Proc. 3rd International Conference on Advancements in Engineering Education (iCAEED2024)
20-23 Nov 2024, Sydney, Australia
ISBN: 978-1-7636843-3-1

Water Sensitive Urban Design Practices in Indian Cities: A Critical Review

Shaik Rehana[1], Mohammad Shikaf Ali S[1], Ataur Rahman[2], Krishnan Sundara Rajan[1]

[1]Hydroclimatic Research Group, Lab for Spatial Informatics, International Institute of Information Technology, Gachibowli, Hyderabad, Telangana – 500032
[2]School of Engineering, Design and Built Environment, Penrith Campus, Western Sydney University, Sydney 2747, Australia
Corresponding author's E-mail: rehana.s@iiit.ac.in

Abstract

Rapid urbanization and climate change have intensified challenges related to urban water management. Water Sensitive Urban Design (WSUD) represents an innovative approach for managing urban water resources, integrating sustainable water management practices within urban planning. This systematic review focuses on the state of WSUD research in India both at a house-hold scale to a catchment or community scale. Despite being in the early stages of WSUD implementation, India's research highlights key themes, methodologies, and outcomes in this domain. Majority of the literatures reviewed the WSUD measures that is being practised in India from the early 19th century, which include rainwater harvesting methods, stormwater diversions, designing of permeable pavements, sustainable urban drainage systems (SuDS) etc. A considerable amount of work discusses about the improvements found in various quality and quantity-based parameters before and after WSUD implementation. The findings provide a detailed understanding of WSUD implementation and its applications, aiming to inform policymakers, practitioners, and researchers engaged in sustainable urban water management.

Keywords: Water Sensitive Urban Design, Sustainable Water Management, Low Impact Development, Sustainable Integrated Rural Water Management, Smart Water Management, Sponge City.

1. INTRODUCTION

Water-related problems have always been a point of consideration among environmentalists, and urban planners due to their significant impact on public health, economic development, and ecosystem sustainability (Mishra et al., 2021). The rapid increase in urbanization and population growth in metropolitan cities of India, has resulted in numerous water management challenges (Wakode et al., 2018). These challenges include increased impervious surfaces that lead to higher surface runoff, decreased groundwater recharge, and deteriorating water quality (Patel & Singhal, 2024). Traditional stormwater management approaches, often reliant on extensive drainage systems, are increasingly insufficient to cope with the hydrological impacts of urbanization and climate change (Fletcher et al., 2015). In this context, Water Sensitive Urban Design (WSUD) also known as Low Impact Development (LID) systems or Nature Based Solutions (NBS) or Sponge city concept emerges as a holistic approach that integrates urban planning with water cycle management to create resilient and sustainable urban environments (Rentachintala et al., 2022; Wong, 2006; Wong & Brown, 2009) . This concept is widely used to address water management challenges in urban areas, such as mitigating flood risks, enhancing water quality, and promoting sustainable water use (Gogate & Jedhe, 2021). WSUD has emerged as a comprehensive approach to managing urban water resources, addressing concerns such as flood control, water quality, and water conservation, and has been practiced around the world since 1960's (Vlotman et al., 2007).

In this study, a systematic review was conducted to focus on the state of WSUD research carried out in

India. Through a comprehensive synthesis of these influential studies, the review highlights the predominant themes, methodologies, and outcomes of WSUD research in India. The findings provide an in-depth understanding of the current practices and future directions for WSUD implementation, as well as the challenges faced during the application of WSUD practices aiming to inform policymakers, practitioners, and researchers engaged in sustainable urban water management.

2. HISTORY AND EVOLUTION OF WSUD PRACTICES

Predominantly, the concept of WSUD was originated in Australia in response to the environmental challenges posed by urbanization, aiming to integrate water management into urban planning (Wong, 2006). Structural methods like the construction of rain gardens, permeable pavements, green roofs and constructed wetlands along with methods like rainwater harvesting, and greywater recycling were initiated and are still followed throughout the world today (Wong & Brown, 2009). There have been more than 300 sites where WSUD projects were implemented in South Australia alone until 2016 (Sharma et al., 2016). Brown et al., (2008) developed a transition framework that describes the progressive stages cities undergo toward achieving sustainable urban water management as shown in Figure 1. This framework identifies six transition states, each driven by distinct socio-political factors and service delivery goals.

The stages form a nested continuum, where the hydro-social contract of each earlier stage influences and shapes the evolution of subsequent stages, guiding cities towards more sustainable futures. The adoption of WSUD methods has been more extensive in the Global North, with countries like the USA and UK, alongside Australia implementing these measures since the 1970s (Radcliffe, 2019; Weiss et al., 2019; Lashford et al., 2019). In contrast, cities in the Global South, such as Porto Alegre in Brazil and Cape Town in South Africa, have only recently begun adopting LID practices due to lack of regulatory support and public resistance (Narasimhan et al., 2023).

2.1 Water Sensitive Urban Design Practices in India

The practice of WSUD measures followed in India is intertwined with its geographical as well as its cultural history (Sinha et al., 2023). These practices rely heavily on the native soil's hydraulic properties, regional topography, groundwater conditions, rainfall patterns, and the overall land use and drainage systems of the area (Narasimhan et al., 2023). The studies done on WSUD in India can be categorized into two broad groups. The first category encompasses studies that describe various WSUD measures implemented historically and currently across India. This includes practices that could be done from a small household scale to a large community-level scale. The second category comprises quantitative and qualitative modeling studies that examine changes in parameters such as runoff rates, groundwater levels, and stormwater network efficiencies.

Water harvesting methods, such as rooftop rainwater harvesting and surface runoff collection, are employed to capture and store rainwater for non-potable uses, such as irrigation and toilet flushing (Rahman, 2018). Patel & Singhal (2024) proposed interventions like rainwater harvesting and water square projects after studying the rainfall pattern shifts in Surat over the last three decades which contributed to an average rise of 1.15 m in the groundwater level. Figure 2(a) shows a typical RWH system installed at the Centre for Science and Environment, New Delhi, India. Griha et al. (2020) describes about the rainwater collection implemented at Indian Institute of Management (IIM) Kozhikode using stormwater runoff from the roofs of campus buildings using downpipes and gutters leading to rainwater ditches.

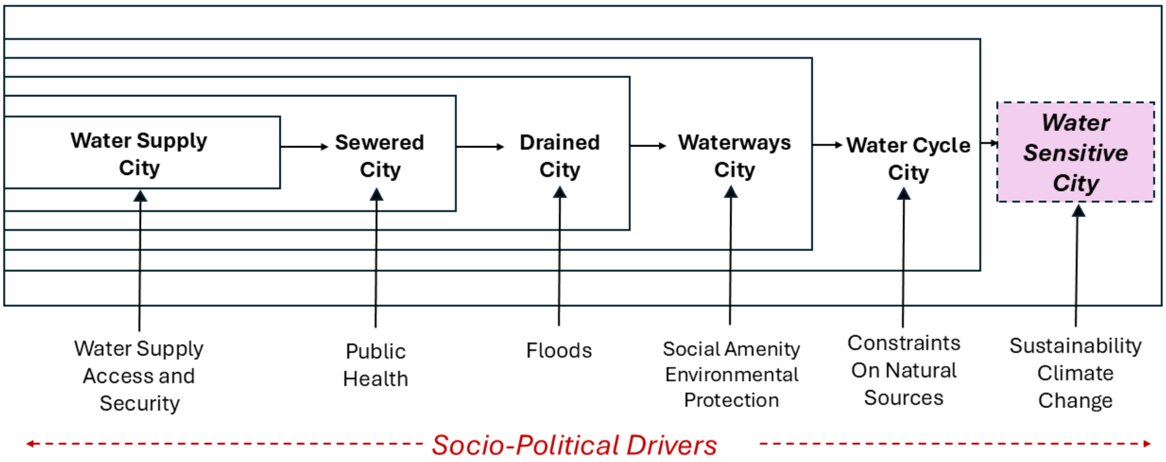

Figure 1. Urban Water Management Transition Framework (Source: Brown et al., 2008)

Kunds, holy ponds in Ayodhya, are not just religious sites but also serve a practical purpose in flood management (Sinha et al., 2023). These ponds act as natural reservoirs, storing excess rainwater and reducing the risk of flooding in the surrounding areas. Figure 2 (c) shows the 'Agni Kund' located south of Yajnavedi built in early 20th century with subterranean bricks alcoves. Juneja & Kumar Gupta, (2022) investigates the efficiency of various filter media for harvesting stormwater, emphasizing the need to treat stormwater to remove pollutants before it infiltrates the aquifers. The study found that coarse sand is the most effective filter medium depicted in Figure 2 (b), demonstrating high resistance to water impact and minimal breakage.

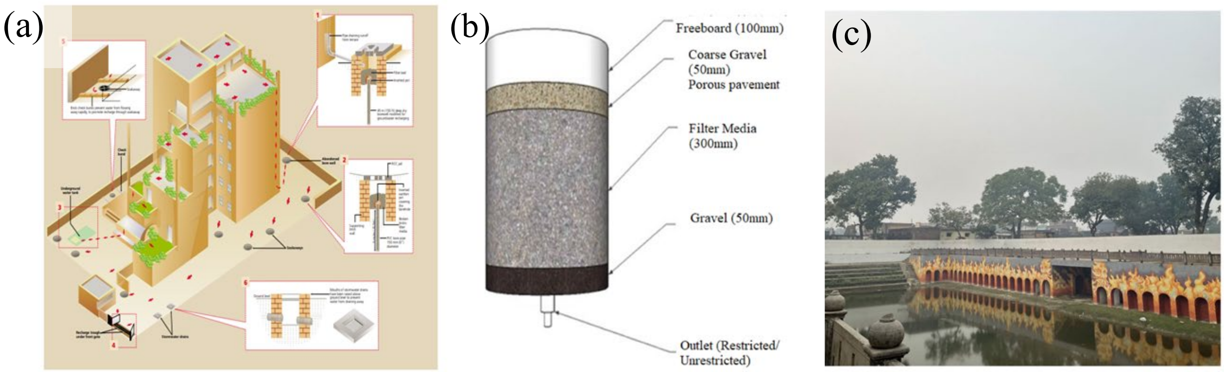

Figure 2. WSUD practices followed in India at a household scale.
(Source: (a) Kavarana et al., 2013 (b) Juneja et al., 2022 (c) Sinha et al., 2023)

BORDA & CDD (2003) utilizes a planted filter bed and polishing ponds at Aravind Eye Hospital in Thavalakuppam, Puducherry, to treat 320 KLD of grey and black water, reusing approximately 200,000 liters daily for landscape maintenance, resulting in an annual cost saving of about 240,000 Indian rupees (Figure 3(a)). Jain (2023) implemented rain garden, swales (Figure 3 (b)), permeable grooves, and filter strips at Women's Polytechnic and Sarojini Naidu Hall at Aligarh Muslim University (AMU), Aligarh, India to make the campus water sensitive. It was found that the rainwater collection tank meets 17% of the landscaping needs, and the remaining 2% to 3% could be used for cleaning or other non-potable purposes. Constructed wetlands, which are artificial ecosystems that filter pollutants and reduce flooding can be integrated into basin-scale stormwater management. Figure 3 (c) shows the application of a flaura-induced constructed wetland study by Jain (2024) to analyze the reduction in pollution.

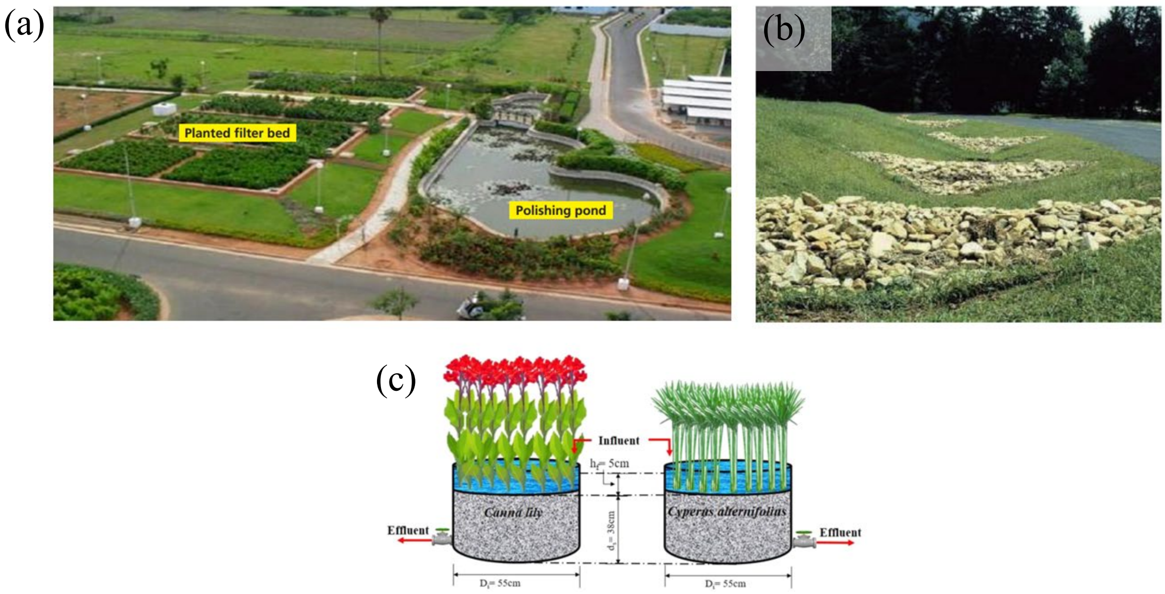

Figure 3. Different WSUD Practices followed in India at a basin/community scale. (Source: (a) BORDA & CDD - 2003 (b) Jain et al., 2023, (c) Jain et al., 2024)

2.2 Quantity and Quality based approaches

For investigating the hydrological impacts of various stormwater management scenarios in urban environments, Gogate & Jedhe (2021) employed the Natural Resources Conservation Service Curve Number (NRCS-CN) method in conjunction with the Arc-CN Runoff tool. They devised seven different scenarios by varying the combinations of leaky wells, rain gardens, and green roofs. Their study demonstrated a significant reduction in runoff volume across these scenarios, starting from the first scenario where no interventions were proposed to the seventh scenario where maximum possible interventions of these measures were taken (23.89% reduction in runoff was observed). Jain et al. (2024) focuses on using Canna lily and Cyperus alternifolius-based constructed wetland to remove phosphate from stormwater runoff through the setup shown in Figure 3(c). Phosphate removal efficiency varied with the average sunshine hours and the biomass concentration, with higher efficiency in summer for the later specimen. Due to the re-entry of phosphate into the wetland system, regular harvesting of plant biomass is necessary to export nutrients away from the system.

Hingmire & Bhaladhare (2023) developed an urban flood control model prototype using fuzzy logic and Internet of Things (IoT). The model's approach of considering input parameters like rainfall intensity, water flow rate, and water level in real-world scenarios aligns with the core principles of WSUD. Fuzzy logic controllers were employed at sub-catchments to regulate storm water pipe network pumps and drainage water pipe network pumps. The system optimized the use of actuators by considering real-time sensor data from all catchments to make collective decisions, thereby conserving power and effectively controlling floodwaters. Storm Water Control Network Model (SWCNM) and IoT are used in a real-time flood control system to calculate runoff on the primary storm water channel network. By achieving significant reductions in water levels during flood events, the study showcases the practical application of WSUD principles in mitigating urban flood risks. Table 2 represents a concise form of the information obtained through these studies. Rentachintala et al. (2022) developed a comprehensive stormwater network model for Amaravati city, India, utilizing StormCAD software. The model incorporates efficient rectangular channels, strategically designed outfall arrangements, and multiple discharge options to handle a designed discharge capacity of 23 m^3/s. Additionally, the study emphasized the importance of WSUD principles by integrating Sustainable Urban Drainage Systems (SUDS) and the Sponge City Programme into the stormwater network design.

Table 2. Details of WSUD-Based Modeling Works Published from India

Author	Region	Type of study	Method	Parameters	Remarks
Gogate & Jedhe (2021)	Pune	Quantity based modelling	NRCS CN	Green Roof Leaky Well Rain Garden	Runoff rates were reduced
Jain et al. (2024)	Delhi	Quality based modelling	APHA Method 4500-P	Canna lily, Cyperus alternifolius Constructed Wetlands	Total phosphate removal efficiency was increased
Hingmire & Bhaladhare, (2023)	Prototype	Prototype development	Storm Water Control Network Model	Rain intensity, water level, water flow rate	Water level reduction by 73.9% was achieved
Rentachintala et al. (2022)	Amaravati	Quantity based modelling	StormCAD software	Design discharge, Section type, Material & rise	Network discharge capacity and efficiency were assessed
Patel & Singhal (2024)	Gujarat	Quantity based modelling	SCS Curve Number	Rainfall pattern, impervious area, pervious area	Groundwater level rose 1.15 m in two years

The research by Sinha et al., 2023 explores the impact of climate change on urban water issues in India, emphasizing WSUD for sustainable management. It highlights challenges like increased runoff and groundwater depletion in cities such as Ahmedabad and Surat, and the need for adaptive stormwater strategies. The study underscores integrating climate change into water management, using localized solutions like flood detention ponds and permeable pavements, to ensure urban resilience and sustainable water availability.

3. APPLICATION IN FLOOD MANAGEMENT

Through the collected literature, it can be summarised that the intersection of WSUD practices with India's rich historical and cultural heritage presents a unique and compelling narrative for sustainable urban development in form of Kunds and Bawari's (Sinha et al.,2023). Way before practices like green roofs and rain gardens mimic natural hydrological processes, promoting infiltration and reducing stormwater runoff (Gogate et al., 2021). By capturing and storing rainwater, WSUD helps to mitigate the peak flow rates that contribute to flooding, thereby reducing the burden on existing drainage infrastructure. Additionally, it provides numerous environmental benefits, including improved water quality, habitat creation, and reduced urban heat island effect (Pritipadmaja et al., 2023). However, the effectiveness of WSUD depends on factors such as site conditions, maintenance practices, and integration with existing infrastructure.

In some cases, WSUD may require additional stormwater management measures, such as detention ponds or underground storage tanks, to address large-scale flooding events. The initial capital investment for WSUD implementation can be substantial, and the maintenance of these systems requires ongoing operational oversight. Also, the cumulative impact of WSUD practices on watershed hydrology remains underexplored, with uncertainties about their broader-scale effects despite their known benefits for flood control and groundwater recharge (Narasimhan et al., 2023).

4.CONCLUSIONS

- WSUD practices in India, such as rainwater harvesting and constructed wetlands can be promising in addressing urban water challenges like flooding and water quality degradation.
- The reviewed case studies showcase a variety of WSUD techniques being implemented, including rainwater harvesting, stormwater biofiltration, and constructed wetlands.
- Quantitative modeling studies demonstrate measurable improvements in hydrological parameters and stormwater management efficiency through WSUD interventions.
- Technological advancements, like IoT-enabled flood control systems, are enhancing the effectiveness of WSUD strategies in urban water management.
- The integration of technological advancements like fuzzy logic into WSUD systems holds promise for enhanced water management efficiency and flood control.
- Emerging WSUD techniques such as green roof (Alim et al., 2023) and permeable pavement systems (Kuruppu et al., should also be explored for India.
- Future research should focus on long-term sustainability and scalability of WSUD solutions, along with developing standardized guidelines for diverse urban contexts in India.

ACKNOWLEDGMENTS

The research presented in this study is funded by the Scheme for Promotion of Academic and Research Collaboration (SPARC) Program funded by Ministry of Human Resource Development, Government of India with Project ID-P2488.

REFERENCES

Alim, M.A., Jahan, S., Rahman, A., Rahman, M.A., Liebman, M., Garner, B., Griffith, R., Griffith, M. & Tao, Z. (2023). Experimental investigation of a multilayer detention roof for stormwater management, *Journal of Cleaner Production*, 395, 136413.

Brown, R. R., Keath, N., & Wong, T. (2008). Transitioning to Water Sensitive Cities: Historical Current and Future Transition States. In R. Ashley (Ed.), *Conference Proceedings: 11th International Conference on Urban Drainage* (pp. CD Rom - CD Rom). IWA Publishing.

Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., ... & Viklander, M. (2015). SUDS, LID, BMPs, WSUD and more–The evolution and application of terminology surrounding urban drainage. *Urban WaterJournal*, *12*(7), 525-542.

Gogate, N. G., & Jedhe, Y. (2021). Alternative storm-water management scenarios for developing.
countries in urban contexts. *Journal of Environmental Engineering and Science*, *16*(4), 195-204.

Griha (2020). IIM Kozhikode Campus. Retrieved January 15, 2022, from https://www.grihaindia.org/sites/default/files/sites/default/files/pdf/case-studies/IIM-Kozhikode-Campus.pdf

Hingmire, A. M., & Bhaladhare, P. R. (2022). Urban Flood Control System using Fuzzy Logic and Internet of Things (IoT) for Smart City. *NeuroQuantology*, *20*(19), 115.

Jain, N., Yadav, S., Taneja, S., Ray, S., Haritash, A. K., & Pipil, H. (2024). Phosphate removal from urban stormwater runoff using Canna lily and Cyperus alternifolius-based bioretention system. *Sustainable Water Resources Management*, *10*(2), 65.

Jain, S., & Kamal, M. A. (2023) Storm Water Management through Water Sensitive Urban Design and Planning: Case of a University Campus in India.

Juneja, D., & Gupta, S. K. (2022). Investigation of various filter media employed in harvesters. *Materials Today: Proceedings*, *68*, 922-926.

Kavarana, G., & Sengupta, S. (2013). Catch water where it falls: toolkit on rainwater harvesting. *Published by center for science and environment India*, 1-8.

Kuruppu, U., Rahman, A., & Sathasivan, A. (2019). Enhanced denitrification by design modifications to the permeable pavement structure, *Journal of Cleaner Production*, 237(2019), 117721.

Lashford, C., Rubinato, M., Cai, Y., Hou, J., Abolfathi, S., Coupe, S., ... & Tait, S. (2019). SuDS & sponge cities: a comparative analysis of the implementation of pluvial flood management in the UK and China. *Sustainability*, *11*(1), 213.

Mishra, B. K., Kumar, P., Saraswat, C., Chakraborty, S., & Gautam, A. (2021). Water security in a changing environment: Concept, challenges and solutions. *Water*, *13*(4), 490.

Narasimhan, B., Sreethu, S., Modi, K., Arun, R. S., Anelli, R., Imani, M., & Bhallamudi, S. M. (2023). Sustainable urban drainage systems. *Technological Solutions for Water Sustainability: Challenges and Prospects*, 255.

PATEL, C., & Singhal, R. (2024). Policy Interventions to Address Urban Water Problems of highly urbanised area due to Climate Change. *MAUSAM*, *75*(1), 35-46.

Pritipadmaja, Garg, R. D., & Sharma, A. K. (2023). Assessing the cooling effect of blue-green spaces: implications for Urban Heat Island mitigation. *Water*, *15*(16), 2983.

Radcliffe, J. C. (2019). History of water sensitive urban design/low impact development adoption in Australia and internationally. In *Approaches to water sensitive urban design* (pp. 1-24). Woodhead Publishing.

Rahman, A. (2018). Rainwater Harvesting: Quantity, Quality, Economics and State Regulations, edited by Rahman, A., *Water*, MDPI, Basel, Switzerland, 168 pp.

Rentachintala, L. R. N. P., Muni Reddy, M. G., & Mohapatra, P. K. (2022, April). Network Model for Sustainable and/or Resilient Integrated Stormwater Management of a Water Sensitive City—A Case Study. In *Recent Developments in Sustainable Infrastructure (ICRDSI-2020)—GEO-TRA-ENV-WRM: Conference Proceedings from ICRDSI-2020 Vol. 2* (pp. 199-209). Singapore: Springer Singapore.

Sinha, A., Kant, R., & Yadav, A. (2023). Sacral waters and the jewel mountain: reclaiming kunds in Ayodhya, India. *Landscape Research*, *48*(7), 950-967.

Sharma, A. K., Pezzaniti, D., Myers, B., Cook, S., Tjandraatmadja, G., Chacko, P., ... & Walton, A. (2016). Water sensitive urban design: An investigation of current systems, implementation drivers, community perceptions and potential to supplement urban water services. *Water*, *8*(7), 272.

van der Meulen, G. J., Mishra, G., van Dorst, M. J., Iyer, M., & Bacchin, T. K. (2023). Reviewing Historic Urban Water Transitions to Advance Water-Sensitive Urban Design for Bhuj, India. *Land*, *12*(10), 1938.

Vlotman, W. F., Wong, T., & Schultz, B. (2007). Integration of drainage, water quality and flood management in rural, urban and lowland areas. *Irrigation and Drainage: The journal of the International Commission on Irrigation and Drainage*, *56*(S1), S161-S177.

Wakode, H. B., Baier, K., Jha, R., & Azzam, R. (2018). Impact of urbanization on groundwater recharge and urban water balance for the city of Hyderabad, India. *International Soil and Water Conservation Research*, *6*(1), 51-62.
Weiss, P. T., Gulliver, J. S., & Ebrahimian, A. (2021). US version of water-wise cities: Low impact development. *AND SUSTAINABLE WATER SYSTEMS*, 77.

Wong, T. H. (2006). Water sensitive urban design-the journey thus far. *Australasian Journal of Water Resources*, *10*(3), 213-222.
Wong, T. H., & Brown, R. R. (2009). The water sensitive city: principles for practice. *Water science and technology*, *60*(3), 673-682.
https://www.youtube.com/watch?v=Pm5y_6iV1q0 (BORDA & CDD), as accessed on 24/08/2024.