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Chapter 23

Sustainable urban drainage systems

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ABSTRACT

Changes in the hydrological processes within watersheds due to rapid urbanization along with climate change have been causing frequent pluvial floods in urban areas. Conventional stormwater drainage systems are unable to cope up with the situation. Therefore, latest practices rely on 'source control techniques', 'permeable conveyance systems' and 'end of pipe systems' for storm water management in urban areas. These measures are variously known as sustainable drainage systems in the United Kingdom, low impact development (LID) techniques in the US, water-sensitive urban designs in Australia, and sponge city approaches in China. In this chapter, we review various LID measures, status of their practice, and implementation challenges faced in India. We also outline further research needs in this area.

Keywords: sustainable urban drainage systems, LID measures, LID modelling, basin-scale LID

23.1 INTRODUCTION

Population growth and changing lifestyles of humankind have paved the way for urbanization. In India, it is estimated that 14.4% of the total area classified as 'statutory town' in the census accounts for 26.3% of the population and is built up in nature. The impact of urbanization on the hydrologic behaviour of catchments has been well-documented in the literature related to the field. Changes in the hydrological processes within watersheds, along with uncertain precipitation patterns due to climate change, have caused urban pluvial floods. Urban areas, being regions of social and economic importance, need to be made more resilient to frequently occurring urban flash floods.

The conventional approach for storm water management focuses on transporting the storm water away from the site in the shortest possible time. This approach not only deprives the catchment from its natural processes such as infiltration, evaporation, and transpiration, but also causes floods

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during precipitation events in which storm sewer design capacities are exceeded. On the other hand, the sustainable approach for water management, known as sustainable drainage systems (SuDS), relies on 'source control techniques' to reduce the generation of runoff from source sites, 'permeable conveyance systems', which reduce the velocity of runoff water to facilitate settlement filtration as well as infiltration, and 'end of pipe systems' to provide passive treatment to collected storm water. The measures adopted for sustainable storm water management are variously known as SuDS in the United Kingdom, low impact development (LID) in the United States of America, water-sensitive urban designs (WSUD) in Australia, and sponge city approaches in China. In this chapter, we use the terms SuDs, LID, and WSUD interchangeably.

In this chapter, we review the current measures available for sustainable urban drainage in India and other countries in the Global South, status of its practice, challenges that are being faced for its implementation, and further research needs in this area.

23.2 LID MEASURES

23.2.1 Green roofs

Green roofs are typically constructed by partially or completely filling the rooftops with soil media that can support plant growth. This soil media, along with vegetation growth, can help reduce the runoff generated from rooftops. Many studies have estimated the effectiveness of LIDs in regulating runoff generation. Experiments have shown that when providing a 200 mm depth for green roofs, runoff can be reduced between 42.8% and 60.8% (Lee *et al.*, 2015). However, the runoff reduction potential of LIDs decreases as the depth of soil media decreases. Other factors that determine the potential of green roofs in reducing runoff include: the type and depth of soil media used, hydraulic parameters of the soil media, type of vegetation grown on the surface, the area occupied by the LID and so on.

In urban areas with limited open space availability, green roofs can be an effective sustainable alternative to reduce runoff and also to mitigate urban heat island effects. However, in arid regions, green roofs may not be viable because maintaining plant growth during water scarcity months may add extra water stress.

23.2.2 Permeable pavements

Permeable pavements are designed with a pervious pavement layer to enhance infiltration and facilitate temporary rainwater storage in the bottom layers consisting of coarse grains. Permeable pavements such as porous concrete and interlocking pavements can reduce peak runoff and increase the time to peak when compared to conventional pavements. These pavements can be laid in lawns and parking spaces in residential as well as non-residential building areas, and also along sidewalks. They have to be designed by considering the climate, moisture conditions, and rainfall characteristics of the region. Permeable pavements in cold regions may have their performance impeded by sediments or frost compared to those in semi-arid or arid regions. The thickness of various pavement layers, porosity, and size distribution of particles can also affect how these structures respond to various rainfall events.

In cities where open space availability is a constraint for implementing other LID measures, retrofitting permeable pavements in the existing impermeable surfaces can help tackle floods to some extent.

23.2.3 Swales and infiltration trenches

Grass-lined conveyance structures that facilitate storage and infiltration of storm water runoff, along with pollution capture, are referred to as swales. Swales can aid in reducing the runoff by allowing infiltration (between 9% and 100%) and can also provide passive treatment to the runoff before disposing it into storm sewer networks (Ahiablame *et al.*, 2012; Yousef *et al.*, 1987). Swales reduce the runoff velocity and thus cause an increase in the time to peak. Factors contributing to the performance of swales include: (a) slope of the conveyance structure; (b) nature of the vegetation grown on it; (c) permeability of the native soil layer; (d) groundwater levels at the site, and (e) provisions for underdrain pipes. Swales can contribute to improving the resilience towards pluvial floods, provided they are effectively designed and placed. Infiltration trenches bear resemblance to swales. They are channels with stones and gravels filled in the ground excavations carried out in a linear pattern. The functionality of trenches differs from swales. Infiltration trenches are implemented to facilitate infiltration and storage of water, rather than to convey the runoff.

23.2.4 Retention ponds and detention basins

Lakes and ponds that exist naturally in the watersheds are classic examples of regional-level LIDs that can aid in runoff regulation. These water bodies have multiple ecosystem functions, and they also act as an additional source of water. However, urban expansion and encroachments have caused a decline in the number of these natural water bodies. Retention ponds try to emulate the runoff regulation functionalities of natural ponds by allowing the retention of the runoff during flooding events. Detention basins, on the contrary, are designed to detain water during floods. The water from the basins will be eventually released through regulated outflow structures. These structures can be adopted as a part of regional-level LID control measures and have been found effective in regulating volume and peak of runoff, especially for storm events of smaller return periods.

23.2.5 Recharge shafts

Exploitation of groundwater levels due to increased demand is a major concern in densely populated regions. Recharge shafts can be implemented in these areas to enhance groundwater recharge to the aquifers. The low space requirements of recharge shafts make them suitable for regions with space constraints. A study conducted in the city of Aurangabad, India, showed that by implementing sufficient number of recharge shafts, the water availability in the region could be significantly increased (Aher *et al.*, 2015). In most of the LID measures discussed earlier, there is a loss of water through evapotranspiration. Hence, there is reduction in the quantity of water available for infiltration and groundwater recharge. However, in the case of recharge shafts, the water loss is minimal as they are constructed deep into the ground. A detailed study on the soil layer stratification, aquifer material, and thickness is required prior to the implementation of recharge shafts.

23.2.6 Bio-retention cells

Bio-retention cells are constructed by replacing the natural soil to certain depths with a porous soil medium that has relatively higher hydraulic conductivity and can support plant growth. The potential of bio-retention cells in reducing runoff increases as the extent of their implantation increases. With higher LID implementation ratios, bio-retention cells can contribute substantially to runoff reduction and augmentation of groundwater levels (Zhang & Chui, 2020). Where the native soil layer has low conductivity, bio-retention cells can be provided with underdrain pipes which would take the flow to storm water networks during high-intensity storm events.

23.2.7 Rain barrels

Rain barrels are similar to conventional rainwater harvesting structures used for capturing water from a roof within the premises of a house. The water held in rain barrels can be used for several non-potable purposes by households. Additionally, capturing rainwater from rooftops reduces the flow in downstream storm water drains, thus reducing the necessary capacity. Rainwater harvesting has been made mandatory in many cities in India, such as Chennai, for tackling water scarcity problems. It is to be noted that rain barrels help in reducing peak flows during storms.

23.3 CURRENT STATUS OF LID PRACTICE

23.3.1 Global North

Urban water management transition framework (Figure 23.1) suggested by Brown *et al.* (2008) indicates that cities evolve in the order: water supply city – sewered city – drained city – waterways city – water cycle city – water-sensitive city, as they attempt to cope with water supply access and security; public health protection; flood protection; environmental protection; constraints on natural sources; intergenerational equity, and resilience to climate change. Figure 23.1 indicates why historically the basic ideas for SuDS originated in the Global North.

Seeds for LID measures were sown in the USA in the 1970s. The first implementation of LID in the USA dates back to its practice in Maryland in 1999. Radcliffe (2019) provides a comprehensive history of LID adoption worldwide. Currently, many cities worldwide, especially in the Global North, have already implemented LID measures. LID practices have recently been adopted by Kansas City, Missouri, Philadelphia, Pennsylvania and New York as primary measures to address the problems caused by old combined sewer systems (Weiss *et al.*, 2019).

From 2014 to 2016, 30 cities including Beijing and Shanghai, were designated as sponge cities in China. China follows a top-down approach for implementing the sponge city program which is expected to control 85% of annual runoff in Beijing through sponge city implementation. Lashford *et al.* (2019) provide an in-depth comparison of the practice of SuDS in the UK with the sponge cities program in China.

In the European Union, the Water Framework Directive requires member states to manage their water resources sustainably. Thishas encouraged the adoption of SuDS and other sustainable water management practices in the continent. Hence, many cities across Europe have implemented SuDS and WSUD in recent years, demonstrating the potential for these approaches to be successful in a variety of contexts.

In the UK, the implementation of SuDS was initiated in 1980 and it has led to a wide range of local, regional and national guidelines, and legislation mandating the incorporation of SuDS into new development plans wherever possible. Schedule 3 of the Flood and Water Management Act (FWMA) was introduced in 2010 for regulation of new development and compliance with the Act.

In Australia, the ACT (Australian Capital Territory) Government introduced the Water-Sensitive Urban Design General Code with a review in 2014 and substantial revisions supported by Practice Guidelines in 2019. The General Code is designed to embrace the SuDS principles by encouraging the reduced use of mains water, improving water quality, and managing stormwater flows in urban areas. There have been more than 300 sites where WSUD projects were implemented in South Australia alone until 2016 (Sharma *et al.*, 2016).

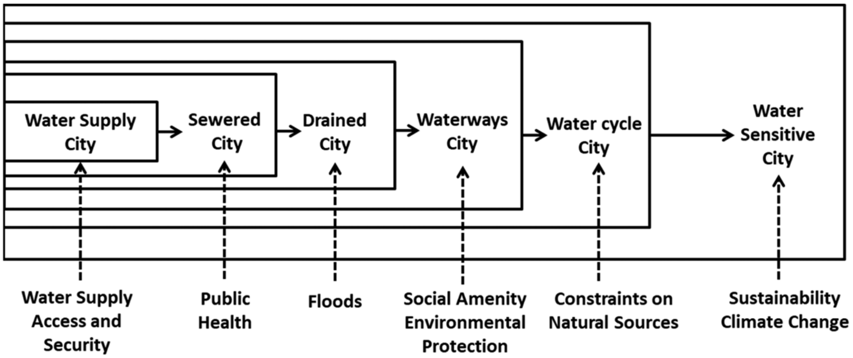

Figure 23.1 Urban water management transition framework. (*Source*: Brown *et al.*, 2008).

23.3.2 Global South

The implementation of LID measures in Global South cities has only recently started. In the Brazilian context, the city of Porto Alegre, in the south of the country, was a pioneer in using low-impact LID-type systems in its Urban Drainage Master Plan prepared in 2003. In 2006, the federal Ministry of Cities proposed national regulation through the Sustainable Urban Drainage Program, encouraging municipalities to use LID techniques in their macro-drainage plans. However, the regulation was not mandatory, and the initiative was not successful in increasing the implementation of LID or equivalent systems. The practices of accelerating the flow through channelling in reinforced concrete remained the main principle applied in urban drainage in the 21st century.

The failure of the 2006 national regulation to introduce LID systems on a large scale in Brazil can be attributed to the lack of managerial capacity to bring together different fields of public management needed for their implementation. Integrated action by municipal departments in São Paulo faced several difficulties including legal instruments, implementation of sanitation actions (clean stream program), creation of a linear parks system along the rivers ('100 Parks in São Paulo' program), and removal and allocation of informal poor settlements in areas at risk of flooding and landslides (Municipal Housing Plan). This sort of problem is absent in wealthy Global North cities but occurs frequently in Global South cities. Besides, the Master Plan of São Paulo underwent a major revision in 2014, which may actually aggravate the risks of flooding. The application of nature based solutions (NBS) and SuDS depends on the existence of areas that are open or likely to be expropriated for their implementation. The analysis of the master plans reveals relevant limits for overcoming the grey infrastructure paradigm. Nevertheless, from 2000 onwards, greater use of large retention ponds can be observed in major cities of Brazil, distributed in a network planned throughout the catchment areas. Initially, multiple uses of these ponds were sought, divided into compartments according to the time of recurrence of the design rains. Leisure and sports squares would occupy the ponds during the dry period, being cleaned after the floods, and returned for community use. However, untreated sewage released into most water bodies made these urban integration spaces unhealthy, which triggered public resistance to having such devices nearby.

In contrast, in South Africa, another major country in the Global South, guidelines for LIDs were formulated almost a decade ago in 2013. Gajjar *et al.* (2021) report on the best management practices, based on environment-based adaptation (EbA) and NBS, adopted by the cities of Cape Town and Durban for disaster risk reduction. These cities have been responding adequately to climate change in terms of appropriate policy, planning, and action frameworks. A comparative study carried out by Gajjar *et al.* (2021) for cities in South Africa and Kenya showed that sustainable water management needs the involvement of a wide range of stakeholders and institutions as well as intra- and cross-organizational collaboration. Practitioners and decision-makers should be well-informed of the latest knowledge so that these practices are adopted. It is also important to involve civil society organizations and NGOs who have the knowledge of local constraints for the practices to be effective.

23.3.3 India

The effectiveness of the LID practices implemented is highly dependent on the hydraulic parameters of the native soil, topography of the region, groundwater conditions at the site, rainfall characteristics as well as overall land use and drainage practices in the region. This necessitates the development of planning and implementation policies that are region-specific. While many countries such as UK, US, Australia, China, and Singapore have developed generic guidelines for LID development plans and have advanced in integrating LID measures into urban landscapes, LID philosophies are only at incubation stage in India. Although there is an increase in the awareness and willingness at institutional level and among the practitioners to adapt to sustainable measures, the availability of directives and guidelines to steer the process is still limited.

Recently, the Centre for Science and Environment (CSE) and the Ministry of Housing and Urban Affairs (MoHUA), Government of India, have developed the 'Water Sensitive Urban Design and

Planning – Practitioner's Guide' to assist practitioners in incorporating sustainable water management strategies into urban planning (Rohilla *et al.*, 2017). The 'Guide for Green Infrastructure', which was developed in conjunction with this, attempts to bring water management and green infrastructure practices together for different geographical settings. MoHUA has also provided guidelines regarding the ratio of built-up to open area that has to be maintained for different land-use types. It suggests that 25–35% of a city's area should be made available as open space. However, the present data indicate that in most of the prominent Indian cities, the percentage of open space available falls much below international norms. From an environmental protection perspective, India has norms and guidelines recommended at the institutional level for the protection of open spaces, water bodies and environmentally sensitive areas. These recommendations tend to emphasize the need for development that is sustainable.

The manual prepared by the Centre for Public Health and Environment Engineering Organization (CPHEEO) emphasizes that the water-sensitive drainage design should be such that it ensures water quality, provides protection against flooding, reduces the runoff from catchments, enhances infiltration, minimizes the dependency on artificial drainage networks, and reduces the changes in the water balance in the natural systems. Most of the guidelines that presently exist in India provide design philosophies and approaches required for planning LIDs. Considering the impact that local site and climatic conditions have on the performance of LID techniques, it is imperative to frame rules for designing LIDs suitable for a region. Currently, manuals and guidelines do not elaborate on how site-specific designing can be carried out.

State governments and local authorities have come up with instructions for implementing water-sensitive drainage systems in Orissa, Delhi, and Uttar Pradesh in collaboration with the Centre for Science and Environment (CSE). The rainwater harvesting (RWH) movement was launched in Tamil Nadu in 2001, making it mandatory to have RWH structures in all newly constructed buildings by bringing amendments in the building codes. Research by CSE has shown that there is significant scope for RWH in the cities of Chandigarh and Noida. CSE has also provided plans for WSUD for Dwarka area in Delhi and Medinipur town in West Bengal (Rohilla *et al.*, 2017). They have suggested: (a) ponds and wetlands; (b) infiltration and retention basins; (c) filter strips; (d) swales; (e) bio-retention; (f) filter drains, and (g) canals and rills for open spaces. Filter strips, swales, bio-retention, and filter drains are recommended for roads. Acknowledging the role of water bodies in providing resilience towards water-related extremities, the Ministry of Jal Shakti has launched a scheme aimed at repairing, renovating, and restoring water bodies in various states. However, given the size of India and the number of urban areas, significantly more efforts are needed to implement LID measures.

23.4 CHALLENGES FOR LID IMPLEMENTATION IN INDIA

Given the urban expansion that has already taken place on the natural watersheds, one of the major challenges is to incorporate LID measures in the existing limited open spaces in urban areas to enhance flood resiliency. Many major Indian cities were developed without allocating sufficient space for open areas and environmental conservation, resulting in haphazard development in environmentally sensitive zones. Retrofitting LIDs in the existing spaces would require detailed study and analysis. Although separate sewerage systems are designed and implemented in Indian cities, due to unplanned or poorly planned urban expansion, the sanitary sewer capacities are often exceeded and hence the existing storm water drains in most Indian cities carry both storm water and sewage. LID implementation, along with storm water drains in such situations, has to be carefully planned to prevent the inflow of sewage to LIDs. Inflow of sewage to LIDs would not only clog the system but also raise issues of health and hygiene by becoming breeding grounds for mosquitoes and insects. For places that receive rainfall only during the monsoon months, the LID objectives should also encompass water conservation to prevent acute shortages during the summer. Thus, LID planning should be done comprehensively, taking into account the regional climate, social, and economic conditions.

Another major challenge comes in the form of willingness of people to shift from conventional drainage solutions to sustainable solutions. The concepts of sustainability may not be popular among the policy makers and community members alike, making adaptation challenging. Installing LID measures might involve taking up private property spaces that would bring in legal challenges. Overcoming these challenges involves creating awareness among the various stakeholders regarding the necessity and benefits of LIDs.

The economics of adopting LID practices are a major aspect that determines the success rate of implementation. Currently, the economic analyses that exist have been performed for countries with different economic and social statuses. Considering the living conditions and economic–social status of the end-user communities in Indian cities, cost–benefit studies need to be performed.

The performance of LIDs during their design life is dependent on how the structures are maintained. Currently, in India, regulations regarding LID maintenance have not been established. While governing bodies can undertake monitoring and maintenance of regional level LIDs such as detention basins, lakes, and ponds, the responsibility for maintaining plot-scale LIDs implemented in the premises of residential and commercial/non-residential buildings will be upon the respective property owners. During the planning stage, identifying and allocating responsibilities among various stakeholders should also take place.

Often decision makers are stuck in the conventional technical paradigm for drainage projects, although the risks and damages are clear. The conventional paradigm may persist in many cities of the Global South because it is intrinsically related to powerful production chains. The first is the production chain of large infrastructure contractors, totally dependent on heavy reinforced-concrete technologies. LID practices challenge established practices, and hence there is a reaction and reaffirmation of consolidated practices. The second is the productive chain of the real estate market, mainly in the allotment sector, which always looks for the highest yield of the land. Areas belonging to rivers (meanders, floodplains, and protection of slopes and springs) are necessary to implement SuDS patterns. But these are often ignored by real estate projects resulting in end-to-end development without adequate buffer or open spaces.

23.5 NEED FOR ENHANCEMENT OF ENABLING METHODS AND TOOLS

Several methods and tools are available which aid in the decision making for implementation of LID measures. They help in the selection of appropriate type of LID measure and its design based on local site conditions (native soil characteristics, groundwater level, topography, and space constraints), rainfall characteristics, and the specific goal to be achieved. In this section of this chapter, we discuss the need for enhancement of existing methods and tools.

23.5.1 Modelling of LID components

To assess the performance of different types of LID measures against different site and storm conditions, it is crucial to represent LID techniques in hydrological models. The storm water management model (SWMM) tool comes with discrete LID modules for bio-retention cells, rain gardens, green roofs, permeable pavements, block pavers, rain barrels, and swales. However, the model is most appropriate for smaller catchments and its overtly simplified representation of the catchment limits its applicability for watersheds with heterogeneous land uses. The model for urban sewers (MOUSE) is a spatially distributed model that can model urban drainage systems. The model has provisions to represent LID measures such as ponds and wetlands, detention tanks, and swales explicitly. It also allows for implicit modelling of other LID measures. However, LID modelling in the software might experience limitations as it is less sensitive towards the soil and rainfall conditions at site (Broekhuizen *et al.*, 2019). Furthermore, the application of both the models in simulating LID processes for large complex watersheds or river basins with different land-use patterns and corresponding hydrological responses may have limitations. Thus, for the modelling of LIDs, it is essential to incorporate process-based modelling of LIDs into river basin-scale models that can adequately capture the complexities of a watershed.

The soil and water assessment tool (SWAT) is a model widely used for simulating the hydrological processes for large river basins. Recent developments in the software have enabled its applicability in storm water management system modelling. SWAT is capable of modelling multiple soil layers, a step which is essential for LID modelling. Recently, the integration of LIDs such as green roof, rain garden, cistern, and porous pavement has opened the potential of SWAT model in aiding sustainable storm water management development plans. Even though SWAT model is effective for hydrological modelling at river basin scales, it needs to be improved with integration of more LID modules to extend its applicability for sustainable watershed management. Thus, it can be inferred that expanding the strengths of river basin-scale models such as SWAT to develop and integrate various types of LID modules will facilitate formulation of comprehensive sustainable drainage solutions for complex river basins.

23.5.2 Multi-criteria decision making for LID planning

The integration of LID into the urban water cycle requires a detailed and systematic design and planning framework at various spatial scales to restore the hydrological conditions to the pre-development level. In this context, the multi-criteria decision making (MCDM) methods can be used to help decision-makers evaluate and select among various potential LID designs based on numerous competing criteria. MCDM methods provide a structured and systematic approach for assessing the importance of criteria and determining the most suitable LID design for a particular site. Over the years, a range of decision support tools, optimization techniques, and site suitability analysis methods have been developed and refined over time to assist with the selection of appropriate LID design (Gogate & Rawal, 2015; Kuller *et al.*, 2019; Martin-Mikle *et al.*, 2015). Most techniques aimed at developing optimal LID interventions do not consider urban planning considerations or stakeholder preferences. Urban biophysical environments and technologies simulator (UrbanBEATS) serves the purpose of integrating an urban planning module and an LID planning module to provide a variety of LID options based on the challenges and opportunities in an urban area (Bach *et al.*, 2020).

Various decision-support systems for implementing blue-green infrastructure measures exist. However, none of them holistically address the increasing monsoon deluge and the alarming exigency for water conservation. This highlights the demand for a comprehensive framework that perceives this issue as a water resources management problem to integrate LIDs. Such a framework, coupled with educational initiatives to define the multifaceted principles and frequently tacit agreements between stakeholders and governments on water management, aimed at raising community awareness of socio-economic and environmental benefits, is likely to have a positive impact and reinforce the acceptance of the LIDs. So, it is important to study and understand the feasibility of LID components using comprehensive site suitability analysis for the development of an integrated planning framework for a watershed at a regional and local scale.

The remote sensing datasets and geographic information systems (GIS) are often integrated with multi-criteria analysis (MCA) methods to develop geospatial models to identify viable sites for any target resource or activity. LID-related spatial planning studies are few and far between. Existing spatial planning models have been prepared using a few parameters that influence the suitability of LID elements. The existing studies are based on ranking the factors or thematic layers influencing the target resource or activity. This sometimes creates an inherent cognitive bias in decision making. Instead, the potential of existing hydrological models can be utilized to analyse and rank the factors considered. A comprehensive framework, which embeds the MCA method as well as an adequate physical process-based model of LIDs, is needed to improve storm water management.

23.5.3 Basin-scale LID implementation

The cumulative effect of LID practices on a watershed is a research problem that has been relatively less explored. Although there is a well-adhered to belief that locale scale LIDs can impact the watershed flow regimes, uncertainties regarding the translation of LIDs to broader spatial scales are still unattended. While flood control is the primary objective for implementing LIDs, they can also facilitate groundwater recharge. This is especially critical in the Global South where groundwater forms a major source of water and must be augmented during the few rainy days of the monsoon season. However, an assessment of the surface – subsurface flow interactions due to LIDs has not yet been achieved. Therefore, an assessment of the impact of LIDs on the hydrological processes of a watershed conducted at a regional scale can be a starting point for a holistic water management practice for river basins.

23.6 SUMMARY

The integration of LIDs as part of managing the urban water cycle requires a thorough design and planning framework at different spatial scales to replicate the pre-development hydrology. Planning frameworks at different scales facilitate the development of site plans tailored to natural topographic constraints while preserving hydrologic functions and offering aesthetically pleasing and cost-effective stormwater management controls. Over the years, several challenges have emerged that hinder the implementation of LIDs. The absence of a reference framework and institutional barriers to guide the creation of a sustainable urban water management strategy are significant obstacles to progress. Future LID advancements should focus on developing a comprehensive design, planning, and development framework at various spatial scales to enhance the watershed's resilience to changing climates and address pluvial flooding and water scarcity. By integrating LIDs, we can transition from a water supply-based watershed to a water-sensitive watershed.

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