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Stormwater Management in Australia: Recent Progress and Future Challenges

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Abstract

Traditionally stormwater management adopted greater impervious areas, pipe networks and concrete gutters to remove runoff away from locality and mitigate flooding quickly. But this traditional approach to stormwater management has been associated with various environmental and social issues, including water quality degradation, erosion, loss of aquatic habitats, unexpected floods and increased urban heat island effects. As of now Australia shifted from traditional stormwater management and following in accordance with the requirements of AS/NZS 3500.3, Australian Rainfall and Runoff, Council's Design Standards (AUS-SPEC) and the National Construction Code which dictate using of different sustainable devices such as Onsite Detention System (OSD), Surface Inlet Pits and Grated Trench Drains, Subsoil drainage, Permeable paving, Light Duty Permeable Asphalt, Rainwater tanks, Overland flow paths and Gross Pollutant Traps (GPTs), but following so, many challenges arise in relation to aging infrastructures, water security, population growth and re-zoning and climate variability and changes. The objective of this paper is to determine current state of stormwater management in Australia, the challenges being faced, and the innovative approaches being explored to ensure a sustainable future using more sustainable stormwater management practices, known as Water Sensitive Urban Design (WSUD). It has been found that WSUD is being embraced by all levels of governments in Australia to implement sustainable urban water cycle modelling. New financial analysis incorporating both direct and indirect benefits provided by WSUD needs to be developed in future research so that this sustainable method is not viewed as financially unviable. WSUD has also challenges such as perceived higher maintenance cost and lack of established design guidelines supported by local data, which need to be addressed in future research.

Keywords: Rainfall and Runoff, Water Sensitive Urban Design, Council's Design Standards

1. INTRODUCTION

Stormwater refers to water that flows over impervious or saturated surfaces in urban areas, including roofs, roads, pavements, and green spaces. In natural environments, vegetation and permeable surfaces allow part of the runoff to seep into the soil, where it is either absorbed by plants or evaporates into the air. However, urban development often replaces these natural surfaces with impervious materials like roofing and paving. As a result, the amount of stormwater runoff increases with urban growth. Effectively managing stormwater is crucial for flood prevention (Arya et al., 2023).The sustainability is the core of current development philosophy in many developed countries as they do not degrade environment nor deplete limited natural resources (Wong, 2006). Fletcher et al. (2014) stated that green systems are emerging across the globe to make urban drainage systems more sustainable. Two broad issues are evident from the evidence received from current studies are: (i) stormwater is often viewed as an underutilized resource in Australia (Leonard et al., 2015); (ii) pollutants in urban stormwater runoff significantly contribute to the degradation of urban waterways (Mamoon et al., 2019; Müller et al., 2020). In Australia, water sensitive urban design (WSUD) was introduced in 1990's which has now been embraced by most of the Australian cities.

In Australia, stormwater drainage systems are designed and built according to AS/NZS 3500.3 standards. This mandates that all grated trench drains must have a minimum width of 200mm. When discharging directly into the kerb and gutter, the maximum allowable velocity is 2.5 m/s, and the maximum flow rate is 20 L/s. Sites with discharge rates exceeding 20 L/s must connect directly to the Council's piped stormwater system via a pit and/or pipe. The standard outlines requirements for materials, design, installation, and testing of roof, surface, and subsoil drainage systems up to the point of connection. Each downpipe must serve no more than 12 meters of gutter and should be positioned as close as possible to valley gutters. The Housing Provisions specify four types of downpipes: 75 mm diameter (round), 90 mm diameter (round), 100 mm x 50 mm (rectangular), and 100 mm x 75 mm (rectangular). According to AS/NZS 3500.3, the minimum gradient for stormwater drains with DN90, DN100, and DN150 sizes is 1:100. Stormwater pits, A and B, are sized according to AS/NZS 3500.3, with each pit measuring 450 mm x 450 mm and a minimum fall of 20 mm from the inlet to the outlet invert. The minimum cover for all stormwater drainage lines should be 250 mm under paved or driveway areas and 350 mm under lawn areas. This helps prevent saturated ground and potential flooding or structural damage to buildings over time. Instead of directing downpipes straight into underground drains, which can lead to overloading, they should discharge into surface water drains or soakaways. These systems allow rainwater to gradually infiltrate the ground safely.

There is no precise record of stormwater volumes in Australia. Research estimates that Australia's urban areas generate approximately 3,000 gigalitres of runoff annually (Stormwater Australia, Submission 19, page 3). Another estimate suggests that 'at least two-thirds' of current urban stormwater runoff exceeds what would have occurred naturally before settlement (Stormwater Australia, Submission 19). Additionally, it is estimated that urbanization increases the volume of water entering streams by up to 90 percent (Chris, 2015). Figure 1 illustrates the water cycle of a major city, indicating the overall volume of stormwater received and the quantities of stormwater that are either utilised in the city or discharged as runoff. Future expansion of Australia's urban centres, combined with more frequent extreme weather events driven by climate change, is likely to further increase stormwater volumes (Moore et al., 2016). Table 1 summarises evolution of WSUD in Australia. These milestones reflect the ongoing development of WSUD practices in Australia, highlighting the country's commitment to sustainable water management and innovative urban planning. Table 2 summarises findings from several key studies on WSUD.

The design guidelines on WSUD published by many local government organisations and large organisations like Sydney Water and Melbourne Water provide useful tips to analyse and design WSUD components. However, there are limited initiatives to verify the performances of WSUD elements at the field level. The claims made by the modellers using MUSIC in relation to reduction of pollutant loads (such as nitrogen and phosphorus) from a proposed new sub-division have hardly been checked by field investigations. The state or federal governments have limited fundings to take these initiatives. There are lacks in study on maintenance and life cycle cost analysis of WSUD elements by considering the full economic benefits that can be offered by WSUD e.g., enhanced recreational values of water bodies, improved public health, delayed upgradation/renovation of drainage infrastructure in established urban localities.

To fill the current knowledge gaps in WSUD, the objectives of this paper are: (i) to review the evolution of WSUD in Australia; (ii) to review and highlight various WSUD components; (iii) to identify the current knowledge gaps on WSUD; (iv) to propose further research opportunities to enhance WSUD practice in near future.

Table 1. Milestones in WSUD practices in Australia

Year	Aspect	Description
1990	Conceptual Foundations	**Initial Recognition**: Concept of WSUD began to take shape as urban planners and engineers started recognising the need for integrating water

		management with urban design in early 1990s in Australia. "Clean Water Act (USA)" published in 1972 provided the conceptual foundation of nature-based solution of urban water cycle management, which inspired WSUD, LID and SUDS.
1994	First major WSUD guideline	**WSUD first guideline:** It was initiated in WA by Whelans et al. (1994)
1996	Melbourne Water's Initiative	**Melbourne Water's Guidelines**: Melbourne Water released its guidelines for managing stormwater, which were among the first to incorporate WSUD principles into urban planning.
2000	The WSUD Initiative	**WSUD Initiatives**: The Australian Government and various state agencies began formally promoting WSUD through initiatives and policies aimed at improving water management in urban areas.
2003	MUSIC software released	**MUSIC software:** It was released as a part of Cooperative Research Centre for Catchment Hydrology (CRCCH) initiatives. Prof Tony Wong was the lead developer of MUSIC software.
2004	National Water Initiative (NWI)	**NWI:** The federal, state and territory governments in Australia signed NWI which recognised nature based urban water cycle management such as WSUD
2004	BASIX and STORM	**BASIX and STORM:** NSW Government introduced BASIX planning tool to promote sustainable urban water cycle management, similarly Melbourne Water introduced "STORM" tool.
2010	Expansion and Innovation	**WSUD Innovations**: The 2010s saw the introduction of innovative WSUD technologies and practices, including green roofs, rain gardens, and permeable pavements.
2014	MUSIC new version (6.1)	**MUSIC Update:** A more versatile version of MUSIC software is built and distributed by eWATER CRC.
2014	National Framework	**National Water Quality Framework**: The National Water Quality Management Strategy was updated to include WSUD as a critical component of managing urban water quality.
2020	Climate Resilience and WSUD	**Climate Adaptation**: WSUD practices began to focus more on climate resilience, incorporating strategies to handle extreme weather events and changing climate conditions.
2024	Current Trends and Future Directions	**Ongoing Developments**: Today, WSUD continues to evolve with advancements in technology, increased focus on climate adaptation, and a growing emphasis on community engagement and collaboration in water management.
1990-2004	Major contributors of WSUD concepts in Australia	C Whelans, John Argue, Tony Wong, Tim Fletcher, Hugh Duncan, Tony Weber, Ana Deletic

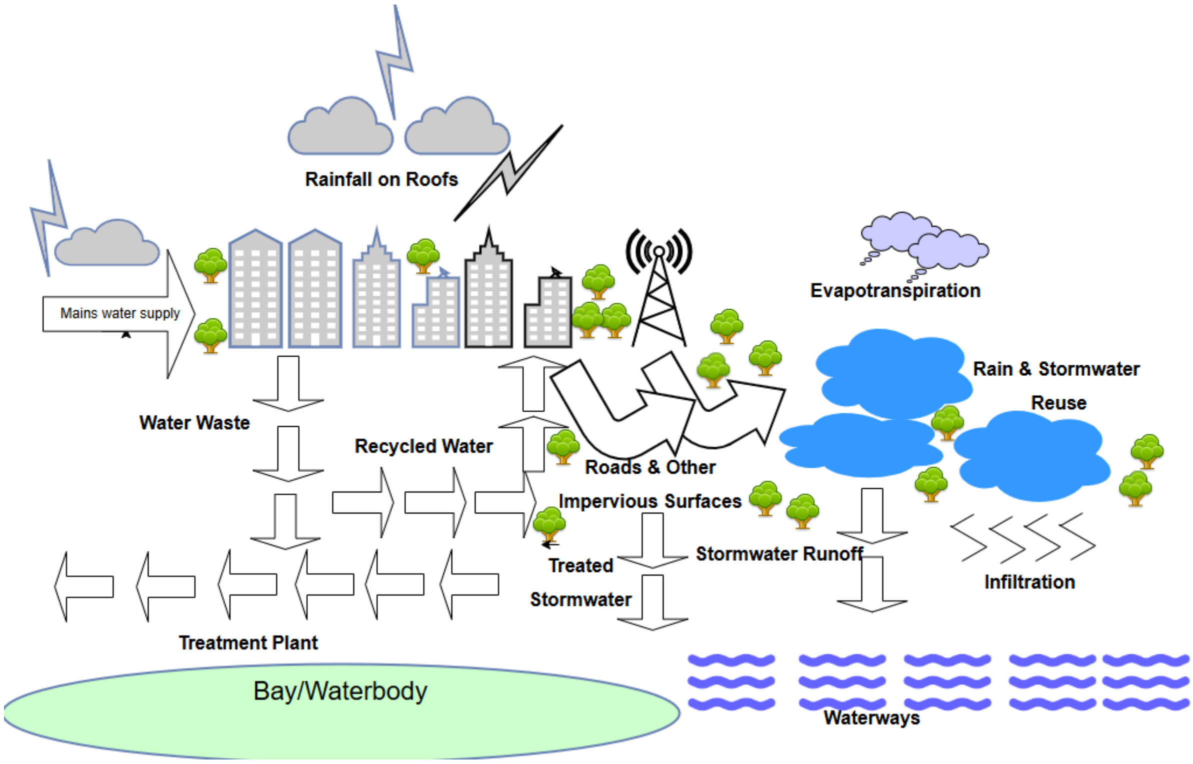

Figure 1. Water cycle in an urban environment

Table 2. Some important features of WSUD

Paper title	Authors	Major Findings	Comments
An Overview of Water Sensitive Urban Design Practices in Australia	Wong (2006)	WSUD is a proactive approach that integrates urban design, landscape architecture, and stormwater management infrastructure to work together seamlessly.	WSUD incorporates stormwater management into the planning and design of urban areas from regional catchments to individual precincts and buildings.
Framing water sensitive urban design as part of the urban form: A critical review of tools for best planning practice	Kuller et al. (2017)	WSUDand related green and distributed stormwater management systems are acknowledged by academics, practitioners, and policymakers as sustainable solutions.	Models, tools, and frameworks designed to support the planning and implementation of WSUD are discussed, including a new suitability framework for WSUD planning.
Transforming Cities through Water-Sensitive Principles and Practices	Wong et al. (2020)	WSUD is a context-specific approach that integrates sustainable water management with urban planning and design.	In the next 10 years, it is likely that water-sensitive practices will become mainstream as city stakeholders collectively adopt this sustainable approach.
Improved stormwater management through the combination of WSUD and pipeline network	Meng et al. (2022)	This study established a foundation for evaluating stormwater pipeline system design and landscape development in the context of retrofitting urban areas. .	The combined WSUD model exhibited the highest performance in managing stormwater across all rainfall scenarios from low to high.

Urban Water Management: A Review of Sustainable Practices in the USA	Nwokediegwuet al. (2024)	The future of sustainable urban water management depends on collaborative efforts, informed policymaking, and innovative research.	This underscored the complex nature of sustainable urban water management practices, covering water efficiency measures, green infrastructure initiatives, climate change resilience strategies, and pollution mitigation efforts.

2. STORMWATER QUALITY

Stormwater carries pollutants from urban environments into local waterways, rivers, and bays. Research has shown that stormwater is a major factor in the degradation of streams, estuaries, and embayments in Australian cities, as well as in cities globally (Van Leeuwen et al., 2019). This outlines the types of pollutants commonly found in stormwater and the harm runoff inflicts on the health of waterways. Several reviews have investigated concentrations of total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), and heavy metals (including copper, lead, and zinc) before any treatment measures are applied. These pollutants are central to current guidelines and standards for stormwater management. Numerous other studies have revealed that construction sites are the major source of pollution in stormwater. It is estimated that these sites generate 50 to 200 times more sediment and particulate pollution compared to fully developed urban areas (Adelaide and Mount Lofty Ranges Natural Resources Management Board, Submission 11*)*. WSUD elements can remove much of these pollutants from urban stormwater.

3. WSUD COMPONENTS

WSUD is a planning and design approach that emphasizes water sustainability, resilience, and environmental protection in urban environments. This approach incorporates the entire urban water cycle—including potable water, wastewater, and stormwater—into both built and natural landscapes, offering multiple benefits to society. A WSUD element is a device, system, or entire catchment designed based on WSUD principles. These elements are intended to manage urban stormwater and can include vegetated swales, living streams, biofilters, constructed wetlands, infiltration basins, soakwells, litter and sediment traps, and rainwater storage and reuse systems. In regions with high groundwater, stormwater management must address both surface water and groundwater, which may be permanent, seasonally perched during the wet season, or temporarily perched due to heavy rainfall events.

When a WSUD element is built in an area with high groundwater, nutrients and other pollutants from the groundwater can be mobilized and mix with surface water. This groundwater contribution can affect the water quality and flow through the WSUD element, potentially reducing its effectiveness in meeting performance objectives. Several studies concentrate on quantitatively monitoring the nutrient removal performance of WSUD elements and provide an overview of monitoring and analysis techniques, particularly in areas where high groundwater might affect their performance. However, it's important to recognize that many WSUD elements are designed to achieve multiple objectives, including water quality improvement, flow attenuation, enhanced amenity, microclimate benefits, public health and safety, and ecological health. These additional objectives can be equally or even more significant for assessing overall performance. Blue/green/purple roofs (vegetated roofs) are used to manage urban stormwater. Figure 2 illustrates its features. This technology advances our understanding of urban hydrology, enabling more effective stormwater management and reducing future flooding risks by vegetated roofs for pollutant control.

Infiltration basin helps to reduce peak runoff, reduces pollutant export to waterways and enhances groundwater recharge. Various studies have confirmed that a highwater table limits the rate of infiltration, decreases the thickness of the unsaturated zone between the basin and the water table, and thus reduces nutrient load attenuation. Figure 3 illustrates important features of infiltration basin.

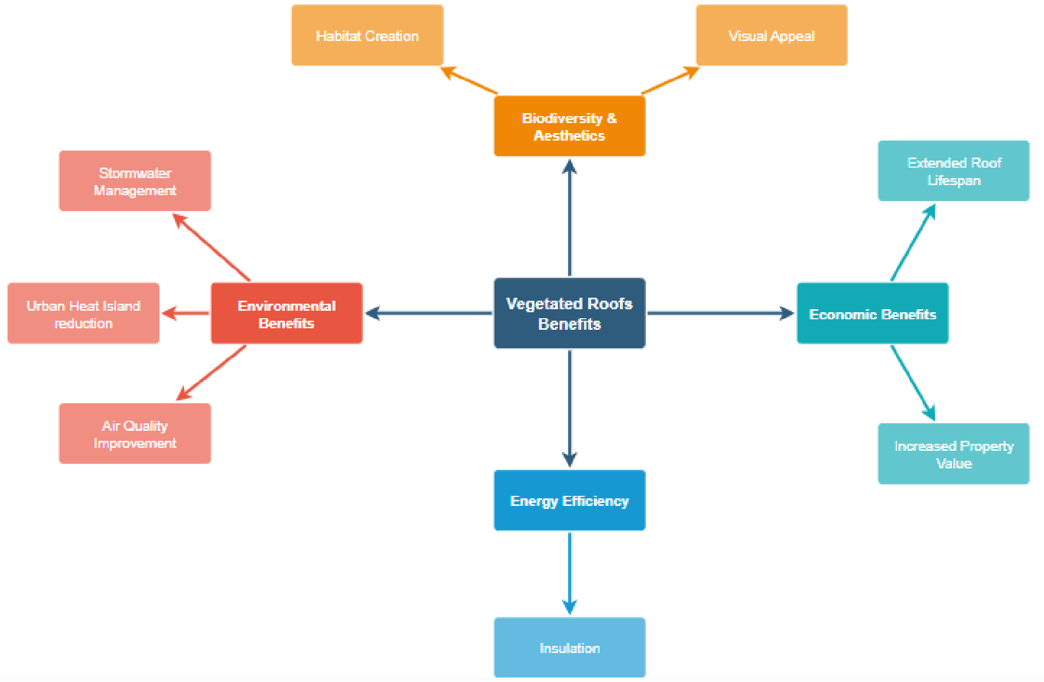

Figure 2. Features of vegetated roof as a WSUD component

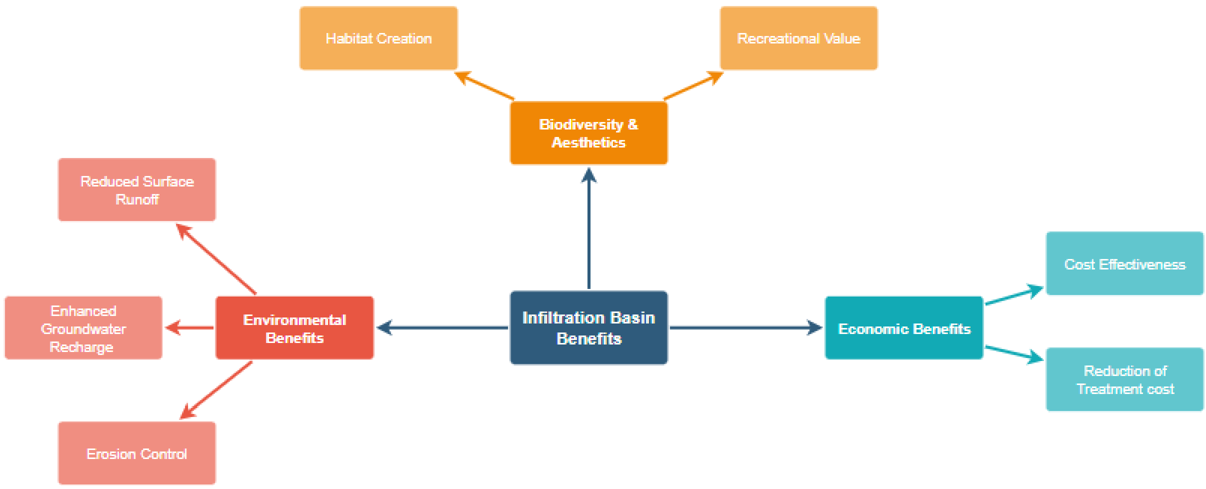

Figure 3. Important features of an infiltration basin as a WSUD component

Raingarden is a common WSUD element that reduces urban peak flow and attenuate nutrient load as illustrated in Figure 4. On average, the raingarden reduces peak storm flows by 89%. The water balance indicated that the water table did not interfere with the raingarden, although elevated water tables did reduce infiltration rates. Monitoring discharge and nutrient concentrations at both the inlet and outlet allowed for the calculation of nutrient load reductions. The raingarden proved highly effective in reducing total phosphorus (TP) loads by up to 90% and performed very well in reducing total nitrogen (TN) loads, with an average reduction of 72%.

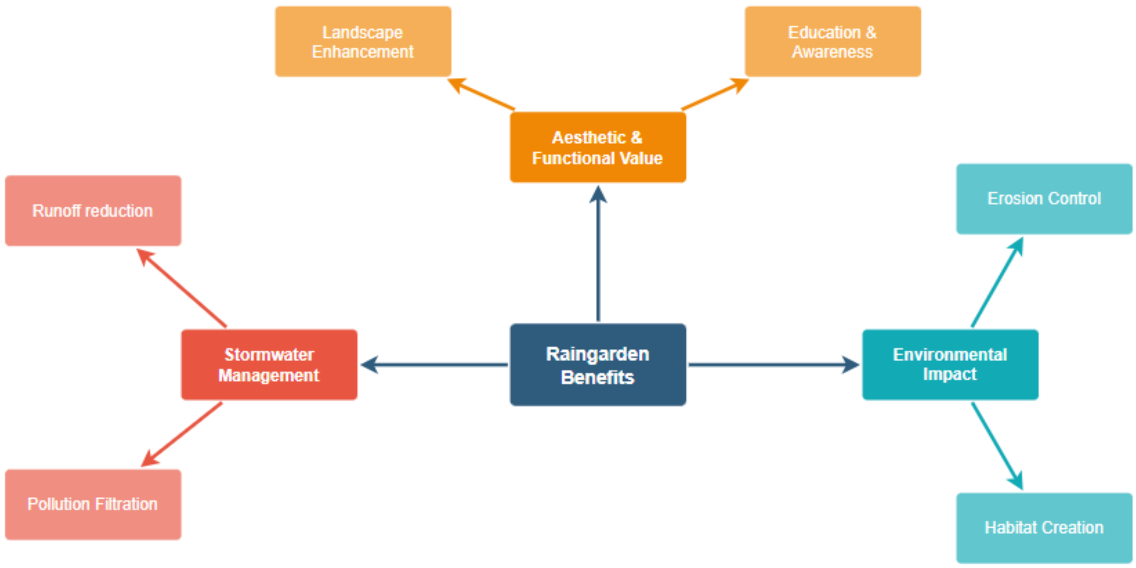

Figure 4. Benefits of raingarden

Bio-retention system is widely used in stormwater management (Figure 5). The detailed water balance analysis showed that groundwater contributed, on average, 20% of the outflow as the water table increased throughout the season. Overall, the bio-retention basin achieved a reduction in nutrient loads by 30%–40% for both total nitrogen (TN) and total phosphorus (TP).

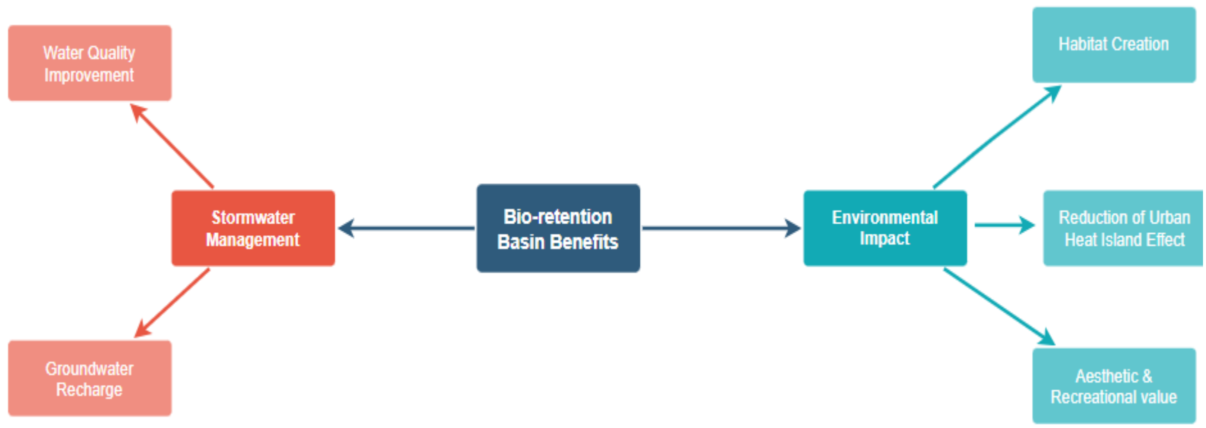

Figure 5. Benefits of bio-retention system

4. MODELING TOOLS USED IN WSUD

WSUD system for a proposed land development project in Australia is generally investigated and modeled using MUSIC software which was developed by Tony Wong at Monash University. This model has been recognised by most of the local government agencies in Australia. Imteaz et al. (2013) examined the relative accuracy of MUSIC model and noted that the inbuilt functions in MUSIC are based on simplified assumptions which may not be satisfied in many field conditions. Also, due to limited field data, MUSIC model cannot be confidently calibrated at many situations. Furthermore, the output of MUSIC model cannot be adequately verified due to lack of established field experiments. Local government organisations should set up few pilot studies at different regions of Australia to check the accuracy of estimated pollutant washoff given by MUSIC and similar models like SWMM.

5. CURRENT CHALLENGES ASSOCIATED WITH WSUD

A key concern with WSUD is the perceived high economic cost. In reality, WSUD elements are not significantly different from conventional 'end-of-pipe' treatment systems; however, the additional design and approval efforts often make WSUD more expensive (Leonard et al., 2019). While initial costs may be higher, the long-term benefits—including improved environmental outcomes and enhanced quality of life for communities—often outweigh these costs. WSUD offers superior environmental and community protection compared to traditional urban stormwater management systems, particularly in adapting to the uncertainties of climate change. Thorough research and site-specific analysis of WSUD features, combined with scenario modeling and comprehensive integration of all aspects of urban water management—such as water supply, waste, and stormwater management—can substantially lower costs and yield more precise and accurate cost assessments (Lloyd, 2001).

Some stakeholders remain sceptical about the effectiveness of WSUD methods, particularly concerning the perceived loss of valuable land due to the installation of WSUD components. Despite this, ponds and wetlands have been integrated into developments over the past decade, and approaches like stormwater treatment trains have demonstrated significant success in improving the quality of receiving waters and reducing flooding (Wong, 2001).However, improper implementation—such as failing to adequately integrate these systems with stormwater management strategies—has led to situations where they have been ineffective or even detrimental, thereby undermining the intended benefits of the approach (Lloyd et al., 2002; Wong, 2001).Wong (2001) highlights that insufficient technical expertise and knowledge within the industry for designing, evaluating, and maintaining water-sensitive development schemes has led to uncertainty about their effectiveness. Although the necessary technical principles and skills exist, they are often confined to specific departments or dispersed among various professions involved in urban water management (Lloyd, 2001).

The absence of standardized best practices and varying requirements can create confusion among agencies and developers (Cullen, 2007). Researchers such as Kay et al. (2004) and Roy et al. (2008) have identified the lack of consistent standards and knowledge among stakeholders as major obstacles to effectively implementing WSUD strategies.The challenges facing WSUD include envisioning urban and environmental sustainability, as well as creating and enforcing consistent planning tools and legislation that mandate its application (Beza et al., 2019). There have been limited studies on life cycle cost analysis on WSUD elements (Ali et al., 2004).

6. INTERNATIONAL DEVELOPMENTS

WSUD practices have increasingly gained international recognition, with various countries adopting these principles to suit their unique environmental, climatic, and urban conditions. Notable international advancements in WSUD and related practices are presented here.

- **Singapore (1990s):** In the 1990s, Singapore started applying WSUD principles to address stormwater management and enhance water quality in its densely populated urban areas. Key initiatives included the development of a comprehensive network of detention ponds and integrated drainage systems.

- **Paris Agreement (2015):** The global climate accord emphasized the importance of sustainable urban development, indirectly supporting WSUD practices by advocating for climate-resilient infrastructure and effective water management strategies.

- **International Conferences:** Events like the International Conference on Sustainable Urban Drainage Systems (SUDS) and other global water management forums have offered platforms for sharing WSUD practices and innovations. These conferences have fostered international collaboration and facilitated the exchange of knowledge.

- **Japan (2020s):** In the 2020s, Japan adopted advanced stormwater management technologies, such as smart drainage systems and real-time monitoring, to tackle frequent flooding and water quality challenges. These solutions reflect WSUD principles tailored to local needs.
- **Australia and New Zealand:** Ongoing advancements in WSUD technologies, including bio-swales, green roofs, and smart water management systems, have had a significant impact globally. Both countries have shared their experiences and research with international partners, contributing to the global development of WSUD practices.
- **Global Trends:** There is now a significant focus on integrating WSUD with broader urban resilience strategies, including climate adaptation, biodiversity enhancement, and community engagement. Globally, there is increasing interest in using digital tools and data analytics to optimize WSUD outcomes.
- **International Frameworks:** The continuous development of international frameworks and guidelines seeks to standardize WSUD practices and encourage their adoption across various regions. These frameworks highlight the importance of local adaptation and active stakeholder involvement.

International advancements in WSUD practices demonstrate a global acknowledgment of the necessity for sustainable water management in urban settings. Although approaches and technologies may differ, the primary objective remains consistent: to develop resilient, water-sensitive urban environments that promote environmental sustainability and improve quality of life. If we now focus on Australia’s aspect find that the majority of stormwater assets in Australian cities are made of concrete and generally require replacement every 100 to 150 years. (Fletcher, 2015). The asset base 'is believed to be in the order of tens of billions of dollars across major urban centres'.

Given the expected lifetime of stormwater infrastructure, examples of ageing urban infrastructure are apparent. The City of Melbourne, for example, advised that most of its drainage infrastructure is over 60 years old, although some drains date back to the 1850s. This infrastructure was built when flood mapping 'was poorly charted and understood', which has implications for effective stormwater management. The city noted that 'much of the existing drain infrastructure is reportedly designed to accommodate 1 in 5-year rainfall events and many road locations are not designed to adequately accommodate overland flow'. Work is underway on some areas of flash flooding risk so that the infrastructure is upgraded to 'cater for 1 in 20-year rainfall events'. Stormwater South Australia informs 'much of the existing trunk urban stormwater drainage infrastructure in Adelaide was constructed during the 1940s to 1980s' (Stormwater Australia, Submission 19). Stormwater South Australia outlined some of the consequences of this: The engineering design of these systems was based on an assumed percentage of impervious area derived from the future expected degree of development at the time of design. Other information such as design rainfalls and a catchments response to rainfall improved over time such that the stormwater design gradually became established on a much more robust technical foundation (Stormwater South Australia, Submission 32). The similar scenario is prevailing on other developed countries of the world specially which got ancient/old cities. Most of the stormwater infrastructure is not coping with the current challenges and alternatives are to be determined to tackle global challenges of population growth and climate change.

It should be noted that WSUD has few limitations such as there could be increased mosquito population and harmful algal growths due to stagnant water in constructed wetlands and natural channels. Also, the maintenance cost of WSUD-based drainage system could be higher in few cases such as regular cleaning of first flash devices with rainwater harvesting systems, bio-retention systems and constructed wetlands. Having said that the additional benefits provided by these WSUD elements need to be considered in their life cycle cost benefit analysis.

7. FUTURE RESEARCH NEEDS

- Claims of the stormwater models in terms of pollutant reduction by adopting certain WSUD elements need to be investigated at field levels, and in this regard the government and universities should take up joint research projects.
- New economic analysis tools should be developed incorporating total benefits (both tangible and intangible) in carrying out the life cycle cost analysis of WSUD system.
- Few WSUD elements such as green roofs have not been well researched in Australia and the current modelling tools (such as MUSIC) do not have capability to analyse and model these elements. Further research is needed in this area.
- Research should be undertaken on the long-term viability of WSUD elements (e.g. permeable pavement systems lose its effectiveness with time).

8. CONCLUSION

Renovating and upgrading traditional Stormwater pipelines are expensive, messy, time consuming and as well as hectic for residents as these brings interruption of services as of its nature of extensive digging and allocation. Moreover, we do not have much control on population growth and climate change. Hence rather it becomes more practicable to retain existing capacity of Stormwater where possible and adhere to WSUD to reduce discharge on these existing structures. Thus, budget on renovating structures can be utilised with WSUD if a wholistic approach could be made through government and respective agencies. Australia has made notable progress in stormwater management, continued innovation and adaptation are essential to address future challenges and maintain the effectiveness of stormwater systems which needs more attention fostering collaboration between governments, communities, and industries. Emphasizing adaptive management strategies, enhancing public engagement, and investing in innovative solutions will be crucial to ensuring sustainable and effective stormwater management in the face of a changing climate and growing urban pressures.

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