Chapter 19
Permeable Pavements as Sustainable Nature-Based Solutions for the Management of Urban Lake Ecosystems

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Abstract Permeable pavement systems (PPS) are becoming integral parts of the urban green infrastructure (UGI) planning approaches for the implementation of nature-based solutions (NbS) especially in rapidly developing regions. Global research has demonstrated that UGI is quite essential to regulate and establish the hydrological and ecological functions of urban aquatic ecosystems such as lakes. At a micro-scale level, design of storm water management systems requires detailed planning, as urban flooding has the potential to affect a huge population dwelling in the cities often without any warning. Such events cause drastic changes in the hydrological statuses of urban lakes, by gradually decreasing their natural resilience over a period. An associated risk with the degradation of urban lake systems pertains to their immense contributions in maintaining the ambient temperature profiles. The loss of the urban lake systems will directly lead to a substantial rise in the ambient air temperature and enhanced heat island effect. PPS can offer successful NbS to improve the resilience of the lake systems. PPS would also prove to be instrumental in mitigating the urban heat island effects by intercepting the excessive run-offs, increasing green water collection and storage, as well as by maintaining close-to-natural flow regimes in the case of urban lakes. Such micro-scale NbS offered by the design and implementation of PPS can offer huge environmental, social, and economic benefits in the long run. PPS can also offer direct benefits towards regulating the lake services and can assist in addressing the sustainable development goals for the lake ecosystems in the urban set-up, which are under stress due to various anthropogenic detrimental activities.

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19.1 Introduction

In the present era of unprecedented floods occurring in the areas of dense human habitations, the urban infrastructure has been under the spotlight for several reasons. First, several incidents of flash floods, especially under the influence of monsoons, have echoed the criticality of sound urban planning of public sewerage and sewer systems around the world (e.g. Thorne et al. 2018). This becomes even more crucial for the Indian scenario (Nagendra 2010), where ambitious city development projects are currently underway. Second, the perspective of how to make sustainable urban drainage systems (SUDS) has been approached from the perspective of providing nature-based solutions (NbS), with the inherent need to adhere realistically to the sustainable development goals (SDG). The third perspective pertains to challenges in preserving the unique urban hydrological cycle, by reinforcing the urban green infrastructure (UGI) using pragmatic NbS for providing effective land management solutions (Keesstra et al. 2018) as well as options for storm water drainage. Woven around these ideas, the unique environmental settings of urban lakes offer the broad scope for utilizing NbS protocols for planning blue-green sustainable infrastructure.

Starting with the classical Forbes' concept of lakes as '*microcosms*' (Forbes 1887), the scientific perspectives of urban ecological values of lakes as environmental, socio-economic, and cultural hotspots have been important to understand their roles in promoting urban resilience. Campanella (2006) also adds to the understanding of urban resilience with an anthropological perspective of voluntary citizen participation as reinforcements for achieving the urban '*stable state*'. The central idea propounded by the studies on urban sustainability stress on the unique capabilities of NbS to provide a 'scientific niche', 'conceptual flexibility' (Nesshöver et al. 2017) or a '*thought space*' towards the conservation of urban lakes, which are threatened by the accelerated pace of urban sprawl. Under the lens of the careful lake management plans, the attention now needs to be drawn to the twofold goals of ensuring water balance as well as the water quality of the urban lakes, which are necessary for the waterbodies for extending the ecological and anthropological services as drivers of UGI. Recognition of the barriers for successful implementation and strengthening of UGI (Fig. 19.1) is increasingly being realized as core to the city development (O'Donnell et al. 2017).

Of the several barriers, the problem of increasing imperviousness around these lakes push the limits to realizing the SDGs unique to the urban planning (Thorne et al. 2018). Under the circumstances, it is important to address the unique opportunities provided by permeable pavement networks (PPS) as ideal NbS options for strengthening the UGI.

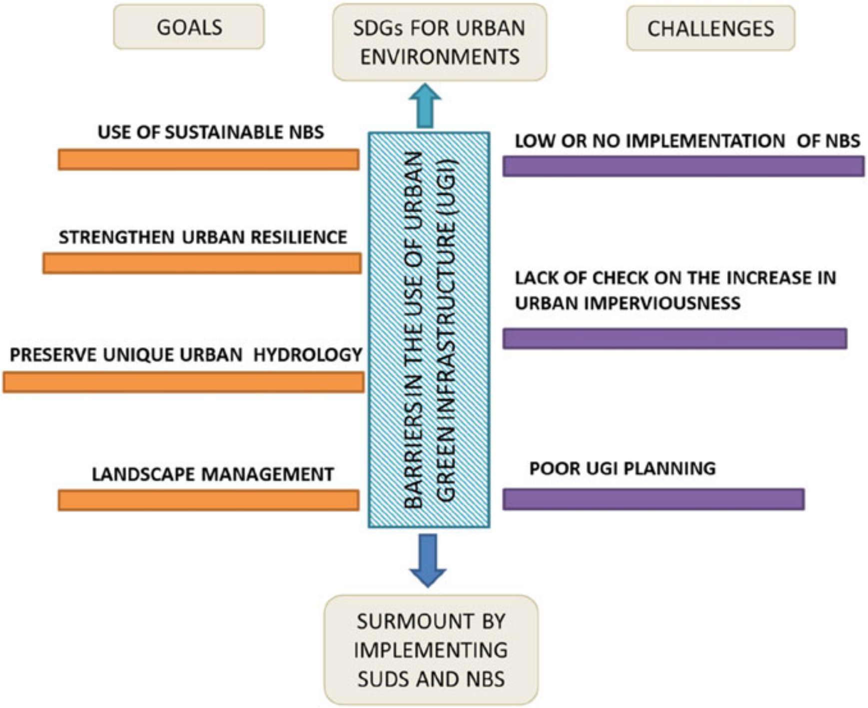

Fig. 19.1 Barriers for implementing UGI for preserving the unique hydrological setting of urban lakes (*SUDS* sustainable urban drainage systems, *NbS* nature-based solutions, *UGI* urban green infrastructure)

19.2 Permeable Pavement Systems (PPS)

Pavements are an intrinsic and integral part of the urban lives. However, the quality of their construction, as well as, the management are usually given much less attention than required (Online Resources: Hun-Dorris 2009). For the urban developers, industrial facilities, and municipal bodies addressing storm water and associated water-quality guidelines and regulations, paved urban sidewalks are of foremost importance in the context of healthy urban planning (Tennis et al. 2004; Rowe et al. 2010; Saadeh et al. 2019). According to Professor Bruce Ferguson, one of the pioneers of the porous pavement research field and the Director of the School of Environmental Design at the University of Georgia in Athens, ‘Pavements are the most ubiquitous structures built by man. They occupy twice the area of buildings. Two-thirds of all the rain that falls on potentially impervious surfaces in urban watersheds is falling on pavement’. Therefore, with a view to facilitating better management of the rainwater, design, and implementation of durable permeable pavement systems (PPS) is of pivotal importance. It is noteworthy that permeable pavement is one of the recommended technologies for the low-impact development

(LID) in the United States of America (USA) (Zahmatkesh et al. 2014; Vogel et al. 2015; Weiss et al. 2019), as well as for the water-sensitive urban design (WSUD) in Australia (Pezzaniti et al. 2009; Beecham et al. 2010).

Permeable pavement or the pervious concrete is a specific kind of pavement that allows rainwater to pass through it into the underground aquifers, owing to its high porosity. The pervious concrete is capable of reasonably mimicking the natural process that occurs on the ground's surface and reduces run-off considerably by returning water into the ground below, thereby recharging the groundwater table (Online Resources: Green Building Alliance (Permeable Pavement) (n.d.); Pavement Interactive (Permeable Pavements) (n.d.)). Pervious pavements can hold the storm water in multiple air voids or cells, and thus can help to curb the pollution of the groundwater table by retaining suspended solids and pollutants present in the runoff stream within the structure (Hun-Dorris 2005; Online Resources: Pavement Interactive (Permeable Pavements) (n.d.)). Such pavements also facilitate degradation of captured hydrocarbons into carbon dioxide and water (Online Resources: Pavement Interactive (Permeable Pavements) (n.d.)).

In an urban environment, with proper arrangements and judicious implementation, porous pavements can facilitate biodegradation of the oils spilled from cars and trucks, help rainwater in infiltrating through the soil, decrease urban heating by reducing the absorption of solar radiation and urban heat storage potential (Sonebia et al. 2016), replenish groundwater, allow the tree roots to extend their roots and breathe and reduce the total run-off, as well as, the frequency of flash flooding by reducing the peak water flow through the drainage channels (Ferguson 2005). Particularly, in the water scarce and water-stressed regions, water reuse becomes essential. This prompts the porous pavements, with their significant and unique potential, to revolutionize storm water management; and emerge as an important futuristic technology option. Pervious pavement technology also facilitates efficient use of land by eliminating the need for retention ponds, swales, and necessary storm water management devices, leading to much reduced overall project costs on a first-cost basis (Tennis et al. 2004; ACI report 2010). Currently, porous pavements constitute only a small fraction of all pavement installations. However, the technology is steadily gaining popularity as the most rapidly developing way of restoring large parts of the urban environment (Ferguson 2006), and they have been installed in all regions of the United States (Chopra et al. 2011; Online Resources: Cahill et al. 2018).

A large fraction of the existing permeable pavement systems has been installed at the parking lots, as well as at the commercial areas that are prone to frequent light traffic loads moving at low speeds (Weiss et al. 2019). However, past two decades have seen a substantial progress in the application-oriented research and development of permeable pavements, which includes mix design, hydrologic design, assessment of hydrologic performance and maintenance requirements. However, this is an emerging field, and there are still many important aspects that need to be addressed before permeable pavements can be fully integrated into urban highways that experience heavy loads and high traffic (Weiss et al. 2019; Saadeh et al. 2019).

Ferguson identified nine categories of the porous pavement, viz. decks, open-celled paving grids, open-graded aggregate, open-jointed paving blocks, plastic geocells, porous asphalt, pervious concrete, porous turf and soft paving (Ferguson 2005). Some of the most commonly used permeable pavement surfaces include pervious concrete, porous asphalt and permeable interlocking concrete pavers (MPCA report 2008). Porous asphalt is used on highways to remove excess water, whereas permeable interlocking concrete pavers (PICP) are popular in public areas due to its architectural appeal. PICP can be laid out in an interlocking grid pattern, with in-between spaces commonly filled with grass or small stones (Online Resources: Green Building Alliance (Permeable Pavement) (n.d.)). Pervious concrete, which is also known by the names like no-fines and gap-graded concrete, is essentially a mixture of gravel or granite stone, cement, water and little or no sand (fine aggregate) with or without admixtures (Obla 2007). Typically, 15–35% of the pervious concrete volume consists of interconnected void network (Tennis et al. 2004; Obla 2007; Kia et al. 2017), and it allows for the passage of a water flow rate of 3–5 gpm (0.014–0.023 m^3/min) through the open cells for each square foot (0.0929 m^2) of the surface area, which far exceeds most of the rain occurrences (Tennis et al. 2004). Pervious concrete is primarily used in residential roads, alleys, driveways, low volume sidewalks and low water crossings. It can be used as the sub-base for the conventional concrete pavements, as well as for the slope stabilization.

Other alternatives include plastic and concrete grids, as well as the amended soils where artificial media is added to soil to maintain soil structure and prevent compaction (MPCA report 2008; Fig. 19.2). Plastic grids allow for a 100% porous system, and they distribute the weight of traffic and prevent compression of the

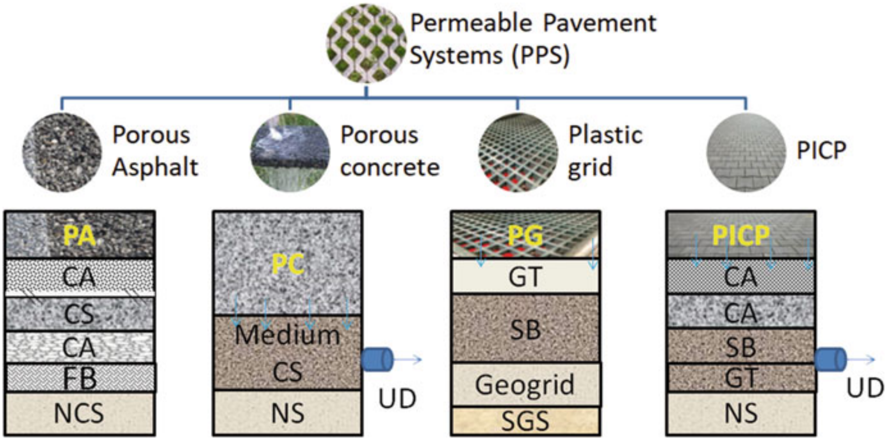

Fig. 19.2 Types of predominant PPS as providers of NbS for the implementation in UGI (*PA* porous asphalt, *PC* porous concrete, *PG* plastic grid, *PICP* permeable interlocking concrete pavers, *CA* coarse aggregates, *CS* coarse stone, *FB* filter blanket, *GT* geotextile, *NCS* non-compacted soil, *NS* native soil, *SB* sub-base, *SGS* sub-grade soil, *UD* under drain)

underlying soil (Online Resources: Plastic Grid Pavers (n.d.)). These grids help in reinforcing the gravel driveways, the parking lots and the fire lanes and are gaining popularity in the Leadership in Energy and Environmental Design (LEED) projects, mainly due to their light weight, ease of installation and durability (Online Resources: Green Building Alliance (Permeable Pavement) (n.d.); Plastic Grid Pavers (n.d.)). Plastic grid pavers are constructed primarily from recycled plastic materials and can be found in the form of interlocking blocks or in rolls. The honeycomb shape of the plastic grids allows grass to grow through the holes, thereby adding to temporary soil stabilization, as well as the urban architectural aesthetics (Online Resources: Plastic Grid Pavers (n.d.)).

From the foregoing discussion, it follows that although several types of permeable pavements and surfaces are available, each of them presents us with unique set of pros and cons. Therefore, the choice of a pervious pavement material revolves around the nature of the application and the project-specific requirements. Some of the key attributes that help an end user in deciding upon a pervious pavement material are cost-effectiveness, durability, the ability to provide safe drainage and effectiveness in flood protection. Furthermore, the larger perspective includes effective land utilization, protection of the landscape and long-term sustainability of the installed permeable paver network (Online Resources: The Complete Guide to Permeable Paving Systems (n.d.)). Maintenance requirements of the permeable pavements invite a lot of attention, as well as detailed planning. The porous media of PPS is prone to clogging by sediment. The extent of clogging depends on several factors such as the rainfall characteristics, characteristics of the catchment soil, air quality and temperature, attributes of the contributing drainage area and the type and volume of the flowing traffic (Razzaghmanesh and Beecham 2018).

A few reported works have analysed and discussed the effectiveness of the techniques such as power blowing, pressure washing and vacuuming, as well as a combination of these methods for restoring infiltration rate on small area pervious concrete pavements. It was found that pressure washing and vacuuming are equally effective as the initial cleaning techniques, both increasing surface infiltration rate by over 90%. Further, it was found that combining vacuuming and pressure washing resulted in more efficient clog removal over either method alone (Hein et al. 2013). Other pivotal concerns include the limited validity of the laboratory permeability test results that usually tend to deviate greatly from the design infiltration rate values of the in-place pervious concrete, as well as the quality control of the in-place pervious concrete (Tong 2011).

Design of a typical permeable pavement system consists of a top permeable concrete layer with sub-base coarse aggregate layer and subgrade soil beneath it. Based on the practical needs, viz. retention of storm water runoff until it infiltrates into the existing soil or the controlled drainage of the run-off traffic following adequate filtration; the number of sub-layers, as well as, the thickness and composition of each layer can vary substantially (Kia et al. 2017). Permeable pavement system designs can be customized to facilitate partial or zero exfiltration for sites with poorly draining soils, contaminated soils or in groundwater sensitive areas by providing sub-drains or an impermeable liner to prevent water reaching the underlying soil.

Pervious concrete typically contains single-sized coarse aggregates, narrowly graded between 3/4 and 3/8 in. (19 and 9.5 mm). Aggregates used in pervious concrete are made to meet the ASTM D488 requirements: 'Specification for Crushed Stone, Crushed Slag and Gravel for Waterbound Base and Surface and Surface Courses of Pavements'; as well as, ASTM C33: 'Standard Specification for Concrete Aggregates'. The coarser aggregates in the mixture enhances skid resistance, void ratio and permeability, whereas the smaller aggregates result in reduced permeability, although the mechanical strength is found to improve. Angular aggregates result in comparatively lower density, accompanied by higher extent of void and permeability. However, pavement structures with angular aggregates tend to offer lower strength compared to rounded aggregates. Sizing of the aggregates is done such that a suitable application-oriented trade-off between the permeability and mechanical strength is ensured (Kevern 2006).

It is worth reiterating that apart from the primary goal reducing the storm water run-off and recharging groundwater table, another important function of PPS is the effective removal of the various pollutants, such as bio-degradable organic matter, nutrients (phosphorus and nitrogen), heavy metals (lead, copper, cadmium and zinc), oils and suspended solids emanating from construction activities, so that the pollutant load reaching the receiving waterbodies (e.g. urban lakes) is minimized (Scholz 2013). Especially, in order to enhance filtration and separation properties in the permeable pavement system, non-woven geotextiles have been manufactured and tried. Non-woven geotextiles are made by putting together small fibres of polyester, polypropylene or a mixture of polyester and polypropylene in the form of a sheet or web, and then binding is facilitated either by needle punching or by the application of chemical and/or heat (Holtz 2009). It is noteworthy that polyesters and polypropylene are highly resistant to chemical and biological degradation and hence can serve as a durable reinforcement material for the sub-surface permeable paving layers of PPS. However, polyester has been found to degrade over time, especially under alkaline conditions. As the urban run-offs are usually acidic in nature, the durability of the geotextile layer remains by and large unfazed by the characteristics of the flow traffic (Boving et al. 2008; Scholz 2010).

The hydrocarbons generated from incomplete combustion in vehicle engines end up in the urban run-offs following unwanted leakages and would prove to be detrimental for the ecological health of the urban waterbodies during the instances of excessive rainfall. Hence, effective decomposition of the hydrocarbons and other greasy pollutants is very important. Recently researchers have identified the geotextiles as a suitable environment for the development of biofilms comprising of the consortium of microorganisms, capable of reducing the presence of hydrocarbons in the storm water (Bayon et al. 2015). Such a controlled microorganism-based solution would prove to be a nature-based solution as additional contributions from the air and other natural sources are likely to favour the establishment of an adequate microbial community within the chosen layers of the pervious pavement network.

19.3 Nature-Based Solutions for Urban Planning

One of the key motives behind the formulation of the guidelines for nature-based solutions (NbSs) is to render sustainable strategies for mainstream land management (Keesstra et al. 2018). The aggressive urban sprawl of the modern era necessitates the development of cost-effective long-term solutions towards mitigating the hydrological risks, as well as the persistent problems related to urban land degradation. Land management-oriented solutions can be divided into two main categories, viz. soil-related solutions and landscape-related solutions. Soil-related solutions are aimed at enhancing the soil health and soil functions for restoring local eco-system services, whereas the landscape solutions mainly focus on making the landscape less connected, facilitating less rainfall to be transformed into the runoffs, thereby reducing the risk of the urban flash floods (Keesstra et al. 2018). Evidently, pervious pavement systems have great potential to meet the primary goal of nature-based landscape-related solutions. Permeable pavement networks are gradually emerging as a popular technology for the sustainable urban drainage systems (SUDS) for storm water management and mitigation of the water pollution in the urban waterbodies (Elizondo-Martínez et al. 2020). Additionally, the PPS system can facilitate other benefits, such as the mitigation of the Urban Heat Island (UHI) effect through the reflection of solar radiation (Fini et al. 2017), sound reduction by absorbing the frictional noise generated owing to the interaction between the vehicle tyres and the pavement (Chu et al. 2017). It can also offer betterment in road safety, which is attributed to the enhanced skid resistance emanating from the high void content within the PPS network (Nicholls 1997).

The use of NbS provides a strong framework to understand and manage lake environments in urban centres. From the perspective of successful implementation and preservation of UGI, the urban lakes themselves are perceived to be providers of NbS (van den Bosch and Sang 2017). The presence of urban waterbodies as reservoirs of water and catchment drainages adds value to the ecological services offered by these ecosystems in the form of providing nesting habitats for several species of flora and fauna, as well as improving groundwater recharge, apart from providing significant socio-cultural spaces for human interactions. However, anthropocentricity of these ecosystems has altered the normal urban biogeochemistry to a vast extent (Kaushal et al. 2014). Nevertheless, quantitative and qualitative studies illustrate the inherent benefits of adopting UGI in the form of NbS (such as the lakes themselves) in mitigating the effects of UHI (Demuzere et al. 2014).

Some successful examples of NbS adopted in relation to sustainable land management, SUDS as well as UGI include creation of green spaces around lakes, such as vegetated trenches, open percolation ditches, artificially created wetlands, filtering fields and biofiltration systems (Dondajewska et al. 2018) and for diversion, as well as retention of flows from the roofs, surfaces of roads, shelters, garages and buildings in order to minimize the risks of overland floods. Creation of UGI also enhances the scope for the NbS to emerge as market instruments towards facilitating the blue-green infrastructure planning (e.g. Sörensen and Emilsson 2019).

19.4 PPS Implementation for Urban Lakes Environments

A major component of the hydrology that influences the role of the urban reservoirs as the NbS pertains to the flow from storm water run-off into the urban waterbodies (Dickie et al. 2010). It brings the challenges of preserving the overall environmental quality, managing the influence of waste assimilation on the aquatic ecology, as well as maintaining the base flows despite the changes in the hydrological flow regimes. In this perspective, while the basic support of UGI is relevant, the use of NbS assumes greater importance as it provides the potential to augment natural flow and feedback mechanisms for urban lakes and water bodies. The anthropological element of UGI, which is often overlooked, becomes crucial in preserving the unique urban biogeochemistry is a driver for preserving urban aquatic ecosystems (Kaye et al. 2006). One major factor pertains to the use of PPS for improving the base flows, as well as for maintaining the water balance by supplementing the losses due to evaporation and human consumption. The use of PPS around the urban aquatic systems can contribute to achieving specific urban SDGs (URDPFI, Ministry of Urban Development 2014) in multiple ways:

1. Sustained release of storm water can prevent the excess floodwater from entering the lakes and water bodies.
2. The occurrences of urban flooding episodes due to excess outflows to the shores can be prevented or minimized.
3. Adequate filtration of excess solids at the transition zone between the lake and land will be possible, before entry of storm water discharges into the urban water bodies, which would help communities to manage and preserve water quality for longer periods of time.
4. Percolation through permeable surfaces and subsurface storage of floodwaters would improve the groundwater recharging.

Concepts and frameworks such as Water Sensitive Urban Design and Planning (WSUDP; Australia), Low Impact Development (LID; USA), Sound Water Cycle on National Planning (Japan), Decentralized Storm Water Management (Germany) and SUDS (UK) provide important insights which can support the designs for PPS as NbS especially for the Indian scenario (Rohilla et al. 2017) and consider the use of PPS as significant contributors to integrated urban water management apart from the use of other NbS protocols, such as rainwater harvesting, water conservation through artificial wetlands, natural wastewater recycling and reuse, as well as bio-retention systems. Some of these approaches are highlighted in Table 19.1.

Among the options listed in Table 19.1, PPS can be well-integrated with the SUDS and WSUDP concepts as shown in Fig. 19.3. Apart from these, the use of reusable materials for NbS in PPS systems is also being explored in detail. For example, Yilmaz et al. (2018) suggested the vast scope of using structural soils in combination with waste materials for urban greening as an innovative NbS for dense urban areas with the goal of resource recycling and reuse.

Table 19.1 NbS solutions for water-centric design and planning in the urban context

NbS for urban water ecosystems	Mode of operation	Ecological services as NbS	Temporal type	Advantages	Disadvantages
Vegetated swales, buffered strips	Natural filtration and recharge	Increase surface area of capture and detention of rainwater and storm water	Long term	Flood minimization, excess salt retention, groundwater recharge	Can be under intense developmental pressures and construction activities and can disappear in short term due to land grabbing without public participatory approaches
Adopting transitional boundaries around the ecosystems	Design and construction of PPS through engineered intervention	Filtration of storm water entering aquatic bodies, preserve ambient concentrations of total dissolved solids and nutrients such as nitrogen	Medium to long-term (based on implementation)	Regulation of baseflows, capture and detention of storm water and enhanced percolation for subsurface storage	Without adequate exposure to their unique advantages, PPS can be adversely managed or not properly maintained without a nexus of administrators and citizens; PPS can also be severely impacted by the growth of urban traffic
Artificial wetlands	Construction of wetland zones as a part of urban landscape design	Increased sequestrations of nutrients and provide urban niches for a variety of flora and fauna	Long term	Provide plenty of habitats and nesting grounds for a variety of flora and fauna; help in natural wastewater recycling	Largely disappear due to construction activities and urban sprawl. Without the social and environmental memories of their existence, it is difficult to recover these systems
Rainwater harvesting systems	Engineered storages	Reservoirs for storage of excess rainwater and divert to aquifers	Medium to long term	Can provide excellent water conservation and reuse at micro- and macro-scales	Implementation requires careful design and maintenance, involving financial investments
Decentralized wastewater treatment system with a natural flow approach, filtering fields and biofiltration systems	Engineered structures including primary, secondary and/or tertiary treatment units	Water recycling and reuse	Long term	Can provide excellent opportunity for natural wastewater treatment and pollution control	Provides a common public amenity for managing waste streams and reduce pollution

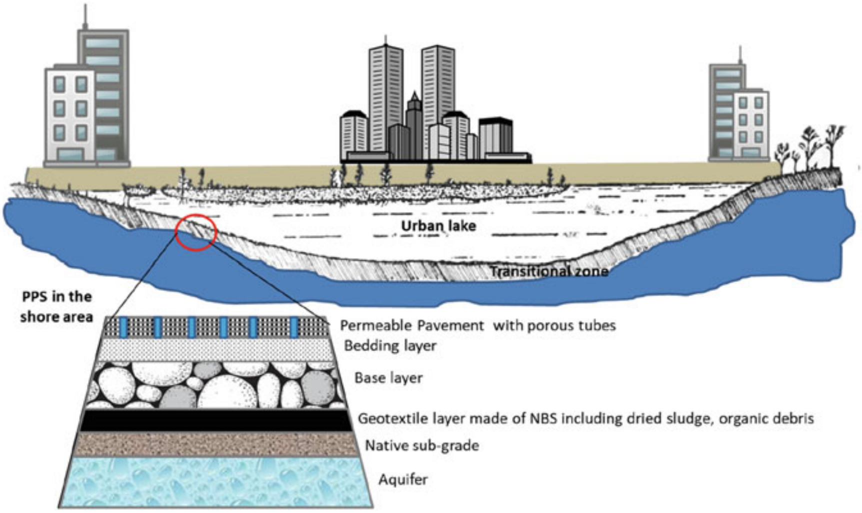

Fig. 19.3 Implementation of PPS in an urban lake environment. Inset of the PPS shows different layers into which NbS options can be examined for sustainable use of resources

The PPS as NbS options can be advantageous due to several reasons. The use of specific types of PPS such as porous asphalt or concrete, as part of the shore area development projects for lake environments will allow a large flow of the storm water to directly flow back into the lake and hence would help in maintaining the water tables even under the excess evaporation induced by densely constructed surfaces in urban centres. Thus, PPS would offer direct support for mitigating the UHI and would serve as a major component of NbS along with the urban lakes for sustainable UGI. The combined effect of the geotextile layers in PPS along with NbS materials such as the dried sludge from the urban wastewater treatment plants, as well as the organic debris are also being investigated (Lin et al. 2006).

Along with the innovation of NbS-oriented PPS, it is also of importance to have an estimate of cost of installation of the pervious pavement along the shorelines of the urban lakes, which would enable us in assessing its economic viability as compared to the impervious conventional concrete. For an example, we can consider Sankey tank (Perimeter = ~1.7 km) in Bengaluru to study the feasibility of paving the lake shore with PPS. A pervious pavement installation of 3 m width has been considered on the bank of the lake (Fig. 19.4). Also, in order to ensure safe discharge of filtered water into the tank, additional 2 m paving is considered along the bathymetric depth from the edge of the tank.

Therefore, the coverage area of the proposed PPS for this chosen waterbody is about 8500 m^2. The usual thickness of the PPS for urban environment is approximately 150 mm (Lucke and Dierkes 2015). Literature suggests that the approximate cost for paving surfaces with pervious concrete is Rs. 558/m^3, whereas that in case of conventional concrete is about Rs. 587/m^3 (Shah et al. 2013). Evidently, the use of pervious concrete saves Rs. 29/m^3. For paving the shoreline of the Sankey tank using

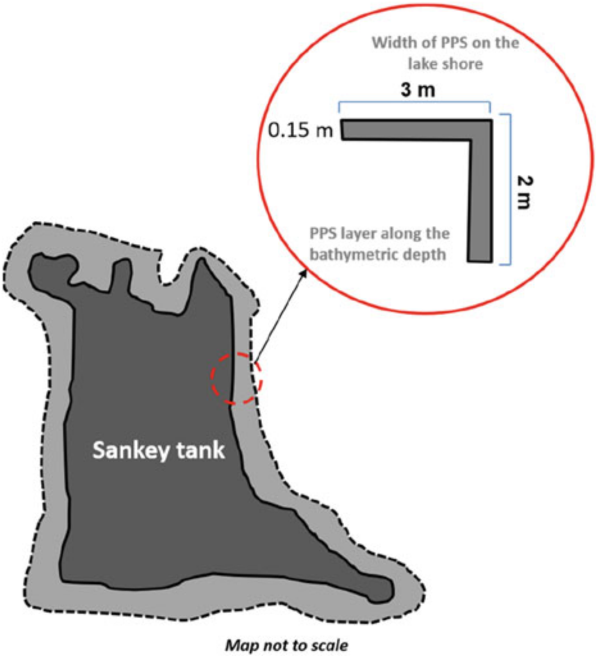

Fig. 19.4 Schematic representation of PPS implementation for a lake system in India (Sankey Tank, North Bengaluru)

pervious concrete, as per the plan discussed above, the total estimated expense will be about Rs. 711,450, and the amount saved by using PPS will be around Rs. 36,975.

19.5 Implementation of PPS for the Indian Scenario

NbS, on a very broad scale, brings together several different aspects such as the biodiversity and ecosystems, natural resource management, sustainable urban development and climate change responses. However, the core idea of NbS revolves around improving the quality the interaction between the people and the existing fragments of nature within the cities, as well as minimizing the severity of the impacts of rapid urbanization. NbS for the urban set-up includes strategies pertinent to the restoration of the wetlands and preservation of urban forestry; greenfield afforestation and retention of the health of brownfields; the greening of grey surfaces such as rooftops and walls; and implementation of efficient flood control techniques (Online Resources: Gajjar 2016a). In the context of sustainable urbanization, it is important to mention that the Ministry of Urban Development, Government of India launched the Atal Mission for Rejuvenation and Urban Transformation (AMRUT) in 2015, with a national priority of providing basic services and civic amenities to the city dwellers, as well as reducing pollution in cities. Some of the key aspects that the AMRUT mission is expected to cater to include supply of clean drinking water, hygienic management of sewerage and septage and effective drainage of storm water (AMRUT, Ministry of Housing and Urban Affairs, Government of India (n.d.)). Cities like Bangalore, Surat and Gorakhpur are looking towards the nature-based solutions for addressing the problems of shortage in water supply. Particularly in Gorakhpur, farmers switched from mono-cropping to rotating multiple crops in order to improve soil health and drainage. They have also adopted several organic practices, which resulted in a reduced level of harmful agricultural run-off to the nearby rivers, and at the same time, the crops also ensured a competitive edge for the farmers at the local markets (Online Resources: Du 2019). Protection of the water bodies and drainage channels has led to a reduced extent of street flooding and stagnant water. Bruhat Bengaluru Mahanagara Palike (BBMP) recently allocated about Rs. 800 crores for constructing new storm water drains and remodelling of the existing ones, where blocks of indigenous pervious concrete with customized proportion of water, cement and other aggregates will be used (Online Resources: Joshi 2017). The colour of this concrete being light grey would result in a considerably reduced level of solar heat absorption when implemented in various urban constructions, as compared to the black bituminous pavement concrete, thereby leading to lesser extent of UHI effect (Online Resources: Rasheeda and Rizvi 2009).

Some of the water-constrained cities of India, such as Jaipur, Bikaner, Bharatpur and Ajmer, have been facing water scarcity with the expansion of the urban population size. Additionally, these cities have recently seen an upsurge in the urban floods with the city's growing built-up footprint. Recharging of the groundwater table and minimization of the flash floods are of pivotal importance for these cities in order to ensure water security and quality of life. Permeable pavement system can serve such cities in the semi-arid regions greatly, as it comes with the ability to remove pollutants from the storm water and to curb the run-offs from flowing into urban waterbodies. PPS can also be employed for the retention of groundwater in the wetlands and harvesting of rainwater through the built environment (Online Resources: Du 2019). Looking at the bigger canvas, it can be seen that the PPS, as a technological tool, offers the promise to reduce the frequency of severe droughts in the semi-arid parts of India, if the installations are made by taking into account the dynamic nature of the land usage in the developing urban environments. Furthermore, the lakes and wooded groves in the periphery of the growing cities need to be protected from being absorbed into the sprawl of real estate development. Conservation and access to the nature should be planned in such a way that these urban natural resources can continue to be harvested harmoniously for a substantial period into the future (Online Resources: Gajjar 2016b).

19.6 Conclusions

Although NbS offers options for long-term sustainable urban development, the implementation poses several challenges as the urban environment comprises of several different components that interact in a complex and dynamic fashion.

Additionally, the customization of NbS is not straightforward as a suitable trade-off between design aspects and cost needs to be drawn. Considering the importance of mitigating urban flash floods as well as preventing the entry of pollutants into the waterbodies, the use of PPS has emerged as a promising NbS for the protection of urban ecology and harmonious usage of fragmented natural resources by the city dwellers. The NbS needs to be implemented such that the UGI does not get compromised in the face of accelerated urban sprawl. This is especially true for several developing cities in India. Preliminary calculations indicate that about 5–10% savings in capital costs can be achieved while opting for the PPS in the urban context as compared to the conventional paving techniques.

While implementing the NbS for long-term sustainable development, structured adaptive management strategies need to be developed as well, so that ecological responses to the implemented solutions can be obtained and assessed to enable prediction of further challenges, as well as the costs of the NbSs. Continued effort and sustained financial support are required to foster research and innovations related to various nature-based solutions, and a global market for the most feasible technologies need to be created to ensure viability of the beneficial technological solution. Policy interventions would also prove to be instrumental at the different levels, once the mettle of such solutions is proven for large-scale installations.

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