pipe. Nevertheless, if the amount of rainfall is high enough, the runoff discharge will still appear in the vegetative area (Peng et al., 2019; Yun et al., 2020). Generally, a vegetative swale is not utilized to decrease stormwater runoff volume, but rather as a method of concurrently improving water quality and decrease flow velocity (Jamil & Davis, 2009; Lucke et al., 2014). One of the best design for vegetative swale is adding a freeboard depth, which can increase the design depth to manage stormwater (Hager et al., 2019). The increased design depth can enlarge the area of vegetative cover. Vegetation in vegetative swale practice plays a major role in the removal of contaminations, mainly including absorption of nutrient pollutants by plants, physical filtration of vegetation, increased sedimentation and bio-chemical interactions with soil (Jamil & Davis, 2009; Lucke et al., 2014; Tang et al., 2016a; Winston et al., 2012).

3.7.3 Performance

The vegetative swale system is designed to slow flow velocity and to ensure predominantly particulate contaminations are removed efficiently and thereby improving water quality during stormwater events (Leroy et al., 2016; Lucke et al., 2014). Pollutant removals by vegetative swale are considered as the main goals on site. These processes are highly dependent on swale length and width, slope, grass type and density, soil type, runoff quality and swale design (Jamil & Davis, 2009). It has been further reported that the vegetative swale can be treated as the primary stormwater treatment facility, which can transport rainwater to secondary treatment facilities such as reservoirs and wetlands. Information on improving water quality at vegetative swale is limited

and inconsistent due to the complexity of swale operation (Lucke et al., 2014). Normally, vegetative swale demonstrates significant reductions in large particulate pollutants level, but in severe storms, the settling particles might be suspended again (Hager et al., 2019; Jamil & Davis, 2009). Leroy et al. (2016) indicate that vegetative swale has demonstrated excellent performance to reduce total suspended solids in the effluent with clearance rates of between 44 and 98%. Additionally, the concentration of nutrients such as nitrogen or phosphorus might be floating because the organic substance in swales is itself a source of nutrients that can move in the flowing water (Hager et al., 2019; Stagge et al., 2012). The improvement of the water quality is mixed results that are composed of the low pollution of runoff water and infiltration through vegetative swale. In the system with a soil depth of more than 30 cm, the passage of water results in the movement of the finest soil particles, which is driven by the permeable water (Leroy et al., 2016). Meanwhile, Leroy et al. (2016) further explain that since these particles are adsorbents for lipophile organic contaminations such as PAHs or trace elements with low solubility such as lead. Additionally, further migration of these pollutants with high molecular weight cannot be ignored in stormwater management. Therefore, the deep root system of the plant should be preferred to limit the particles transfer.

3.7.4 Advantages and Disadvantages

Concentration reduction of total suspended solids is the main advantage for vegetative swale for most storm events (Flanagan et al., 2018; Hager et al., 2019; Leroy et al., 2016). Moreover, a vegetative swale can also reduce runoff velocities (Hager et al., 2019). Although vegetative swale is effective in management storm runoff in plain areas, it is not applicable in mountains areas because of the application range limitation and fast flooding of mountain floods (Luan et al., 2017). Furthermore, poor performance in particulate removal is observed during the cold climate (Flanagan et al., 2018). The control effect of the vegetative swale on surface runoff will gradually weaken. With the increase of precipitation, the growth of surface runoff is much greater than the detention storage capacity of the vegetative swale, which could cause water to spill over into runoff (Peng et al., 2019).

3.7.5 Costs

The study of cost-effective has a positive impact on the development of vegetative swale. The design and maintenance requirements in vegetative swale are basic, which will lessen the cost of the system (Lucke et al., 2014). The construction cost of vegetative swales system is about 0.20 USD/m^2 (Li et al., 2021). The report further states that the maintenance cost is 6% of its construction cost, which is still lower than the rain barrel system. Therefore, the cost-effectiveness of vegetative swale is better than other traditional curbs and gutters systems (Hager et al., 2019).

4 Challenges for Implementation

The basic awareness of LID practices and the limitations of traditional stormwater management systems should be recognized. Part of local government staff and engineering companies has noticed the benefits of LID practices. However, most professionals and officials have only a limited understanding of LID methods (Earles et al., 2009; Shafique & Kim, 2017; Wulkan, 2008). Although some of rainwater management projects have already been designed to use these technologies, different LID practices are usually not integrated into the early design process (Ahiablame et al., 2012; Son et al., 2017). Meanwhile, different government departments have no consensus about LID schemes

Fig. 7 The design of vegetative swale (adapted from Hager et al., 2019)
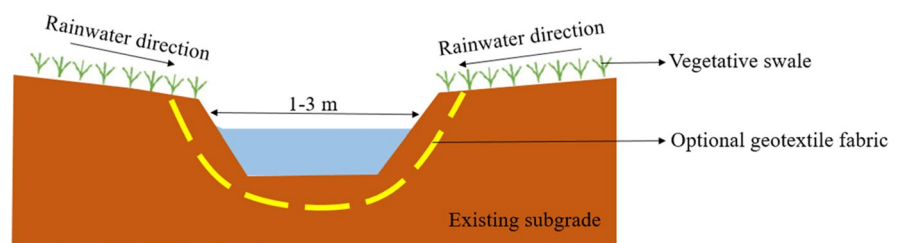
(Son et al., 2017). The process of the stormwater management plan should not only consider the land using planning, but also the environmental improvement of urban areas such as water contamination management and urban landscape. Additionally, local regulatory and policy barriers might also retard the implementation of the project (Shaver & Puddephatt, 2008; Wulkan, 2008).

The knowledge of LID techniques including proper design, construction and maintenance need to be further improved. Many professionals lack technical guidance because specialized training courses are limited (Doberstein et al., 2010; Earles et al., 2009; Fisher-Jeffes et al., 2016). Technical specifications according to local geologic and meteorological situations are mostly absent (Shafique & Kim, 2017; Sprouse et al., 2020; Taylor et al., 2011; Wulkan, 2008). LID technical guidance manual should provide a common understanding of objectives and principles for all participants, which can be acceptable all around the world (Earles et al., 2018). In addition, it is likely that some LID practices as implemented in countries which have cold climates may not be quite effective in Asian countries due to the different climate conditions. According to Shafique et al. (2018), swales can be implemented in Asian countries such as South Korea and China, but the challenge is to design an effective swale system for sustainable stormwater management. The suitable construction places for LID practices are also difficult to find, which can be a challenge in the urban regions with existing complex infrastructure (Dhakal & Chevalier, 2015; Schuster, 2010; Shafique & Kim, 2017). The maintenance of these practices is difficult and the related cost is high (Akther et al., 2018; Houle et al., 2013; Sanicola et al., 2018; Shafique & Kim, 2017). Although LID activities are more predictable than traditional systems, the size and location of LID maintenance need new standards and different equipment during the implementation (Houle et al., 2013). Moreover, the assumption of additional liability by the design engineering could be another challenge during the system design (Schuster, 2010). The engineer might undertake the additional risk for the implementation of LID practices.

The financial issue can restrict the development of LID practices. These innovative technologies require more time to be approved, which depends on how receptive local government officials are to innovative approaches (Fisher-Jeffes et al., 2016). If they are not acceptable, the reviewer will either not allow to modify them or need a large amount of research to prove their equivalence with the current regulations (Schuster, 2010). The loan incidental cost of developers will be increased because of a longer review period. Inexperienced consultants and contractors could require more time to design and construct for the new technology, respectively (Doberstein et al., 2010). They will charge more for their services, which can raise the cost of implementation to limit the development of innovative technologies (Earles et al., 2009; Roy et al., 2008).

5 Opportunities for Further Developments

Although LID practices have made great progress in understanding the mechanism of these systems, there are still many opportunities for further developments. The sustainability of the stormwater management system can likely be accomplished if all the physical and socioeconomic attributes are considered during the design process. Characterization of stormwater runoff quantity and weather patterns from different urban land need using requires further investigation. Data on the transportation of nutrients and system material selection should be continually collected, which could have an impact on the water quality over diverse spatial and temporal scales and climatic circumstances. The assessment of LID practices is associated with extensive parameters. Therefore, it is necessary to study evaluated performance metrics and modelling techniques. A user-friendly model is conducive to assist participants to select proper one type of LID practices or different types of combinations. Furthermore, consideration of the improvement of LID specifications and standards promotes the design and implementation of these innovative technologies in a wider area.

6 Recommendations for Future Directions

Water shortages might be the most concerned problem in the world. The application of rainwater might

address this issue in a sustainable manner. However, there are still many deficiencies that need to be improved in LID practices. There is a need to comprehend the basic functions of each practice. The best combination of LID practices can be selected to apply them at the appropriate regions to achieve multiple goals. Stormwater management is a dynamic process. The effectiveness of LID practices depends on many parameters such as stormwater runoff quantity, soil conditions, weather patterns, seasonality, operation, maintenance and cost. The key parameter should be determined in each LID practice system, which can effectively conduct these variations in performance. Table 3 presents the performance of the reduction of pollutant loading from different LID practices. Further research could be presented on a larger study range that includes the residential, commercial, agricultural and industrial sector. The comparison could be made with different stormwater management systems based on energy saving and water conservation. The energy consumption of rainwater system should be analysed to help determine the best sustainable scheme with the increasing population and water demand. The general manual should involve all standards and methods of LID practices such as construction, management and maintenance, which can be suitable all around the world. The information of successful application in LID practices can also be shared with the rest of the world. Moreover, a cost-effective analysis in different climate regions should be performed to provide the economic viability assessment of the rainwater management system. The comprehensive research for the influence of human health risk and ecological aspects should minutely be explained for the proper development of the LID practice system.

7 Conclusions

Recent academic literatures associated with LID are reviewed in this article. LID practices such as bioretention cell, green roof, infiltration trench, continuous permeable pavement, rain barrel, rooftop disconnection and vegetative swale have been comprehensively elucidated. These practices can be innovation techniques to manage stormwater in order to address the effect of urbanization and climate change in urban areas. A critical review of LID practices shows green infrastructure is an effective method to improve stormwater management benefits. Moreover, the amount of the benefit depends on various factors such as system operation and maintenance. This means that information about LID stormwater control performance is required under specific environmental conditions. LID practices can reduce runoff and peak flow. Additionally, the water quality can also be improved by physical and biological approaches. There are many challenges during the LID implementation such as construction cost. For larger events, LID practices should be combined with traditional stormwater management practices such as reservoirs to achieve the best results. Overall, LID practices are becoming popular in many cities and will continue to play an important role in future stormwater management.

Table 3 The reduction of pollutant loading from LID practices

References	LID practices	Study region	TSS	TN	TP
Johnson and Hunt (2019)	Bioretention cell	North Carolina, USA	-	72.0%	79.0%
Kim et al. (2017)	Green roof	Scotland, UK	99.0%	82.7%	52.3%
Trenouth and Vander Linden (2018)	Infiltration trench	Southern Ontario, Canada	97.0%	98.0%	95.0%
Ahiablame et al. (2013)	Permeable pavement	Indianapolis, USA	-	12.0%	11.0%
Shuster et al. (2013)	Rain barrel or cistern	Brisbane, Australia	-	10.0%	-
Walsh et al. (2014)	Rooftop disconnection	San Diego, USA	-	12.7%	13.1%
Nazari-Sharabian et al. (2019)	Vegetative swale	West Azerbaijan, Iran	17.0%	8.0%	17.0%

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