Strategy and Action plan for Bengaluru

Building resilience to urban floods

Water and Society Programme
Centre for Environment and Development
Ashoka Trust for Research in Ecology and the Environment

Authors: Dr. Priyanka Jamwal, Hymavathi P, Aishwarya Nair, Samhitha D
Co-author for Chapter 1: Vardhini Suresh
Project coordinator: Vardhini Suresh

Ashoka Trust for Research in Ecology and the Environment (ATREE), PO, Royal Enclave, Srirampura, Jakkur, Bengaluru, Karnataka 560064

ISBN: 978-81-940887-9-0

Printed at: Print Central, Bengaluru

Book Design: Ashwin H V

Published by: Ashoka Trust for Research in Ecology and the Environment (ATREE), Royal Enclave, Sriramapura, Jakkur, Bangalore - 560064, India. www.atree.org

Suggested citation: Jamwal, P., Hymavathi, P., Nair, A., Samhitha, D., & Suresh, V. (2024). *Building resilience to urban floods: Strategy and action plan for Bengaluru*. Ashoka Trust for Research in Ecology and the Environment. ISBN: 978-81-940887-9-0

March 2024

Table of Contents

List of Figures

List of Tables

List of Plates

Acknowledgements

We extend our heartfelt gratitude and sincere thanks to Ashoka Trust for Research in Ecology and the Environment (ATREE) for generously providing the necessary infrastructure that enabled us to conduct the project work.

We acknowledge the indispensable support and assistance provided by Dr. Renukumar K. S, Additional Chief Engineer (Design) from Bangalore Water Supply and Sewerage Board (BWSSB), Ms. Arpitha H. M, Hydrology Department from Karnataka State Natural Disaster Monitoring Centre (KSNDMC), and Dr. M. Inayathulla, Professor, Department of Civil Engineering, University of Visvesvaraya College of Engineering, Bangalore University, without which the finalization of this document would not have been possible.

We thank Dr. Soubadra Devy, Dr. Vinay Shankar, Dr. Ashish Kumar and Dr. Sachin Tiwale for their valuable inputs.

A special mention goes to Dr. Sharachchandra Lele for his invaluable guidance and providing the data that is required to carry out the work.

We sincerely appreciate the attendees ATREE, Center for Study of Science, Technology and Policy (CSTEP), Consortium for DEWATS Dissemination Society, Ellara Bengaluru, Federation of Bengaluru Lakes, Janaagraha, Manipal Academy of Higher Education, Paani Earth, Public Landscape and Urbanism Studio, University of Visvesvaraya College of Engineering, Vanalok Ventures Pvt Ltd, Well Labs, and World Resources Institute India for their invaluable contributions during the workshop on “Co-creating strategy and action plan for Bengaluru in the context of urban flooding.” Their insights, expertise, and active participation enriched the discussions and played a crucial role in shaping the outcomes of the workshop.

Chapter 1

Introduction

Bengaluru city is located at 12°58′N latitude and 77°35′E longitude, almost equidistant from both eastern and western coast of the South Indian peninsula, and is situated at an altitude of 920 metres above mean sea level. The city has a distinct wet and dry season; summers are hot and dry, with temperatures often reaching over 35°C, while the monsoon season from June to September brings heavy rainfall.

The Doddabettadahalli, the tallest ridge in the city at 962 meters above mean sea level, is a central ridge that runs natural routes across the city's hills and valleys from northeast to southwest. The city has three major valleys separated by naturally occurring centre ridge namely, Koramangala Challaghatta valley, Hebbal-Nagawara valley and Vrishabhavathi valley, as shown in the figure 1-1 (Avinash et al., 2018).

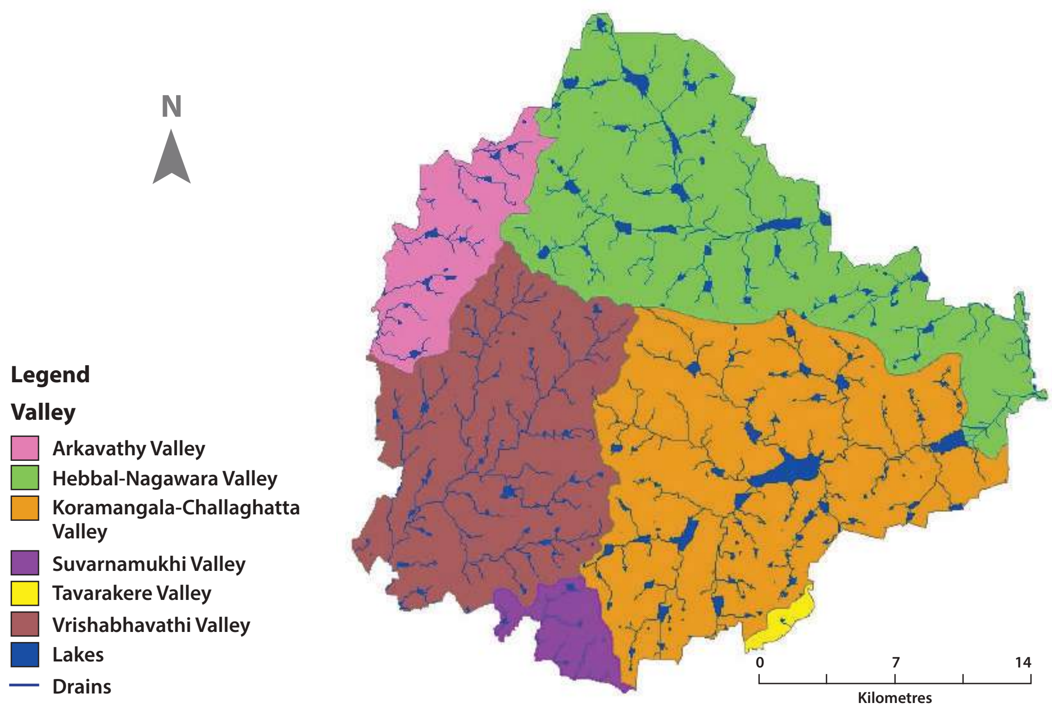


Figure 1-1: Valley map of Bengaluru

1.1 History of Bengaluru city

The early inhabitants of Bengaluru took advantage of the undulating topography of the land to build artificial lakes. Lakes also called as kere in local language facilitated the collection of rainwater and percolation into the porous ground. Excess rainwater from lakes at higher altitude was channelled through primary stormwater drains which are called as Rajakaluves in local language, ensuring a continuous flow into the lakes at the downstream. This ingenious system prevented flooding and provided water for the city and its surroundings. However, as Bengaluru's population grew, water demand increased, leading to the development of water treatment and supply infrastructure. Notable developments included the establishment of the Yele Mallappa Shetty Lake in 1926, named after a betel merchant who established this lake, to supplement water sources, followed by the construction of the Tippagondanahalli reservoir in 1930 to meet rising demands. By 1974, water sourcing extended to the Cauvery River, located 856 km south of the city (Nagendra & Mundoli, 2023)

Bengaluru saw a period of rapid growth between 1941 and 1951, which helped it rise to become India's fifth-largest metropolis by 1961. Growing employment prospects drove this expansion, first in the public sector and then in the textile and IT industries, drawing immigrants from throughout the nation.

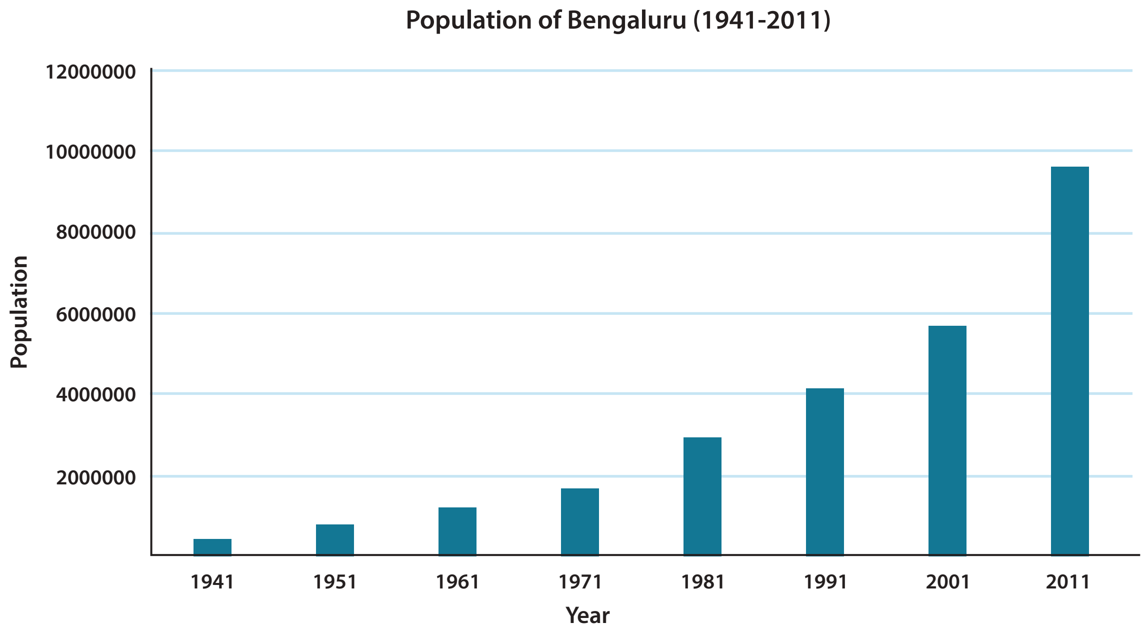


Figure 1-2: Graph showing decadal population of Bengaluru (Sudhira, 2008)

Following are the reasons behind the major transformations of Bengaluru from a town to a cosmopolitan as mentioned in the report by 'JNNURM- Revised City Development Plan, Volume I: Urban Infrastructure and Governance, 2009':

1. The relocation of the State Capital from Mysore to Bengaluru, in 1831.

2. The establishment of the Cantonment, which played a crucial role in the city's core development.

3. The establishment of public sector undertakings and academic institutions, contributing to job creation and economic growth.

4. The growth of the textile industry, which emerged as a significant economic driver.

5. The development of Information Technology (IT), Information Technology Enabled Services (ITES), and biotech-based industries, positioning Bengaluru as a global hub for innovation and technology-driven growth

The population growth of Bengaluru 2011 represents a significant surge as shown in figure 1-2, from 5.6 million in 2001 to 9.6 million in 2011, driven by factors such as migration for employment opportunities in the IT and service sectors, and coupled with its cosmopolitan atmosphere and vibrant culture, attracted a diverse workforce from across the country and abroad (Sudhira, 2008).

Moreover, infrastructure development initiatives, including the expansion of transportation networks and the establishment of new residential and commercial hubs, contributed to the city's population growth. However, this rapid urbanization also posed challenges such as increased strain on public services, inadequate housing, and environmental degradation.

The increasing population in Bengaluru city has put strain on wastewater collection and infrastructure. Despite efforts to expand and upgrade infrastructure, the pace of development has not kept up with the rapid population growth in the city. As a result approximately 60 percent of the untreated wastewater finds its way to the open stormwater drains that is discharged to the lakes (Jamwal et al., 2014; CSE, 2012).

Overall, the population increase in Bengaluru underscores the complex interplay of socio-economic factors shaping urban growth in India, highlighting the need for sustainable urban planning and effective governance to address the evolving needs of a rapidly expanding city.

1.2 Rapid urbanization

The escalating pace of urbanization in South Asian cities has rendered them increasingly vulnerable to natural disasters, resulting in high rates of economic losses, property damage, and fatalities. Among these rapidly growing urban centers, including Mumbai, Kolkata, Bengaluru, Delhi, and Chennai, climate change poses a significant risk due to their massive populations. Currently, 54% of the world's urban populace resides in Asia, and projections indicate that by 2050, 64% of the continent's 3.3 billion inhabitants will be concentrated in these urban hubs, making Asia home to the largest urban agglomerations globally (Manandhar et al., 2023).

Between 2000 and 2016, Bengaluru witnessed a staggering loss of 75% of its vegetation cover, as revealed by data sourced from the Moderate Resolution Imaging Spectroradiometer (MODIS) (Alex et al., 2017). This is also evident from the land use land cover change data from 2017- 2022 presented in figure 1-3 for Yelahanka which is of 157 square kilometers (sq.km) catchment located in northern part of urban Bengaluru. Utilizing Sentinel-2 satellite imagery with a resolution of 10 meters, the analysis indicates a notable increase in impervious area within the Yelahanka catchment, escalating from 74.48% to 80% over the past six years.

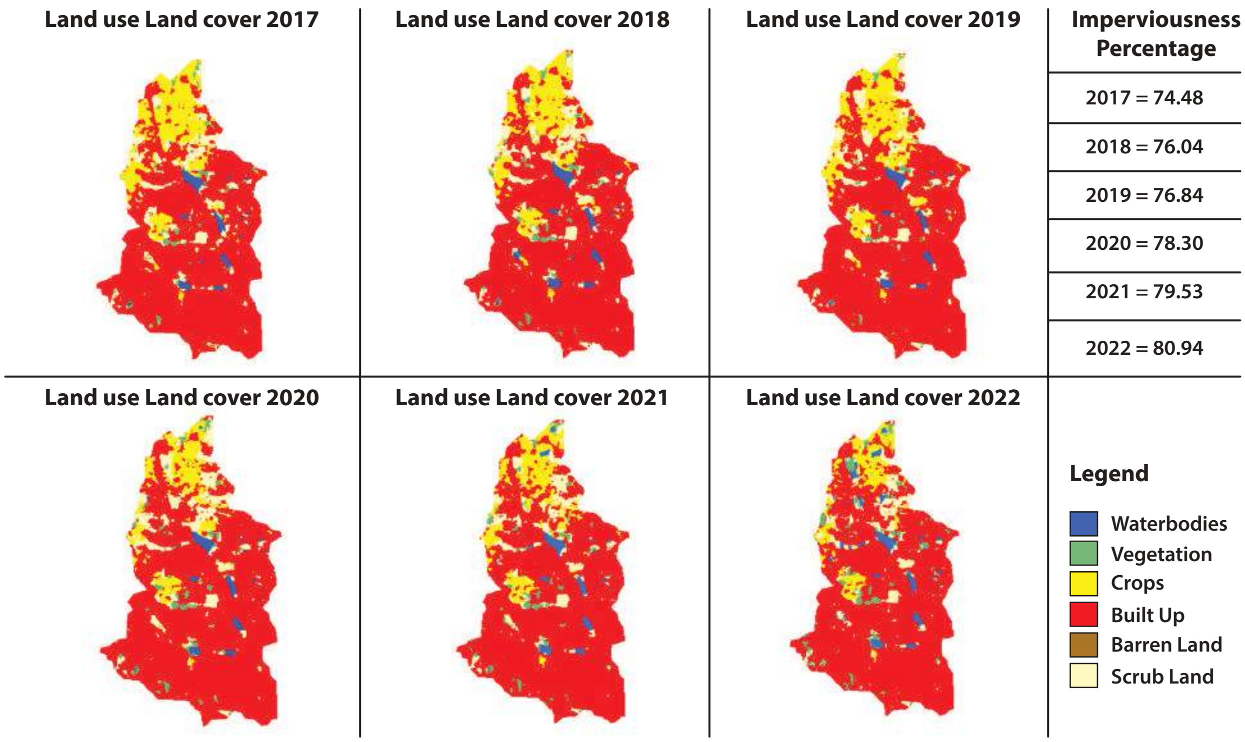


Figure 1-3: Land use and Land cover changes of Yelahanka catchment from 2017- 2022

The rise in imperviousness and the depletion of blue and green cover are strongly correlated with heightened incidences of flooding during rainfall events. Furthermore, encroachments upon stormwater drains exacerbate this issue by disrupting the natural connectivity of the landscape, impeding its ability to effectively manage rainfall runoff (Ramachandra & Mujumdar, 2009).

1.3 Urban floods in Bengaluru

In 1961, Bengaluru accounted for 262 water bodies. However, urbanization led to a 58% decline in these water bodies, with the built-up area experiencing a staggering 466% increase between 1973 and 2007(Gupta, 2009). Bengaluru Urban experienced a total of 73 flood events from 1969 to 2019, leading to significant loss of life and property (Jahnavi T. R. 2024). During 2022 rainfall 96 lives were lost between June to September across the state of Karnataka and the estimated property loss reported was 7647 crores (Varghese et al., 2022).

The United Nation's Intergovernmental Panel on Climate Change (IPCC) has issued a warning about an increase in extreme weather occurrences throughout South Asia in the upcoming years. Urban regions in Asia are deemed to be high-risk due to anticipated changes in climate, intense weather, unplanned urbanization, and swift changes in land use (Behl, 2022). The subsequent sections will delve into the direct and indirect causes of urban flooding in Bengaluru.

1.3.1. Direct causes of urban flooding in Bengaluru

Urban flooding arises from an intricate interplay of factors, presenting formidable challenges for stakeholders in risk management. The following are primary causes of urban flooding documented in various studies:

1. **Climate Change:** The shifting climate patterns coupled with heightened frequency and intensity of rainfall events, attributed to climate change, exacerbate urban flooding in Bengaluru (T. V. Ramachandra et al., 2017).
2. **Poor drainage maintenance:** The "Performance Audit of Management of Storm Water in Bengaluru Urban Area, 2021" highlights deficiencies in stormwater drain upkeep. Substandard maintenance fails to efficiently channel stormwater runoff, often obstructed by solid waste disposal, as depicted in plate 1-1. Consequently, waterlogging and flooding occur during heavy rainfall.
3. **Encroachment of water bodies:** Unplanned urban expansion leads to encroachment upon lakes, ponds, and natural drainage pathways. This encroachment diminishes their capacity to retain or divert water, heightening the vulnerability to flooding (T. V. Ramachandra et al., 2017).

Plate 1-1: Stormwater drain choked with solid waste

1.3.2. Indirect causes of urban flooding in Bengaluru

The indirect causes of urban flooding in Bengaluru are underlying conditions that contribute to the phenomenon. While these causes may not directly trigger the disaster, they significantly influence the city's vulnerability to flooding and exacerbate its severity. The following are the indirect causes of urban flooding in Bengaluru:

1. **Rapid Increase in impervious areas:** The rapid urbanization and unchecked development result in the conversion of natural landscapes into impervious surfaces. This transformation intensifies runoff and elevates the risk of flooding (Ramachandra & Mujumdar, 2009)
2. **Urban planning:** Unplanned urban expansion neglects considerations for flood risk and fails to integrate preventive measures such as green spaces, retention ponds, and flood-resistant infrastructure (Singh et al., 2023)
3. **Population growth:** The swift population growth strains existing infrastructure and amplifies the demand for housing, leading to the expansion of urban areas into flood-prone zones (Jamwal et al., 2014)
4. **Socio-economic disparities:** Vulnerable communities residing in low-lying areas or informal settlements bear a disproportionate burden of urban flooding. This exacerbates social inequalities and widens disparities in access to resources and services (Chatterjee, 2010).

1.4 Systems elements approach

We used systems approach employed to understand and analyse the problem of urban floods in Bengaluru, illustrated in figure 1-4. This approach identifies water as a central element, recognizing its multifaceted hazards to society, encompassing urban flooding, water contamination, and biohazards like pathogens. Further elaborating, this approach outlines the exposed elements, including communities, hospitals, biodiversity, residential buildings, infrastructure (encompassing blue, green, and grey infrastructure), transportation infrastructure, commercial establishments, industrial facilities, and office complexes. However, vulnerability remains a pivotal factor even post-exposure, influenced by various determinants such as age, gender, topography/location, income, and disability, all of which elevate the susceptibility of the exposed elements to risk.

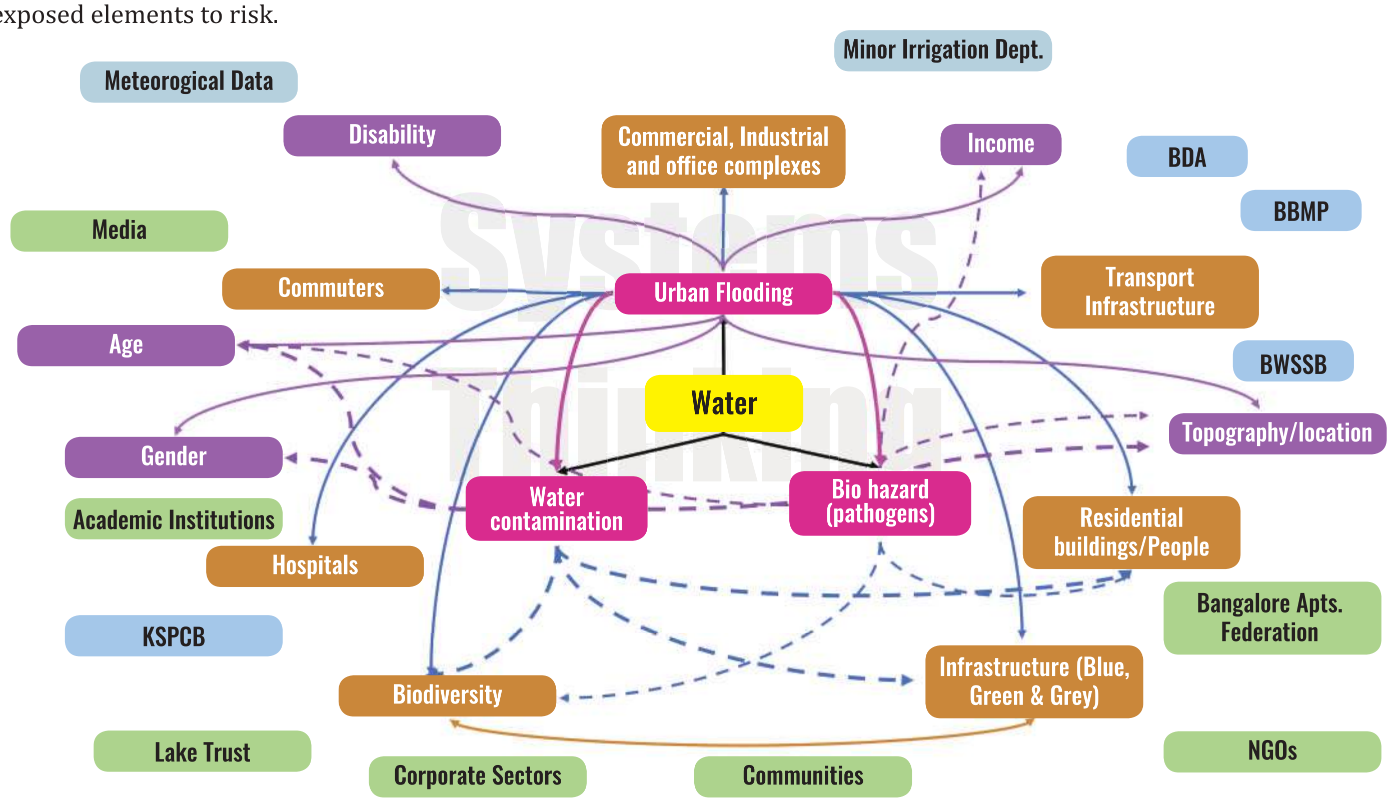


Figure 1-4: Diagrammatic representation of systems elements approach

A diverse array of stakeholders and actors play pivotal roles in addressing and mitigating the challenges posed by urban flooding. Each possesses unique capacities and resources that contribute to comprehensive flood management strategies:

1. **Karnataka State Natural Disaster Monitoring Centre (KSNDMC):** KSNDMC monitors and operates early warning systems for natural disasters, including floods, facilitating timely responses and interventions.
2. **Karnataka State Pollution Control Board (KSPCB):** KSPCB regulates pollution and ensures water quality standards, addressing water contamination issues linked with urban flooding.
3. **Bangalore Water Supply and Sewerage Board (BWSSB):** BWSSB manages water supply and sewage systems in Bengaluru, playing a crucial role in flood mitigation through efficient drainage systems and infrastructure upkeep.
4. **Bruhat Bengaluru Mahanagara Palike (BBMP):** BBMP, the municipal corporation, oversees urban governance and is pivotal in disaster preparedness, response, and recovery, including infrastructure development and community engagement.
5. **Bangalore Development Authority (BDA):** BDA is involved in urban planning and development, including land-use planning and infrastructure development aimed at mitigating flood risks and enhancing urban resilience.
6. **Minor Irrigation Department:** This department manages minor irrigation projects and water resources, contributing to flood management efforts through water diversion and retention strategies.
7. **Media:** Media plays a crucial role in disseminating information, raising awareness, and fostering public participation in flood preparedness and response activities.

8. **Academic Institutions:** Academic institutions contribute to flood research, data analysis, and capacity-building initiatives, providing valuable insights and expertise to inform flood management strategies.
9. **Lake Trust Groups:** These groups focus on the conservation and restoration of Bengaluru's lakes, which play a significant role in flood regulation and water management.
10. **Corporate Sectors:** Corporations can contribute through Corporate Social Responsibility (CSR) initiatives, funding support, and expertise in technology and innovation for flood management solutions.
11. **Communities:** Local communities are vital stakeholders in flood management, contributing to resilience-building efforts through community-based approaches and grassroots initiatives.
12. **Non-Governmental Organizations (NGOs):** NGOs advocate for flood management, undertake capacity-building initiatives, and implement community-led projects for flood preparedness, response, and recovery.
13. **Bangalore Apartment Federation:** Representing residential complexes and apartment communities, this federation facilitates coordination and cooperation among its members for flood preparedness and mitigation efforts at the local level.

Collaboration and coordination among these stakeholders are essential for implementing effective flood management strategies in Bengaluru. By comprehensively outlining these elements, the systems approach provides insight into interconnected vulnerabilities in the urban environment, empowering policymakers and stakeholders to craft precise interventions and strategies for mitigating the complex challenges presented by urban floods. While government efforts are significant, implementing Low Impact interventions at the local level can also play a crucial role in mitigating flood risk. The Water and Society Programme at ATREE conducted an assessment to evaluate the impacts of various Nature-based Solutions (NbS) on flood inundation and runoff volume, using mathematical modelling approaches for a 10-year return period.

Roadmap to this document

After establishing the problem of urban flooding and dissecting its intricate components using the systems elements approach in Chapter 1, the subsequent chapters of this report delve into specific aspects of flood management and mitigation strategies. In Chapter 2, we describe the mathematical models utilized to evaluate the effectiveness of existing stormwater drainage networks against ten-year return period events. This assessment is carried out for the Yelahanka sub-catchment which is of 21 sq.km situated in the northern part of the city. Moving on to Chapter 3, we provide a comprehensive overview of low development infrastructure, or Nature-based Solutions, implemented globally to tackle urban flooding issues. In Chapter 4, we employ a risk framework to meticulously examine the hazards, exposure, and vulnerability within the Yelahanka sub-catchment. Subsequently, using advanced modelling techniques and Geographic Information System (GIS) tools, we simulate and visualize the impact of deploying Nature-based Solutions on urban flood parameters such as inundation depth and flooded area. This chapter also includes estimating the reduction in hazard, exposure, vulnerability, and overall risk within the catchment following the implementation of Nature-based Solutions.

Chapter 5 is the formulation of existing measures, suggestions and steps to be taken for “Urban flood strategy and action plan” that were proposed during the co-creating workshop and targeted meetings with the stakeholders. Lastly, in the annexure we summarize the discussion from the stakeholder workshop organised by ATREE on co-creating strategy and action plan for addressing urban flooding issues in Bengaluru.

Chapter 2

Comprehensive Hydrologic and Hydraulic modelling

This chapter outlines a flood modelling approach using cutting-edge software tools for data management, statistical analysis, hydrological modelling, and hydraulic analysis as outlined in figure 2-1. The impact of stormwater drain network in routing the stormwater was quantified will be discussed in subsequent sections. This exercise serves as a baseline to assess the effectiveness of Nature-based Solutions (NbS) in Yelahanka sub-catchment which is of 21 sq.km located in Bengaluru as shown in figure 2-2. The results and findings presented in this section lay the groundwork for informed decision-making in flood risk management.

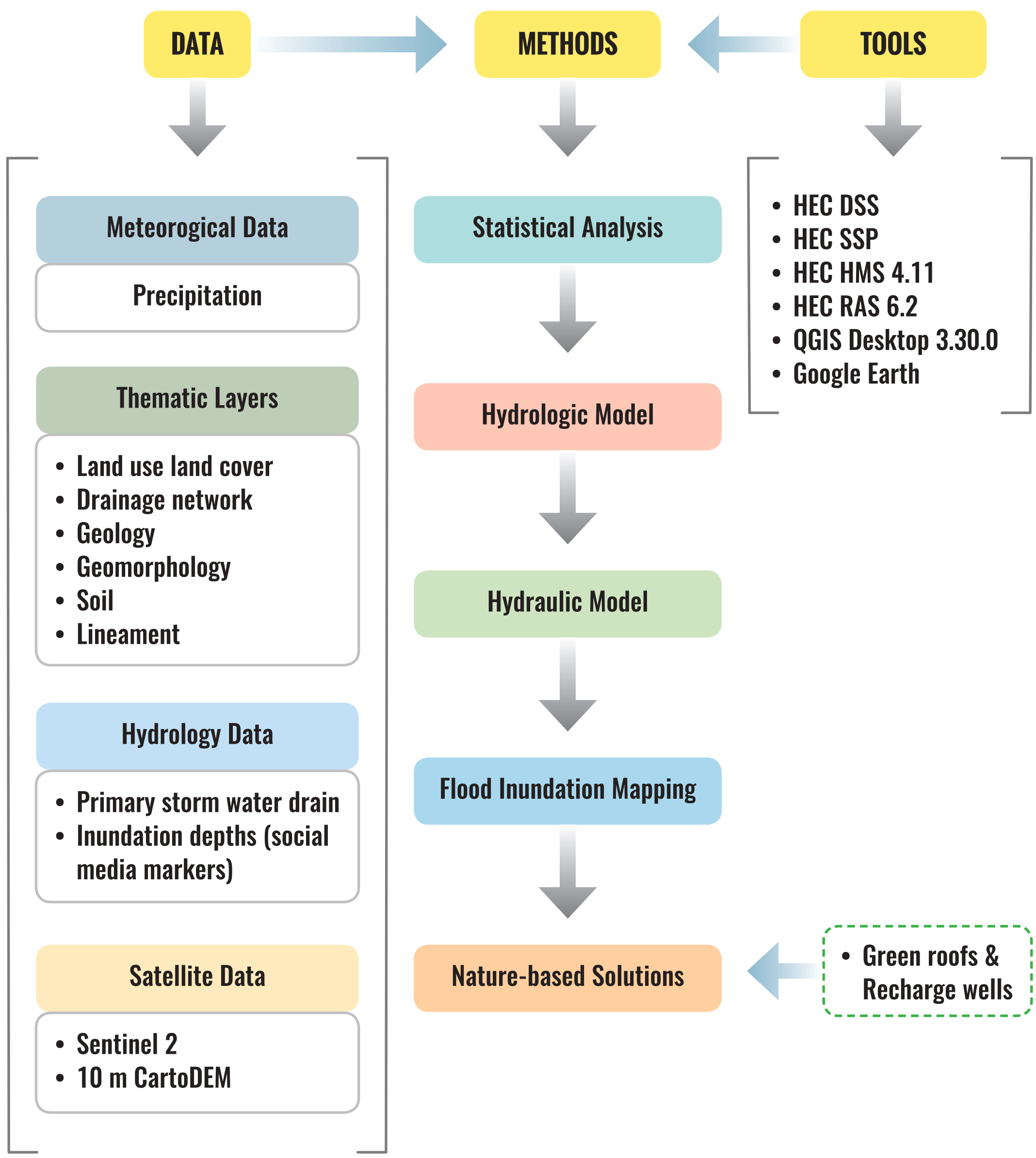


Figure 2-1: Hydrologic and Hydraulic modelling framework

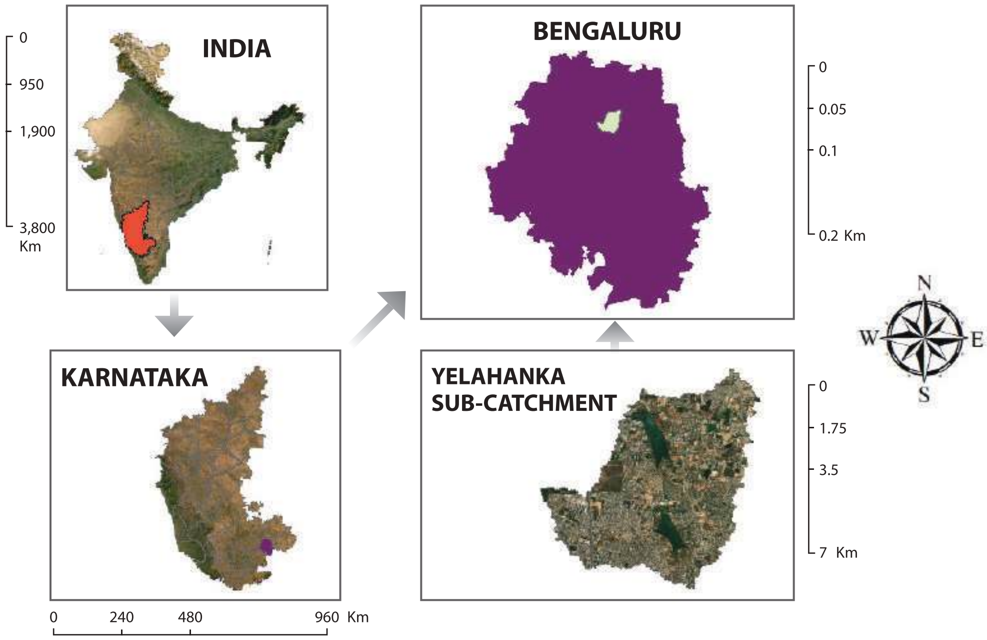


Figure 2-2: Yelahanka sub-catchment: Study area map

Step 1: Data processing and storage

Data storage is a critical aspect of any hydrological study. Hydrologic Engineering Center-Data Storage System (HEC-DSS) excels in providing a structured environment for storing time-series data. HEC-DSS is a software tool developed by the Hydrologic Engineering Center of the United States Army Corps of Engineers. It is designed to facilitate the analysis and management of hydrologic and hydraulic data.

Meteorological data such as daily rainfall data for 30 years from 1992-2002 received from KSNDMC for the Yelahanka zone has been processed for accuracy & reliability and used for the study.

Step 2: Statistical analysis

The next crucial step is statistical analysis of meteorological data which is essential for understanding the probability distributions and characteristics of extreme events. HEC-SSP, which stands for Hydrologic Engineering Center - Storage and Software Program, is a software package used in the field of hydrology to perform a range of tasks related to storage and analysis of water data. It is a comprehensive tool developed by the Hydrologic Engineering Center to support water resources engineering and planning studies. The software enables users to develop and maintain a database of hydrologic data, including rainfall, runoff, evaporation, and other relevant variables (Davis & Burnham, 2000)

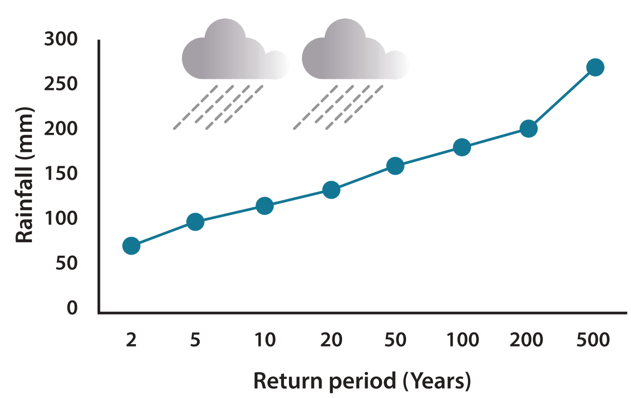


Figure 2-3: Rainfall for different return periods

In our project, we applied Gumbel's distribution within HEC-SSP to calculate rainfall for different return periods. The software's user-friendly interface and powerful statistical capabilities enabled us to derive meaningful insights from the data. The results, as depicted in figure 2-3, provided a clear representation of the rainfall patterns for various return periods, forming a foundation for subsequent modelling and analysis.

Step 3: Hydrological modelling

Hydrological modelling plays a pivotal role in understanding and predicting the flow patterns of water within a given watershed. We have adopted rainfall runoff modelling and used Hydrologic Engineering Center – Hydrologic Modelling System (HEC-HMS) software. The methodology will be discussed in the subsequent sections.

Data sources and pre-processing

To initiate the hydrological modelling process, delineated sub-catchments utilizing a 10-meter resolution Digital Elevation Model (DEM) obtained from the National Remote Sensing Centre, Hyderabad and the elevation map is attached as figure 2-4. This high-resolution DEM facilitated the accurate identification of drainage patterns and watershed boundaries. The spatial data for drains and nodes were identified, and a drainage layer was generated to represent the network of water pathways within the watershed (NEH, Part 630, Chapter 6).

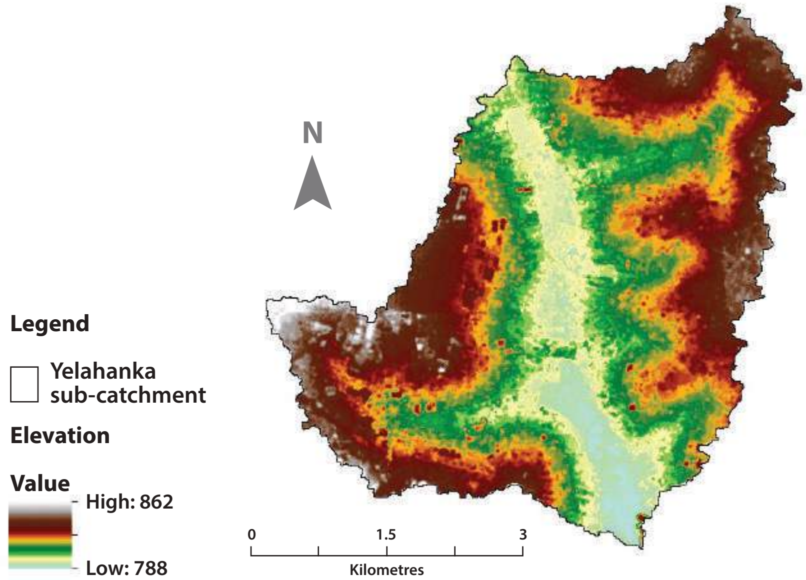


Figure 2-4: Yelahanka sub-catchment elevation map

Land use and soil characteristics

The accuracy of hydrological models heavily relies on the representation of land cover and soil properties. In this study, we used Sentinel-2 satellite imagery to create a diversified Land Use Land Cover (LULC) map. The classification of land cover types was essential for determining the Curve Number (CN) grid, a key parameter in rainfall-runoff modelling as illustrated in figure 2-5.

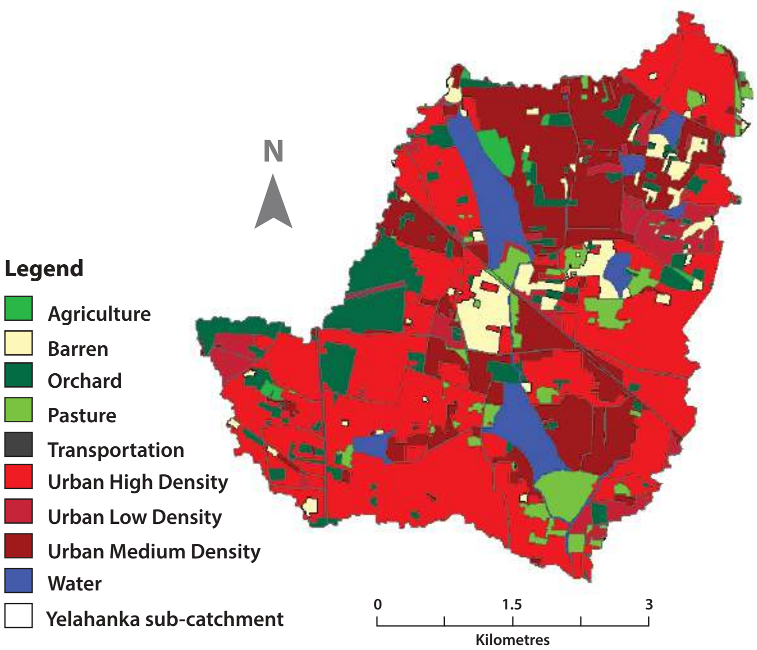


Figure 2-5: Land Use Land Cover map of the Yelahanka sub-catchment of 2023

Simultaneously, the soil layer was digitized to incorporate soil characteristics into the model as shown in figure 2-6.

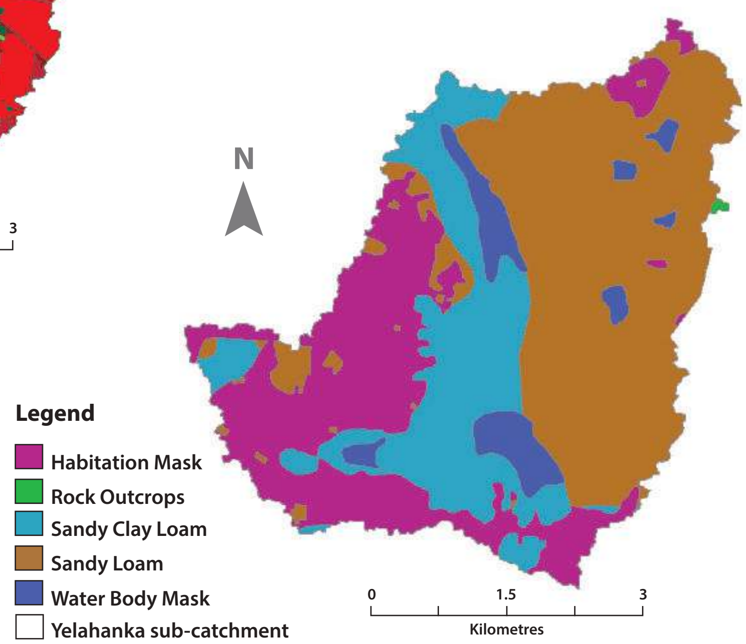


Figure 2-6: Soil map of the Yelahanka sub-catchment

Curve number grid generation

The Curve Number (CN) method is widely used in hydrological modelling to estimate runoff based on land cover and soil characteristics. In our study, the CN grid was generated by overlaying the LULC map and the digitized soil layer. CN numbers were assigned in accordance with NRCS, 1986 as illustrated in figure 2-7. This grid served as a spatial representation of the CN values across the watershed, influencing the runoff potential for different areas.

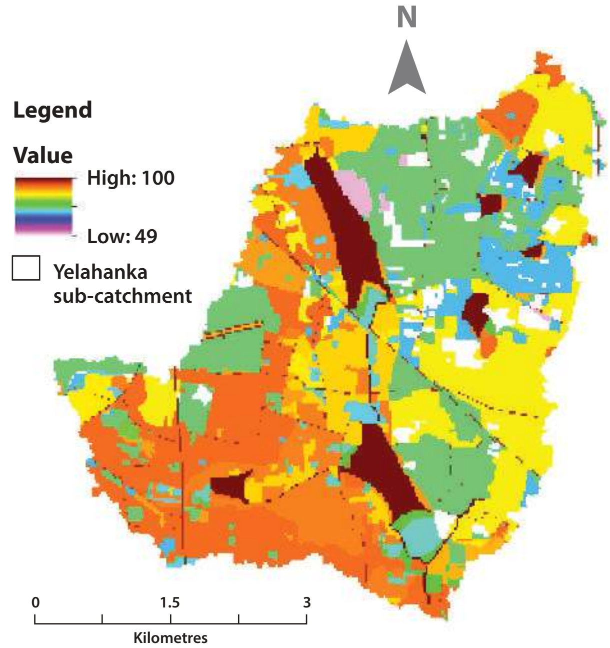


Figure 2-7: CN grid map based on Land Use Land Cover and soil characteristics

Rainfall-runoff simulation

The hydrological model was developed using a 10-year return period rainfall event. This specific design choice allows for the assessment of extreme weather conditions, contributing to a more comprehensive understanding of the watershed's response to intense precipitation of 116 mm rainfall in 24 hours. In this study, we employed rainfall-runoff modelling with loss-transform method using Soil Conservation Service Curve Number (SCS-CN) method to generate flow hydrographs. The Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) software was chosen for its robust capabilities in simulating the complex interactions of precipitation, land surface, and drainage systems.

The resulting flow hydrograph from SCS type 2 rainfall (NEH, Part 630, Chapter 4), a graphical representation of the temporal variation in flow rates, was generated by the HEC-HMS model. This hydrograph provides valuable insights into the dynamics of water flow within the watershed during the specified return period and will serve as an input for hydraulic modelling.

Step 4: Hydraulic modelling

Reconnaissance survey

Building upon our initial reconnaissance survey on the locations identified by Karnataka State Natural Disaster Monitoring Centre (KSNDMC) [see Plate 2-1], we conducted an updated assessment of the primary storm drain network and employed a hydraulic model to evaluate its performance. The hydraulic model used in this study is a coupled one-dimensional and two-dimensional (1D-2D) model, allowing for a comprehensive analysis of both one-dimensional and two-dimensional flow dynamics within the catchment.

Plate 2-1: Gathering insights from residents and shop owners on flood vulnerable zones identified by KSNDMC.

Hydraulic analysis

The hydraulic analysis phase was conducted using the Hydrologic Engineering Center - River Analysis System (HEC-RAS). This software was chosen for its capability to simulate the flow of water through the drainage system and the overland flow and assess the impact of stormwater drainage infrastructure. Two distinct scenarios were considered: one with the primary stormwater drain network and another without.

HEC-RAS facilitated the simulation of flow patterns, providing a detailed understanding of potential impacts on the surrounding areas under different conditions. This comprehensive analysis aimed to capture the complex interplay between the stormwater drainage and the overall hydraulic behaviour of the environment.

Influence of primary stormwater drain network

The results of the hydraulic analysis revealed that, with the presence of the primary stormwater drain (SWD) network, a significant 38% reduction in runoff was observed as depicted in figure 2-8. This reduction indicated the effectiveness of the stormwater management infrastructure in diverting and controlling the flow of water during storm events. These insights serve as a crucial guide for future infrastructure planning and improvements, aiding decision-makers in developing effective strategies for flood risk reduction.

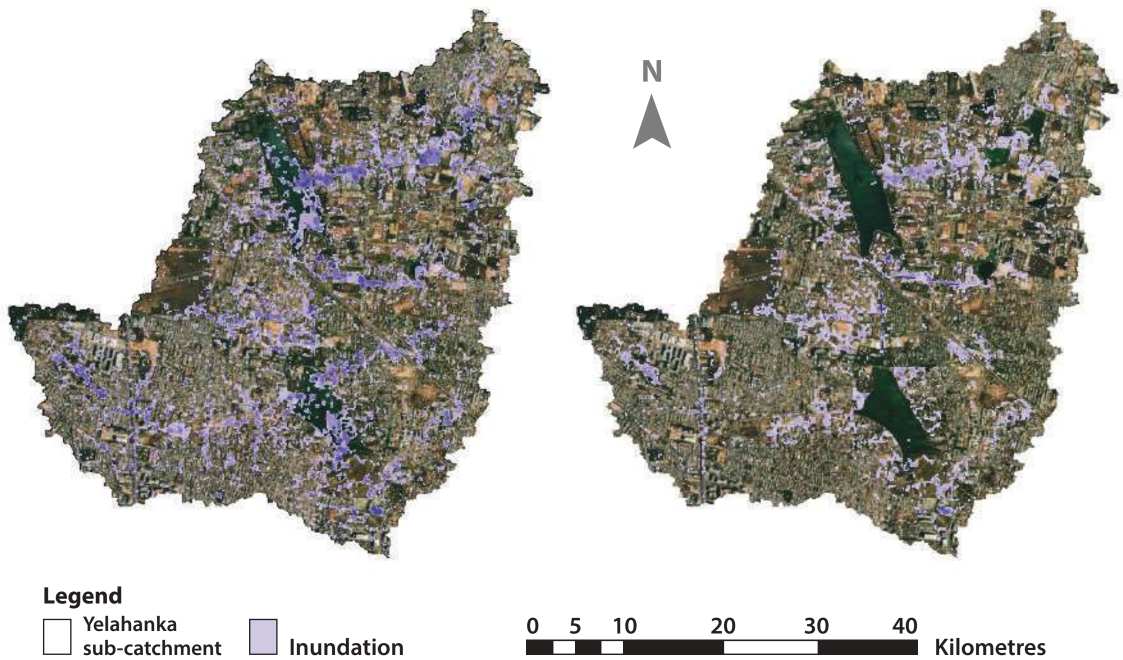


Figure 2-8: Flood inundation map without primary SWD (left) and with primary SWD (right)

The identified 34% inundation of the area with the primary stormwater drain network highlighted the critical role it played in mitigating flooding. This finding underscored the importance of maintaining and enhancing stormwater management infrastructure to reduce the risk of inundation in urban areas.

Plate 2-2: A shop owner shows the inundation depth during extreme events.

Validation

To ensure the credibility of our results, the inundation depth findings were validated using data from the reconnaissance survey for the locations as seen in figure 2-9. The local people provided information on the flood inundation depths [Plate 2.2].

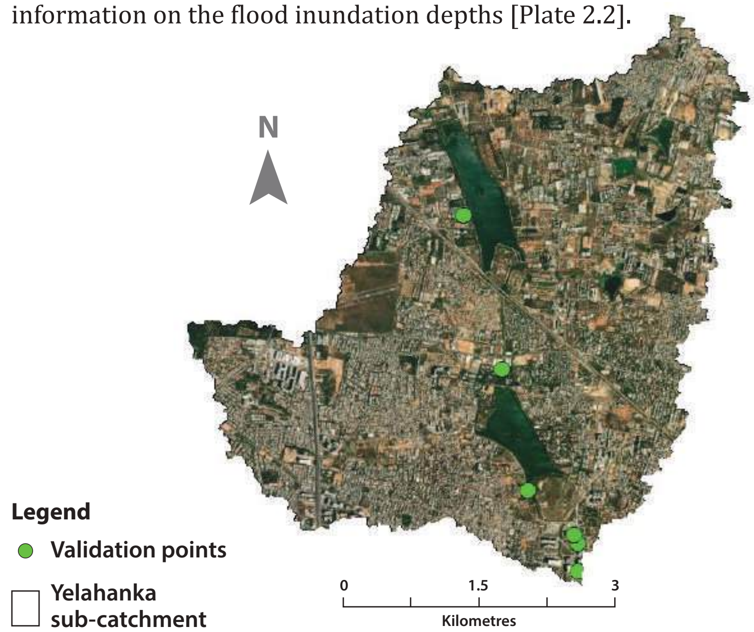


Figure 2-9: Locations considered for the model validation

The coefficient of regression (R^2 = 0.75) demonstrated a strong correlation between the modelled results and the observed data, enhancing the reliability of the hydraulic analysis outcomes as shown in figure 2-10.

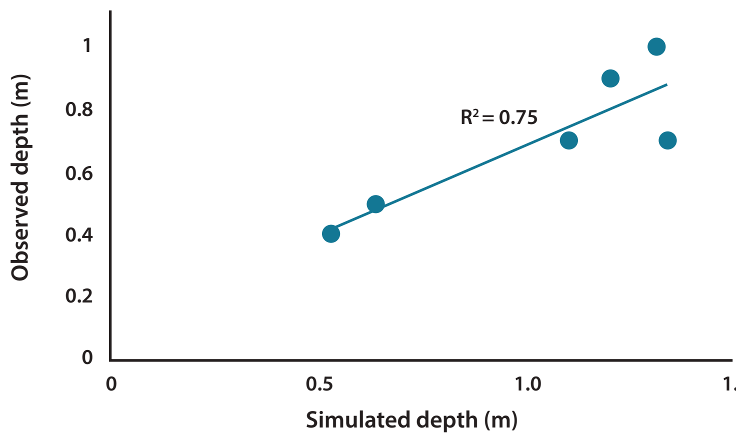


Figure 2-10: Correlation between observed inundation depth and simulated inundation depth

Limitations of the modelling

Hydrologic and hydraulic modelling plays a crucial role in understanding and managing water resources. However, it is important to acknowledge the limitations of these models in order to interpret their results accurately and make informed decisions. These models rely on various data inputs, including precipitation data, soil characteristics, topography, and land use information. Obtaining accurate and reliable data for these inputs can be challenging, especially in remote or poorly monitored areas. These models are limited by the spatial and temporal scales at which they operate which is typically at a watershed or river basin scale, making it difficult to capture and analyze local variability and small-scale features which impacts the reliability of model simulations. These models are based on simplified representations of complex hydrological and hydraulic processes, such as runoff generation, flow routing, and channel hydraulics. These simplifications and assumptions may not fully capture the intricacies of real-world systems and can introduce errors and uncertainties in the model results. Furthermore, hydrologic and hydraulic models often rely on historical data to calibrate and validate the model outputs. This scarcity of data, especially during extreme events, makes it challenging to comprehensively assess the model's performance leading to discrepancies between simulated and observed data.

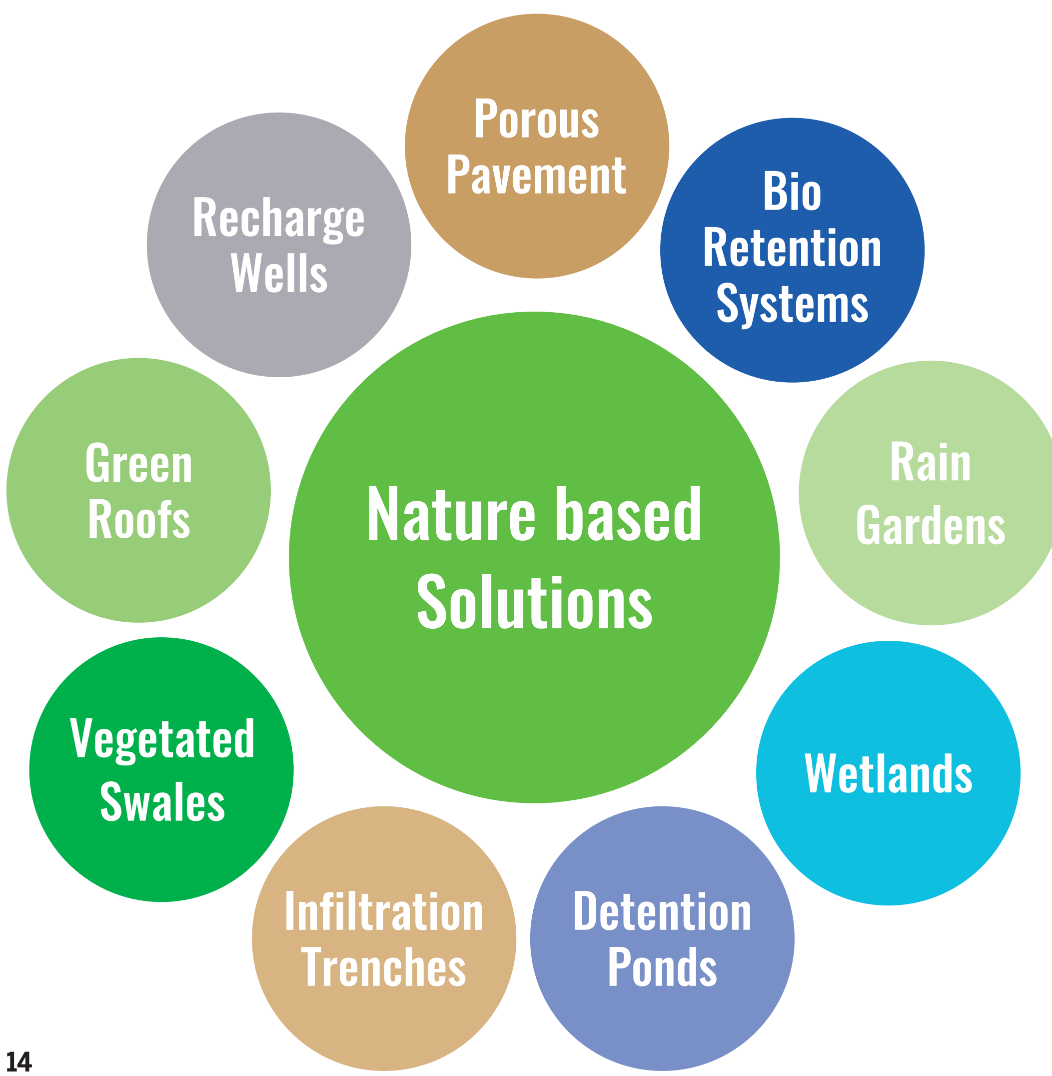
Chapter 3

Nature-based Solutions and Global Case Studies

Urban green infrastructure integrates green and blue spaces in urban areas to sustain water resources, biodiversity, and ecological functions (Edward T. McMahon, 2002). Various terms like Sustainable Urban Drainage Systems (SUDS), Best Management Practices , Low-Impact Development, Water-Sensitive Urban Design, Integrated Urban Water Management, and Sponge city denote similar concepts globally (Casal-Campos et al., 2015; Zevenbergen et al., 2018)

NbS therefore contain solutions ranging from specific drainage techniques to broader sustainable urban development principles, contribute to ecosystem restoration, climate change adaptation (Casal-Campos et al., 2015). The various functions of NbS contribute to the implementation of the UN 2030 Agenda for Sustainable Development Goals, fostering a circular economy.

The transition from traditional urban water management to nature-based urban flood management aims to restore the site's pre-hydrological conditions by reducing and delaying runoff. This is achieved through integrating green elements that enhance infiltration, evaporation, and water retention (Ferreira et al., 2022). However, the discourse on NbS in Urban Flood mitigation is yet to become mainstream worldwide, in order to be executed at scale to make a tangible impact on climate change (Zhai et al., 2023).



This chapter aims to present and discuss the most widely implemented NbS for Urban flood mitigation, based on literature reviews drawing from empirical data from various case studies across the globe.

Porous Pavement

Adverse urbanization has replaced the natural surface with impervious infrastructure which have decreased the natural infiltration rate of the soil (Moglen, 2009; Todeschini, 2016). To mitigate these adverse impacts, porous pavement is generally used to collect, treat, and absorb rainfall runoff; allowing groundwater recharge (Brattebo & Booth, 2003; Scholz & Grabowiecki, 2007). Permeable pavement comprises permeable block pavers featuring open joint spaces, facilitating the infiltration of surface water. Beneath the pavers, there are storage layers consisting typically of open grated aggregate ranging in size from 2mm- 20mm, encompassing bedding aggregate and a base course aggregate (Moglen, 2009).

Utilized in Seoul, South Korea, porous pavement is effective in managing stormwater in both gentle and steep-sloped areas and both highland and lowland areas and can be laid over moderately infiltrated sandy-loamy soil. The study showcased a significant reduction in runoff volume by 30-60% during a 4-month duration, particularly under rainfall intensities ranging from 30 to 120 mm/h (Shafique et al., 2018). The effectiveness of technology lies in its ability to also remove diffusive pollutants such as heavy metals, oil, and grease, thereby contributing to water quality improvement (Shabalala, 2021). It is also effective on clay soils for managing small storm events and retaining the 'first flush' during larger storms, while the voids in the sand media facilitate the nitrification process (Dreelin et al., 2006).

Bioretention Systems

There are systems that can mimic the pre-development hydrologic conditions by gradually infiltrating water into the surrounding soil and through evapotranspiration (Fletcher et al., 2015). Furthermore, bioretention harnesses the chemical, biological and physical properties of plants, microbes and soils to remove contaminants from stormwater (Wang et al., 2016).

Implemented in various locations including China, Connecticut, and Pennsylvania, bio retention systems are effective in stormwater management for areas with poor soil infiltration rates (Kõiv-Vainik et al., 2022). These systems demonstrated significant runoff volume reduction of 74.8-99% in China (Gao et al., 2018). Adding underdrains allows for stormwater percolation through the media and can be effectively channelled downstream.

Rain Gardens

Rain gardens are a type of bio retention system, consisting of shallow depressions in the landscape that are planted with trees and/or shrubs and are typically covered with a layer of bark mulch or ground cover (Dietz & Clausen, 2005). They are essentially well-drained porous beds where water typically accumulates to a depth of 100 to 300 mm for several hours, and up to a maximum of 36 hours after rainfall, aiming to disrupt mosquito breeding (Ishimatsu et al., 2017).

In Brazil, rain gardens serve as a viable stormwater management solution for horizontal and gently sloped areas with sandy-loamy soil. Implemented over a 10-year design storm period, rain gardens exhibited runoff volume reduction ranging from 30% to 50% (Goncalves et al., 2018). Additionally, these systems enhance biodiversity while reducing ammoniacal nitrogen and total nitrogen levels, contributing to ecosystem health (Kasprzyk et al., 2022; Yousaf et al., 2021). While rain gardens offer numerous benefits, they also come with drawbacks. These drawbacks include the potential for stagnant water, which may attract pests, moreover if not properly isolated from the groundwater table, rain gardens can lead to groundwater contamination (Malaviya et al., 2019).

Wetlands

One of the most effective Nature-based Solutions for enhancing water quality is the restoration and establishment of wetlands. Wetlands act as highly efficient natural filters, extracting pollutants like nutrients, sediments, and chemicals from water. Furthermore, they serve as natural water storage areas, helping to alleviate the potential for downstream flooding.

In the current climate, wetland restoration reduces the risk of water overspill. A study of the Devil's lake watershed in the North Dakota region proved that an increase in wetland area from the current 10.7% of the watershed to the moderate estimate of the historical area (16% of the watershed area) reduces the overspill risk from 5% to 1% (Gulbin et al., 2019).

In response to the limitations of structural interventions, scholars and practitioners are advocating for a "watershed approach," wherein the management focus extends to the entirety of the watershed, including its ecological structures, functions, and processes (Birkland et al., 2003). Adopting this approach entails managing the entire watershed to understand how flooding in one area may be influenced by development upstream or human activities elsewhere within the natural system. In line with this philosophy, a study investigated the influence of wetland location and size on downstream flooding within a watershed. The findings of this study demonstrate that inland wetlands can effectively mitigate floods by serving as additional storage within the watershed. Notably, wetlands located further upstream exhibit enhanced flood control capabilities (Tang et al., 2020).

Detention Ponds

Detention ponds and wetlands are centralized measures that treat stormwater runoff at the end of a catchment or drainage zone (Gilroy & McCuen, 2009), where-as green roofs, bioswales, pervious pavements are employed to manage the stormwater at source (Dietz, 2007). The primary operational goal of detention ponds is to reduce downstream flood hazards and water contamination by temporarily retaining stormwater within the basin (Nascimento et al., 1999). This stored water is then gradually released over an extended duration, thereby controlling the flow rates of stormwater by storing the accumulated runoff and allowing the pollutants to settle trapping suspended sediments

Deployed in Malaysia, dry detention ponds are designed to manage stormwater in large drainage areas with a minimum of 10 acres and maximum slopes of 15%. The study highlighted their effectiveness in delaying peak flow by 30-45 minutes and reducing peak flow rates by 33-46%. However, challenges such as limited water treatment capacity and the potential for mosquito breeding due to stagnant water require consideration (Liew et al., 2012)

The sedimentation potential of these ponds is determined by several key factors: soil characteristics, vegetative cover, topography and microclimate. Sedimentation control involves implementing a blend of structural modifications and site specific construction techniques tailored to the topography of the location (Abduljaleel et al., 2023).

Infiltration Trenches

Infiltration trenches typically involve a narrow rectangle excavated reservoir filled with gravel or stone aggregates and lined with geo textiles. The void volume of the gravel aggregate inside the trench acts as the storage space for capturing runoff (Wang & Guo, 2020).

Employed in Haihe, China, infiltration trenches are designed for areas with impervious surfaces and specific soil characteristics. Over a 10-year duration, these trenches achieved notable runoff volume reduction 30.80% and peak flow reduction of 19.44% with a lag time of 12 minutes (Huang et al., 2014). The technology's effectiveness lies in its capacity to infiltrate stormwater while mitigating peak flows, contributing to flood risk reduction.

Vegetated Swales

In urban areas, the predominant stormwater management approach has historically prioritized the rapid evacuation of water through branched networks, aiming to remove it quickly and at a distance. However, with the densification of population and urban expansion, this strategy has become inadequate due to the overwhelming volume of water, particularly during heavy rainfall. To tackle this challenge one increasingly popular method involves managing water closer to its source, on a smaller scale, as a more sustainable solution (Leroy et al., 2016).

To manage, store, and facilitate the infiltration of road water runoff, drainage structures like swales can be utilized. These are flat-bottomed linear channels, typically 0.5 m deep, designed to receive and redirect roadway flows laterally, often through grassed or vegetated side slopes (Leroy et al., 2016).

Deployed in the Hai He basin China, vegetated swales effectively manage stormwater by reducing the peak flows by 23.56% (Huang et al., 2014).

Green Roofs

Mitigation and adaptation strategies, including increasing green areas and utilizing natural heat sinks face challenges in urban areas due the escalating demand for buildings, space, water, and energy. Given that urban rooftops are largely unused impervious surfaces, green roof technology offers a documented solution to not only boost building energy efficiency, but also delivers various environmental, aesthetic, psychological, physiological, and economic benefits, transforming rooftops into multifunctional, sustainable spaces through soil, vegetation, and plants.

Studies have shown that incorporating green roofs into urban landscapes can lead to significant reductions in stormwater runoff and flood volumes. For instance, extensive roof greening on just 10% of buildings can result in 2.7% runoff reduction for the entire region. Additionally, a coupled system of multilayer blue-green roofs and Rainwater Harvesting tanks ensures a 5% discharge reduction even during extreme weather events (Cristiano et al., 2023) .

Moreover, the annual rainfall-runoff relationship for green roofs is closely linked to the depth of the substrate layer, indicating the importance of proper design and implementation techniques to optimize their effectiveness (Cian Twohig et al., 2022)

Implemented in Wroclaw, Poland, and Milan, Italy, green roofs contribute to stormwater management by significantly reducing runoff volume by 54%-96% in Wroclaw and 15%-70% in Milan (Burszta-Adamiak & Mrowiec, 2013; Ercolani et al., 2018). Their effectiveness is strongly related upon sewer infrastructure characteristics, emphasizing the need for integrated planning approaches.

Recharge Wells

Recharge wells emerge as a Nature-based Solutions for flood control, offering a versatile approach that is most appropriate in the urban context, as it consumes little real estate and can be retrofitted in multiple ways. While the focus has primarily been on water quantity and quality improvements, the flood mitigation aspect requires further detailed exploration.

Artificial recharging of groundwater aquifers through recharge wells presents several advantages. Firstly, it provides subsurface storage space at no cost while avoiding inundation, making it an economically viable solution. Additionally, negligible evaporation losses and minimal temperature variations ensure efficient water storage. Moreover, the infiltration process through permeable media contributes to water quality improvement. Unlike other interventions, recharge wells have minimal adverse social impacts, such as displacement of populations or loss of agricultural land, making them an environmentally friendly and socially acceptable solution. Furthermore, this technology plays a crucial role in controlling soil erosion and mitigating flood situations, while also providing adequate soil moisture during dry spells or water deficit conditions, thereby enhancing overall resilience (Hussain et al., 2019).

A study in Iran saw that the total recharge capacity was 4.46 hm3 which was 61% of the floodwater (Pakparvar et al., 2016). Also implemented in Bengaluru, recharge wells facilitate groundwater replenishment by reducing 84.2% of runoff volume and enhancing natural percolation. Challenges such as data availability and feasibility assessment underscore the need for comprehensive aquifer study.

In conclusion, it is evident that developing countries show a greater emphasis on Nature-based Solutions (NbS) compared to developed nations (Zhai et al., 2023). The green infrastructure measures discussed in this chapter offer effective solutions for sustainable stormwater management. Each technology presents unique strengths and considerations, which are crucial to consider based on site-specific conditions and design criteria. In our study, we are focusing on modelling the effectiveness of green roofs and recharge wells in particular amongst all the other NbS.

Chapter 4

Flood risk framework and impact assessment of NbS using modelling approaches

Floods are among the most devastating natural disasters, causing widespread damage and loss of life. In order to effectively manage and mitigate the risks associated with floods, it is crucial to conduct a comprehensive flood risk assessment. This assessment should consider three key elements: hazard, vulnerability, and exposure (Brouwer et al., 2007; UNESCO, 2009)

Risk = Hazard x vulnerability x exposure — (1)

This chapter outlines a comprehensive flood risk assessment framework, incorporating hazard, vulnerability, and exposure elements to evaluate flood risk in Yelahanka sub-catchment located in Bengaluru city as shown in figure2-2. It includes a detailed classification system based on the level of risk, considering factors such as inundation depth, elevation, slope, type of roads, population density, female population density, built-up density, number of hospitals and schools. Furthermore, this chapter presents the results of implementing NbS, such as green roofs and recharge wells, to mitigate flood risk. It comprises before-and-after assessments, demonstrating the reduction in flood hazard, vulnerability, exposure, and overall flood risk in different classes.

Recognizing the importance of sustainable and ecologically friendly approaches, we explored the deployment of NbS in urban high-density built-up areas to address the surplus runoff after considering primary stormwater drain.

We considered six scenarios and used modelling tools to assess the impact of each scenario on the reduction of flood risk.

Table 4-1: Different scenarios considered for the impact assessment of NbS

SCENARIO	DESCRIPTION
S1	50% houses with green roofs in urban high density land use
S2	75% houses with green roofs in urban high density land use
S3	50% houses with recharge wells in urban high density land use
S4	75% houses with recharge wells in urban high density land use
S5	25% houses with green roofs and 25% houses with recharge wells in urban high density land use
S6	37.5% houses with green roofs and 37.5% houses with recharge wells in urban high density land use

To ensure the practicality and effectiveness of the interventions, we proposed scenario S5 which has an areal coverage of 25% each for green roofs and recharge wells in high-density built-up areas. This deliberate allocation aimed to strike a balance between maximizing intervention impact and allowing for continued urban development and which helps in reducing runoff and promoting sustainable urban development (Twohig et al., 2022; Kolasa-Więcek & Suszanowicz, 2021; Mora-Melià et al., 2018). A 45% reduction in runoff was found as shown in figure 4-1.

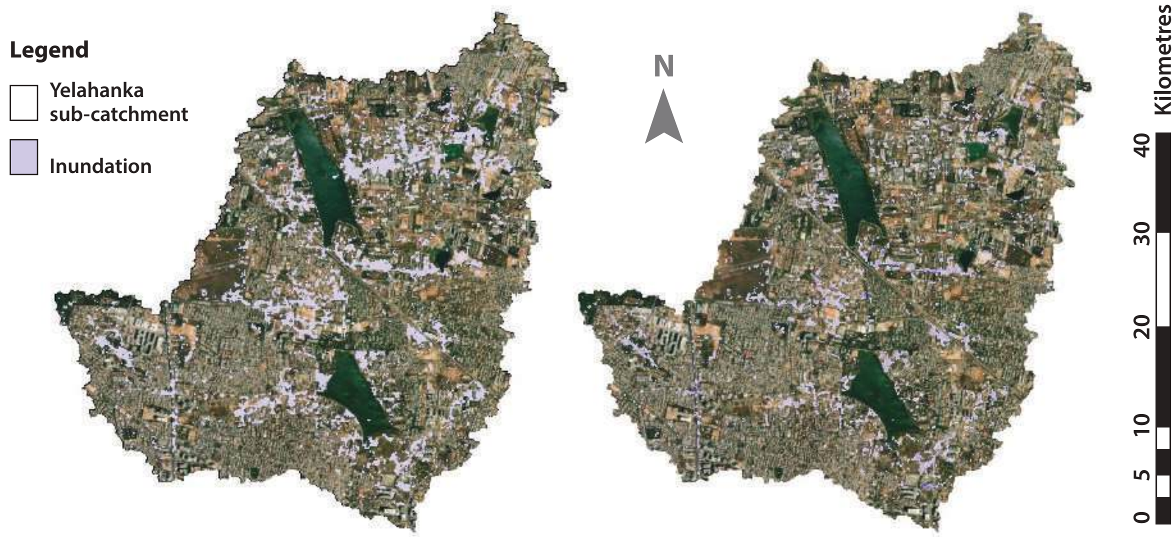


Figure 4-1: Flood inundation map without NbS (left) and with NbS (right)

In the following section we discuss the flood hazard, vulnerability and exposure assessment for 10 years return period rain event followed by assessing the impact of interventions (scenario S5) on the of various components of risk assessment (equation 1).

4.1 Flood hazard assessment

The flood hazard was assessed pre and post incorporation of NbS using flood inundation map obtained from hydrologic and hydraulic analysis to check the efficacy. It has been classified into four classes namely low, moderate, high and very high based on the impact of inundation on the communities and the infrastructure as these areas can become impassable, hindering evacuation efforts and emergency response (Jamrussri & Toda, 2018; Srinivasa Rao et al., 2019).

4.2 Flood vulnerability assessment

Flood vulnerability is a critical aspect to consider when assessing the potential impact of flooding in a particular area. Understanding the vulnerability of a region to floods is crucial in managing the risks associated with such events. Several factors contribute to flood vulnerability, including slope, elevation, and types of roads, as shown in figure 1-4. Slope plays a significant role in flood vulnerability as it affects the flow of water during an inundation event. Areas with steep slopes are more prone to flash flooding, as water can quickly accumulate and flow downstream, causing rapid and destructive inundation. On the other hand, areas with flat or moderate slopes may experience prolonged inundation as water does not drain quickly. Areas with low elevation are typically more vulnerable to flooding as they are more likely to be affected by rising water levels from rivers or heavy rainfall events. The types of roads in an area can impact flood vulnerability based on their footprint (Ibrahim et al., 2024; Scheuer et al., 2011; Sowmya et al., 2015; Rafiei-Sardooi et al., 2021; Rincón et al., 2018)

4.3 Flood exposure assessment

Flood exposure is a critical concern that varies based on various factors, including population density, female population, built-up density, and the presence of essential infrastructure such as hospitals and schools, as shown in figure 1-4. Areas with high population density are more likely to experience higher flood exposure, as a larger number of people are at risk. Similarly, areas with a higher female population may have specific vulnerabilities, as women tend to be more affected by disasters due to social and cultural factors. Additionally, areas with high built-up density, characterized by a dense concentration of structures and infrastructure, are at greater risk of flood exposure as there are more assets and critical infrastructure to be impacted by floods. The presence of hospitals and schools also plays a significant role in determining the extent of disaster in the flooded area. Areas with higher number of hospitals under inundation may struggle to provide adequate healthcare in the event of a flood, putting the health and well-being of the population at greater risk. The presence and distribution of schools play a significant role, as flooding can jeopardize the safety and well-being of students and hinder educational continuity (Scheuer et al., 2011; Rafiei-Sardooi et al., 2021; Rincón et al., 2018).

4.4 Flood risk assessment

The criteria considered for creating and classifying the base layers based on hazard, vulnerability and exposure elements is detailed in table 4-2 (Ibrahim et al., 2024; Jamrussri & Toda, 2018; Rafiei-Sardooi et al., 2021; Rincón et al., 2018; Scheuer et al., 2011; Shuaibu et al., 2022; Sowmya et al., 2015; Srinivasa Rao et al., 2019). With the help of weighted overlay analysis tool in QGIS Desktop 3.30, the spatial distributions of different classes among different elements were generated following the procedure in the flood risk assessment framework as explained in figure 4-2 and the resultant maps are attached as figure 4-3. Flood risk map was generated by combining the three elements i.e., hazard, vulnerability and exposure.

Table 4-2: Flood risk elements classifying criteria

Element	Variable	Variable sub-weight	Range	Class
Hazard	Flood inundation (m)	1	Shallow	Low
			Medium	Moderate
			Deep	High
			Very deep	Very high
Vulnerability	Elevation (AMSL)	0.4	835 - 862	Low
			825 - 835	Moderate
			815 - 825	High
			788 - 815	Very high
	Slope (degrees)	0.3	> 30	Low
			20 - 30	Moderate
			Oct-20	High
			0 - 10	Very high
	Type of roads	0.3	Airport	Low
			State /National Highways	Moderate
			Major district road	High
			City major/minor road	Very high
Exposure	Population density (persons/sq.km)	0.3	0 - 305	Low
			305 - 450	Moderate
			450 - 700	High
			> 700	Very high
	Female pop. density (persons/sq.km)	0.25	0 - 150	Low
			150 - 200	Moderate
			200 - 400	High
			> 400	Very high
	Built-up density	0.2	Low dense area	Low
			Medium dense area	Moderate
			High dense area	High
			Very high dense area	Very high
	Hospitals	0.13	0	Low
			1	Moderate
			2	High
			>3	Very high
	Schools	0.12	0	Low
			1	Moderate
			2	High
			>3	Very high

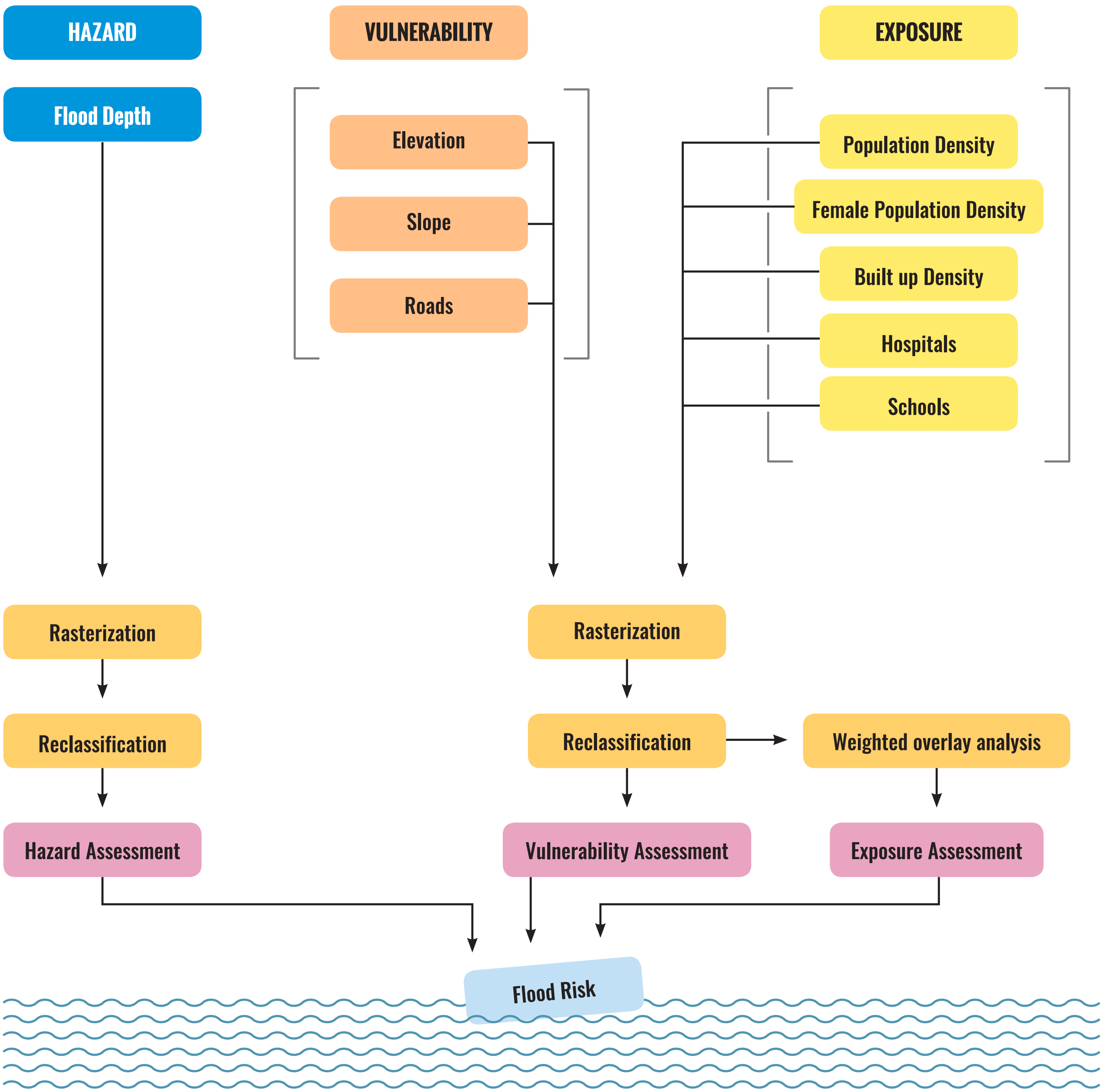


Figure 4-2: Flood risk assessment framework

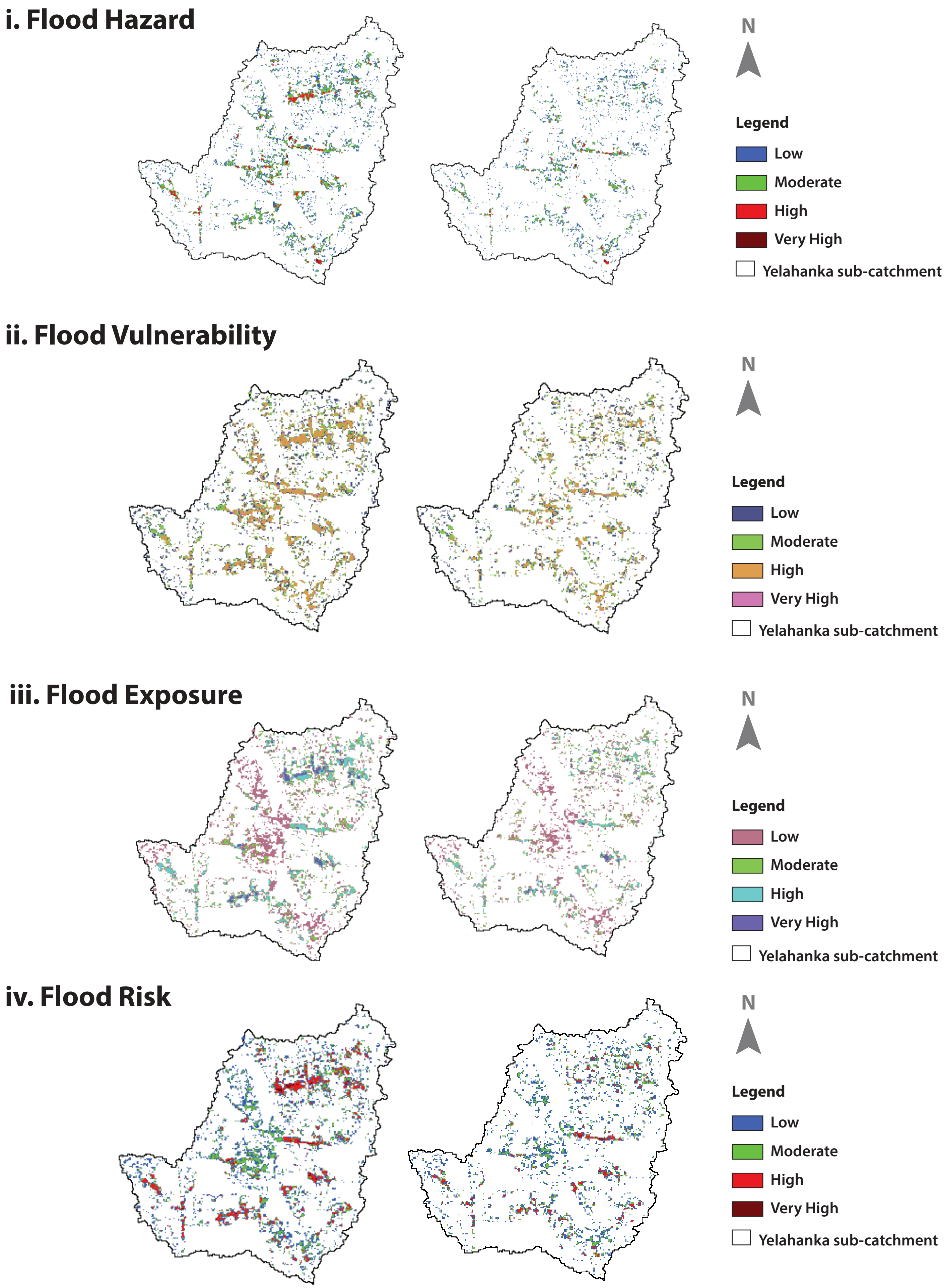


Figure 4-3: Spatial distribution of (i) Flood Hazard, (ii) Flood Vulnerabaility, (iii) Flood Exposure (iv) Flood Risk

The table 4-3 represents percent reduction in class under each component of risk assessment after incorporation of the NbS proposed under scenario S5. The modelling results clearly shows that the incorporation of NbS significantly reduce the hazard, vulnerability and exposure under thereby significantly reducing the risk to urban floods. The following insights are made from the study.

- High hazard areas experience the highest reduction among the hazard classes, with a 67% decrease in the affected area followed by moderate hazard areas that experienced 47% reduction. Low hazard areas demonstrate a 27% reduction in affected area with interventions, while very high hazard areas show a 36% reduction, indicating improved flood hazard mitigation.
- High vulnerability areas exhibit a significant 52% reduction, with very high vulnerability areas also showing a notable 52% reduction. Moderate vulnerability areas demonstrate a 33% reduction, and low vulnerability areas experience a 30% reduction with interventions, reflecting positive impacts across different vulnerability classes and effectiveness of the interventions in lowering vulnerability.
- Very high exposure areas show the highest reduction at 72%, indicating the effectiveness of interventions in lowering exposure to flooding. Moderate exposure areas demonstrate a 36% reduction, high exposure areas show a notable 50% reduction, and low exposure areas exhibit a 33% reduction, emphasizing the positive impact of interventions across different exposure classes.
- Low-risk areas show a 31% reduction, moderate-risk areas demonstrate a 39% reduction, high-risk areas shows a substantial 60% reduction, while very high-risk areas experience the highest reduction at 77%, which implies that green roofs with 40% effective area and recharge wells of size 1.2m x 7.5m can be an effective strategy for reducing flood risk when implemented at a household level or at community level with policy revisions by providing incentives to the public which contributes to a more resilient and sustainable flood management approach.

Table 4-3: Area coverage of different elements across different classes without NbS and with NbS

Class	Area-without NbS (sq.km)	% Area-without NbS	Area-with NbS (sq.km)	% Area-with NbS	% reduction in the class after incorporating NbS
FLOOD HAZARD					
Low	1.16	47	0.85	57	27
Moderate	1.05	42	0.56	37	47
High	0.24	10	0.08	5	67
Very high	0.02	1	0.01	1	36
FLOOD VULNERABILITY					
Low	0.80	32	0.56	37	30
Moderate	0.73	30	0.49	33	33
High	0.86	35	0.41	28	52
Very high	0.08	3	0.04	3	52
FLOOD EXPOSURE					
Low	1.30	53	0.87	58	33
Moderate	0.52	21	0.34	22	36
High	0.50	20	0.25	17	50
Very high	0.14	6	0.04	3	72
FLOOD RISK					
Low	1.30	53	0.89	60	31
Moderate	0.68	28	0.42	28	39
High	0.45	18	0.18	12	60
Very high	0.03	1	0.01	0.44	77

Chapter 5

Urban flood Strategy and Action plan

The approach to managing extreme events in India is steered by multiple entities, including the National Disaster Management Agency (NDMA), urban climate action plans, adaptation strategies, and sectoral plans crafted by governmental and non-governmental bodies. Recent efforts by WRI India on developing Bengaluru Climate Action and Resilience plan, have addressed risks to extreme events comprehensively. Despite the breadth of topics covered in these action plans, ranging from urban heat to droughts, this report narrows its focus to mitigating the risk of urban floods. Specifically, taking a case of Yelahanka sub-catchment within Bengaluru city.

The objective of this strategy and action plan is to enhance urban flood resilience to promote sustainable development. Our vision is for Bengaluru to emerge as a beacon of innovation and effectiveness in risk management related to urban flooding. This aspiration can only be realized through the reinforcement of stakeholders' capacities in Bengaluru to adapt to and mitigate the impacts of flooding risks through Nature-based Solutions (NbS).

This section explores the five strategies as shown in the figure 5-1, for; preparedness for disaster with respect to flooding and disease outbreak, management of lake water levels: regulate discharge, optimize storage, revive lakes, implementation of NbS and Blue-Green infrastructure at public and private spaces, maintenance of stormwater infrastructure, community and stakeholder engagement in context of urban flooding and highlights efficient approaches.

The following section is also the culmination of insights from expert meetings convened with a diverse array of stakeholders. These meetings provided a platform for discussions, comments and suggestions from experts representing a range of perspectives and expertise. These contributions from stakeholders are compiled and tailored to finalise this action plan for Bengaluru urban floods. The pictures captured during the meeting with Ms. Arpitha H. M, Hydrology Department. KSNDMC, with Dr. Renukumar K. S Additional Chief Engineer (Design), BWSSB and with Dr. M. Inayathullah, Professor, Department of Civil Engineering, University of Visvesvaraya College of Engineering, Bengaluru are attached as plate 5-1, plate 5-2 and plate 5-3 respectively.

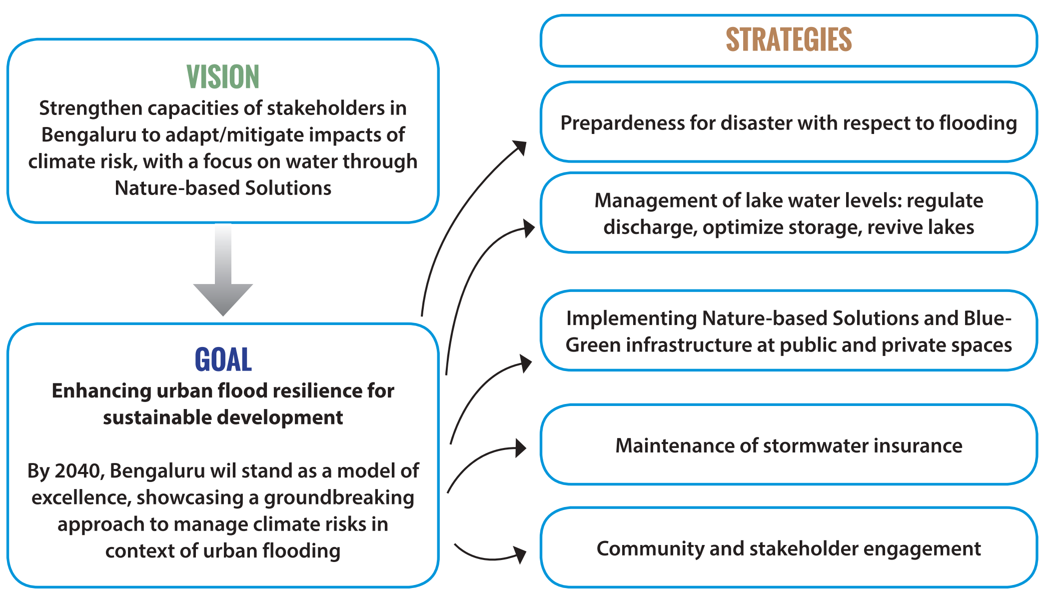


Figure 5-1: Vision, Goal and Strategies for the action plan

Plate 5-1: Targeted stakeholder meeting with Ms. Arpitha H. M, Hydrology Department, KSNDMC on 19 February, 2024.

Plate 5-2: Targeted stakeholder meeting with Dr. Renukumar K. S, Additional Chief Engineer (Design), BWSSB on 20 February, 2024.

Plate 5-3: Targeted stakeholder meeting with Dr. M. Inayathullah, University of Visvesvaraya College of Engineering, Bengaluru on 22 February, 2024.

Strategy 1: Preparedness for disaster with respect to flooding

Preparedness measures play a crucial role in mitigating the potential risks posed by disasters, particularly in the context of flooding. Operating at both societal and individual levels, preparedness aims to reduce flood risks to manageable levels while establishing strategies to effectively manage any remaining risks (Tingsanchali, T., 2012).

In collaboration with the Bruhat Bengaluru Mahanagara Palike (BBMP) and the Karnataka State Natural Disaster Monitoring Centre (KSNDMC), significant strides have been made in enhancing flood forecasting and early warning systems in Bengaluru. This strategy outlines key actions required to further strengthen preparedness efforts for flood disasters in the city.

1. Scaling up early warning systems:
Expanding the implementation of early warning systems by leveraging the collaboration between BBMP and KSNDMC, by building upon the existing infrastructure of 102 automatic telemetric rain gauges (ATGs) and 105 water level sensors and also enhancing the accessibility and functionality of early warning systems such as the Megha Sandesha App and Varuna Mitra web portal. This entails ensuring real-time data collection, accurate forecasting, and timely dissemination of alerts to vulnerable communities, enabling proactive response measures.

2. Detailed surveys of flood-prone areas:
Conducting detailed surveys of low-lying areas using LiDAR technology and investigation surveys to accurately identify flood-prone zones. By understanding the historical patterns of flooding and root causes, stakeholders can develop targeted flood management strategies and infrastructure improvements.

3. Aquifer mapping for groundwater dynamics:
Undertaking aquifer mapping comprehensively, will help understand the groundwater dynamics and facilitate sustainable utilization of surplus water. Identify discharge zones and measure underground water flow to inform groundwater management strategies and recharge initiatives. By optimizing groundwater resources and recharge potential, communities can enhance water security and resilience against droughts and fluctuations in surface water availability.

4. Promoting interactive learning and awareness:
Engaging students in flood/stormwater drains surveys and awareness campaigns will foster interactive learning and promote disaster preparedness from an early age. By involving young individuals in data collection activities and educational programs, raise awareness about the importance of disaster preparedness, mitigation measures, and community resilience. Empower students to become advocates for flood resilience within their communities, encouraging proactive participation in disaster response and recovery efforts.

Leveraging advanced technologies, data-driven approaches, and community engagement initiatives, stakeholders can improve early warning systems, identify flood-prone areas accurately, manage groundwater resources sustainably, and promote a culture of disaster preparedness among future generations.

Strategy 2: Management of lake water levels: regulate discharge, optimize storage, revive lakes

Effectively managing urban lakes requires a collaborative approach involving multiple stakeholders and targeted interventions. Addressing the challenges associated with lake water levels and their impact on flood mitigation demands a comprehensive action plan. The following actions outline management solutions aimed at optimizing lake water levels, regulating discharge, and reviving lakes to enhance flood resilience in urban areas.

1. Context-specific dredging operations:
Dredging of lakes with careful consideration of site-specific factors, including groundwater potential, treated wastewater generation, and lake ecology, will promote sustainable dredging practices that preserve the ecological balance of lakes while improving their capacity to mitigate flooding. By evaluating these aspects, authorities can ensure that dredging activities contribute to flood resilience without compromising the integrity of lake ecosystems.

2. **Integrated micro-watershed planning**:
Formulating an integrated micro-watershed water balance and planning reports within sub-catchments will enhance lake management efforts. By analyzing hydrological dynamics and land use patterns, stakeholders can develop targeted strategies to optimize water storage, regulate discharge, and mitigate flood risks effectively. This holistic approach ensures that management interventions are tailored to the specific needs and challenges of each sub-catchment, maximizing their impact on flood resilience.

3. **Stakeholder engagement and assessment:**
Conducting micro-stakeholder assessments with local stakeholders, including residents, businesses, community organizations, and government agencies will gather insights into the unique challenges and opportunities associated with lake ecosystems and sub-catchments. By understanding diverse perspectives and needs, authorities can develop inclusive and participatory strategies for lake management and flood resilience.

4. **Integrated Public-Private Partnerships (PPP) and Corporate Social Responsibility Model for Lake ownership:**
Establishing integrated public-private partnerships and corporate social responsibility models for lake ownership will prevent commercialization of lakes while leveraging resources for lake restoration and flood management. Encouraging collaboration between the public and private sectors facilitates responsible stewardship of lakes and harnesses corporate resources to enhance flood resilience.

Through context-specific dredging operations, integrated watershed planning, stakeholder engagement and public-private partnerships, authorities can optimize lake management efforts and mitigate flood risks effectively.

The government has implemented various steps to enhance flood management and resilience in Bengaluru:

1. **Infrastructure development:** Investments have been made in constructing and upgrading stormwater drains, sewage systems, and reservoirs to improve drainage and mitigate flood risks.

2. **Research and innovation:** Collaboration with academic institutions such as Indian Institute of Science (IISc) and research organizations facilitates the development of advanced flood modelling, mapping, and forecasting techniques, enabling better understanding and prediction of flood patterns.

3. **Regulatory measures:** Zoning regulations, building codes, and land-use planning strategies are enforced to prevent encroachment on floodplains, regulate construction in flood-prone areas, and ensure sustainable urban development practices.

Strategy 3: Implementing Nature-based Solutions and Blue-Green infrastructure at public and private spaces

When devising an action plan to tackle urban flooding in Bengaluru, it's crucial to embrace a comprehensive strategy that incorporates diverse Nature-based Solutions. The proposed actions outlined in this section encompass a range of initiatives designed to incorporate more Blue-Green infrastructure into the development of the city.

1. **In-depth literature review of low impact development interventions:**
Conducting a thorough literature review to analyze existing Low Impact Development (LID) interventions worldwide, and evaluating its effectiveness considering factors such as site-specific requirements, geographical variations, and urban characteristics, will serve as the foundation for informed decision-making and tailored implementation strategies.

2. **Community-level recharge wells/vertical shafts:**
Initiating the construction of recharge wells or vertical shafts within public parks across Bengaluru. These decentralized water recharge structures will enable rainwater harvesting and groundwater replenishment at the community level.

3. **Mandate buffer zones around stormwater drains:**
Implementing regulatory measures mandating the establishment of buffer zones around stormwater drains in urban layouts approved by the Bangalore Development Authority (BDA) and Bangalore Metropolitan Region Development

Authority (BMRDA). Scientific data reports that buffer zones safeguard natural drainage channels, prevent encroachments, and preserve ecological integrity of a water body. Collaboration with urban planners, developers, and regulatory agencies is the key to enforce zoning regulations effectively.

4. Prioritizing harvested rainwater for secondary use:
Developing a prioritization framework for the utilization of harvested rainwater, emphasizing its secondary use before groundwater recharge. Establish guidelines for storing and treating harvested rainwater and implement filtration systems and permeable tanks to ensure the quality and efficient recharge of surplus rainwater into groundwater aquifers.

By implementing these actions, Bengaluru can harness the potential of Nature-based Solutions to address urban water challenges effectively. Through a combination of informed decision-making, community engagement, regulatory enforcement, and innovative water management practices, the city can enhance its resilience to floods and water scarcity. Continuous monitoring, stakeholder collaboration, and adaptive management will be essential for the successful implementation and long-term sustainability of these nature-based initiatives.

Strategy 4: Maintenance of stormwater infrastructure

In response to the pressing need for improved stormwater infrastructure in Bengaluru, key stakeholders such as the Karnataka State Natural Disaster Monitoring Centre (KSNDMC) and Bangalore Water Supply and Sewerage Board (BWSSB) have put forth several recommendations to enhance the maintenance of stormwater infrastructure across the city. By adopting a proactive approach and leveraging innovative technologies, these actions aim to bolster surveillance, prevent encroachments, optimize drainage efficiency, and enhance overall resilience against urban flooding.

1. Equipping water level sensors (WLS) with cameras:
Installing cameras on water level sensors (WLS) to augment surveillance and monitoring capabilities, will serve a dual purpose: deterring thefts and facilitating efficient monitoring of solid waste disposal activities near water bodies. By integrating visual surveillance with data collection, authorities can promptly identify and address any illicit activities, ensuring the integrity of stormwater infrastructure and preserving water quality.

2. Ensuring no wastewater flows into the stormwater drains during the dry periods

3. Ensuring budget allocation for buffer space clearance:
Allocating sufficient funds for the regular clearing of buffer spaces around stormwater drains from upstream areas, is a crucial proactive measure for preventing encroachments and maintaining unobstructed flow paths for stormwater. By prioritizing budgetary allocations for buffer space maintenance, authorities can safeguard critical infrastructure and minimize the risk of flooding during heavy rainfall events.

4. Consideration of slope gradients in stormwater drain design:
By carefully considering topographical variations, and incorporating slope gradients into the design of stormwater drains engineers can optimize drain alignments and gradients to ensure efficient water flow and minimize the risk of stagnation or blockages, enhancing the overall effectiveness of the drainage system, reducing the likelihood of urban flooding.

5. Acquisition of high-resolution Digital Elevation Model (DEM):
Procuring a high-resolution DEM for comprehensive mapping and identification of elevation changes and drainage patterns across Bengaluru, enables accurate siting of stormwater drains to capitalize on the city's undulating topography effectively. By leveraging DEM data, authorities can strategically plan drainage infrastructure placement, maximizing its efficiency and resilience during extreme rain events.

By implementing these actions, Bengaluru can significantly enhance the maintenance and resilience of its stormwater infrastructure. Collaboration among stakeholders, sustained investment, and continuous monitoring will be essential for the successful implementation and long-term effectiveness of these initiatives.

Strategy 5: Community and stakeholder engagement

Effective urban flood management necessitates collaboration among stakeholders, sustained investment, and continuous monitoring. This section delves into various initiatives aimed at fostering community and stakeholder engagement, raising awareness, and building capacity at the local level.

1. On ground vulnerability analysis:

Conduct on-ground vulnerability analysis to identify communities at heightened risk of flooding, such as slums. This data-driven approach enables targeted interventions and support measures to be implemented where they are most needed. Collaborate with local authorities, community organizations, and academic institutions to gather and analyze socio-economic and geographic data, ensuring equitable distribution of resources and assistance.

2. Local stakeholder stewardship training:

Provide training sessions for local stakeholders to enhance their capacity and empower them to take ownership of flood management efforts in their neighborhoods. These sessions should be conducted in the local language, ensuring accessibility and inclusivity. Equip community members with knowledge and skills to actively participate in decision-making processes, implement resilience-building activities, and effectively respond to flood events. Foster partnerships with grassroots organizations and NGOs to facilitate training programs and promote community-led initiatives.

3. Raising public awareness of incentives:

Increase public awareness of available incentives for flood management initiatives to encourage community engagement and participation. Disseminate information about government schemes, subsidies, and support programs aimed at incentivizing flood-resilient practices. Utilize various communication channels, including community meetings, social media platforms, and informational campaigns, to reach a wide audience and ensure accessibility of information.

4. Promoting civic responsibility and awareness:

Promote civic responsibility and awareness of common property among civilians to enhance collective efforts in flood management. Collaborate with organizations like the Bangalore Water Supply and Sewerage Board (BWSSB) to educate individuals about their rights and responsibilities in maintaining shared resources.

5. Crowd based data sourcing and academic partnerships:

Facilitate crowd-based data sourcing, led by academic institutions, to enhance social accountability and transparency in stormwater surveillance and mapping. This approach encourages community involvement in data collection, leveraging local knowledge to improve flood management. Collaborate with universities to develop digital platforms for real-time monitoring. Implement standardized certification of schools under the National Education Policy to incentivize flood education integration. Offer flood-related projects and internships for university students to foster collaboration and innovation, enriching flood management practices and raising awareness among the younger generation.

Engagement among diverse stakeholders, including teachers, children, parents, and the wider community, is central to enhancing social accountability and ownership in flood management. Embracing crowd-based data sourcing, academic collaborations, and standardized school certification promotes transparency and empowers contributions to flood management. These initiatives enhance accountability and encourage active participation, ensuring a more effective response to flooding challenges in the city.

References

1. Abduljaleel, Y., Salem, A., Ul Haq, F., Awad, A., & Amiri, M. (2023). Improving detention ponds for effective stormwater management and water quality enhancement under future climate change: A simulation study using the PCSWMM model. *Scientific Reports, 13*(1), 5555. https://doi.org/10.1038/s41598-023-32556-x

2. Alex, E. C., Ramesh, K., & Sridevi, H. (2017). Quantification and understanding the observed changes in land cover patterns in Bangalore. *International Journal of Civil Engineering and Technology, 8*(4), 597–603.

3. Avinash, S., Prasad, K. L., Reddy, G., & Mukund, D. (2018). Urban flood forecast system-a case study of Bangalore, India. *Univ Rev.*

4. Behl, M. (2022, September 15). *Bengaluru floods: The urgency of urban flooding; What Bengaluru floods 2022 taught us | Nagpur news - Times of India.* The Times of India. https://timesofindia.indiatimes.com/city/nagpur/the-urgency-of-urban-flooding-what-bengaluru-floods-2022-taught-us/articleshow/94212135.cms

5. Birkland, T. A., Burby, R. J., Conrad, D., Cortner, H., & Michener, W. K. (2003). River Ecology and Flood Hazard Mitigation. *Natural Hazards Review, 4*(1), 46–54. https://doi.org/10.1061/(ASCE)1527-6988(2003)4:1(46)

6. Brattebo, B. O., & Booth, D. B. (2003). Long-term stormwater quantity and quality performance of permeable pavement systems. *Water Research, 37*(18), 4369–4376. https://doi.org/10.1016/S0043-1354(03)00410-X

7. Brouwer, R., Akter, S., Brander, L., & Haque, E. (2007). Socioeconomic vulnerability and adaptation to environmental risk: A case study of climate change and flooding in Bangladesh. *Risk Analysis: An International Journal, 27*(2), 313–326.

8. Burszta-Adamiak, E., & Mrowiec, M. (2013). Modelling of green roofs' hydrologic performance using EPA's SWMM. *Water Science and Technology, 68*(1), 36–42. https://doi.org/10.2166/wst.2013.219

9. Casal-Campos, A., Fu, G., Butler, D., & Moore, A. (2015). An Integrated Environmental Assessment of Green and Gray Infrastructure Strategies for Robust Decision Making. *Environmental Science & Technology, 49*(14), 8307–8314. https://doi.org/10.1021/es506144f

10. Chatterjee, M. (2010). Slum dwellers response to flooding events in the megacities of India. *Mitigation and Adaptation Strategies for Global Change, 15*, 337–353.

11. Cristiano, E., Farris, S., Deidda, R., & Viola, F. (2023). How much green roofs and rainwater harvesting systems can contribute to urban flood mitigation? *Urban Water Journal, 20*(2), 140–157. https://doi.org/10.1080/1573062X.2022.2155849

12. CSE. (2012). *Excreta Matters: State of India's Environment: A Citizens' Report-7* (Vol. 2). Centre for Science and Environment.

13. Davis, D. W., & Burnham, M. W. (2000). HEC Software—Present Status and Activities, Future Prospects. In *Building Partnerships,* 1–9.

14. Davoudi, S. (2014). Climate change, securitisation of nature, and resilient urbanism. *Environment and Planning C: Government and Policy, 32*(2), 360–375.

15. Dietz, M. E. (2007). Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions. *Water, Air, and Soil Pollution, 186*(1–4), 351–363. https://doi.org/10.1007/s11270-007-9484-z

16. Dietz, M. E., & Clausen, J. C. (2005). A Field Evaluation of Rain Garden Flow and Pollutant Treatment. *Water, Air, and Soil Pollution, 167*(1–4), 123–138. https://doi.org/10.1007/s11270-005-8266-8

17. Dreelin, E. A., Fowler, L., & Ronald Carroll, C. (2006). A test of porous pavement effectiveness on clay soils during natural storm events. *Water Research, 40*(4), 799–805. https://doi.org/10.1016/j.watres.2005.12.002

18. Edward T. McMahon, M. A. B. (2002). *Green Infrastructure: Smart Conservation for the 21st Century.*

19. Ercolani, G., Chiaradia, E. A., Gandolfi, C., Castelli, F., & Masseroni, D. (2018). Evaluating performances of green roofs for stormwater runoff mitigation in a high flood risk urban catchment. *Journal of Hydrology, 566*, 830–845. https://doi.org/10.1016/j.jhydrol.2018.09.050

20. Ferreira, C. S. S., Kalantari, Z., Hartmann, T., & Pereira, P. (Eds.). (2022). *Nature-based solutions for flood mitigation: Environmental and socio-economic aspects.* Springer.

21. Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J.-L., Mikkelsen, P. S., Rivard, G., Uhl, M., Dagenais, D., & Viklander, M. (2015). SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. *Urban Water Journal, 12*(7), 525–542. https://doi.org/10.1080/1573062X.2014.916314

22. Gao, J., Pan, J., Hu, N., & Xie, C. (2018). Hydrologic performance of bioretention in an expressway service area. *Water Science and Technology, 77*(7), 1829–1837. https://doi.org/10.2166/wst.2018.048

23. Gilroy, K. L., & McCuen, R. H. (2009). Spatio-temporal effects of low impact development practices. *Journal of Hydrology, 367*(3–4), 228–236. https://doi.org/10.1016/j.jhydrol.2009.01.008

24. Goncalves, M., Zischg, J., Rau, S., Sitzmann, M., Rauch, W., & Kleidorfer, M. (2018). Modeling the Effects of Introducing Low Impact Development in a Tropical City: A Case Study from Joinville, Brazil. *Sustainability, 10*(3), 728. https://doi.org/10.3390/su10030728

25. Gulbin, S., Kirilenko, A. P., Kharel, G., & Zhang, X. (2019). Wetland loss impact on long term flood risks in a closed watershed. *Environmental Science & Policy, 94*, 112–122. https://doi.org/10.1016/j.envsci.2018.12.032

26. Gupta, A. K. (2009). Flood disaster mitigation and management: A synthesis and key lessons. *Disast. Dev, 3,* 163–175.

27. Hernández-Guzmán, R., & Ruiz-Luna, A. (2013). SARA–An enhanced curve number-based tool for estimating direct runoff. *Journal of Hydroinformatics, 15*(3), 881–887.

28. Huang, J. J., Li, Y., Niu, S., & Zhou, S. H. (2014). Assessing the performances of low impact development alternatives by long-term simulation for a semi-arid area in Tianjin, northern China. *Water Science and Technology, 70*(11), 1740–1745. https://doi.org/10.2166/wst.2014.228

29. Hussain, F., Hussain, R., Wu, R.-S., & Abbas, T. (2019). Rainwater Harvesting Potential and Utilization for Artificial Recharge of Groundwater Using Recharge Wells. *Processes, 7*(9), 623. https://doi.org/10.3390/pr7090623

30. Ibrahim, M., Huo, A., Ullah, W., Ullah, S., Ahmad, A., & Zhong, F. (2024). Flood vulnerability assessment in the flood prone area of Khyber Pakhtunkhwa, Pakistan. *Frontiers in Environmental Science.*

31. Jahnavi T. R. (2024). *Bengaluru most vulnerable to urban flooding: IMD data.* https://www.thehindu.com/news/cities/bangalore/bengaluru-most-vulnerable-to-urban-flooding-imd-data/article67878838.ece

32. Jamrussri, S., & Toda, Y. (2018). Available flood evacuation time for high-risk areas in the middle reach of Chao Phraya River Basin. *Water, 10*(12), 1871.

33. Jamwal, P., Thomas, B. K., Lele, S., & Srinivasan, V. (2014). *Addressing water stress through wastewater reuse: Complexities and challenges in Bangalore, India.*

34. Kasprzyk, M., Szpakowski, W., Poznańska, E., Boogaard, F. C., Bobkowska, K., & Gajewska, M. (2022). Technical solutions and benefits of introducing rain gardens – Gdańsk case study. *Science of The Total Environment, 835,* 155487. https://doi.org/10.1016/j.scitotenv.2022.155487

35. Kõiv-Vainik, M., Kill, K., Espenberg, M., Uuemaa, E., Teemusk, A., Maddison, M., Palta, M. M., Török, L., Mander, Ü., Scholz, M., & Kasak, K. (2022). Urban stormwater retention capacity of nature-based solutions at different climatic conditions. *Nature-Based Solutions, 2,* 100038. https://doi.org/10.1016/j.nbsj.2022.100038

36. Kolasa-Więcek, A., & Suszanowicz, D. (2021). The green roofs for reduction in the load on rainwater drainage in highly urbanised areas. *Environmental Science and Pollution Research, 28*(26), 34269–34277. https://doi.org/10.1007/s11356-021-12616-3

37. Leroy, M., Portet-Koltalo, F., Legras, M., Lederf, F., Moncond'huy, V., Polaert, I., & Marcotte, S. (2016). Performance of vegetated swales for improving road runoff quality in a moderate traffic urban area. *Science of The Total Environment, 566–567,* 113–121. https://doi.org/10.1016/j.scitotenv.2016.05.027

38. Liew, Y. S., Selamat, Z., Ab. Ghani, A., & Zakaria, N. A. (2012). Performance of a dry detention pond: Case study of Kota Damansara, Selangor, Malaysia. *Urban Water Journal, 9*(2), 129–136. https://doi.org/10.1080/1573062X.2011.644567

39. Malaviya, P., Sharma, R., & Sharma, P. K. (2019). Rain Gardens as Stormwater Management Tool. In S. Shah, V. Venkatramanan, & R. Prasad (Eds.), *Sustainable Green Technologies for Environmental Management* (pp. 141–166). Springer Singapore. https://doi.org/10.1007/978-981-13-2772-8_7

40. Manandhar, B., Cui, S., Wang, L., & Shrestha, S. (2023). Urban flood hazard assessment and management practices in south asia: A review. *Land, 12*(3), 627.

41. Moglen, G. E. (2009). Hydrology and Impervious Areas. *Journal of Hydrologic Engineering, 14*(4), 303–304. https://doi.org/10.1061/(ASCE)1084-0699(2009)14:4(303)

42. Mora-Melià, D., López-Aburto, C., Ballesteros-Pérez, P., & Muñoz-Velasco, P. (2018). Viability of Green Roofs as a Flood Mitigation Element in the Central Region of Chile. *Sustainability, 10*(4), 1130. https://doi.org/10.3390/su10041130

43. Nascimento, N. O., Ellis, J. B., Baptista, M. B., & Deutsch, J.-C. (1999). Using detention basins: Operational experience and lessons. *Urban Water, 1*(2), 113–124. https://doi.org/10.1016/S1462-0758(00)00009-1

44. Natural Resources Conservation Service (1986). Urban Hydrology for Small Watersheds. Technical Release 55. 1-164

45. Natural Resources Conservation Service (2015). Part 630 Hydrology National Engineering Handbook, Chapter 4:Storm Rainfall Depth and Distribution

46. Natural Resources Conservation Service (2015). Part 630 Hydrology National Engineering Handbook, Chapter 6: Stream reaches and Hydrologic units

47. Pakparvar, M., Walraevens, K., Cheraghi, S. A. M., Ghahari, Gh., Cornelis, W., Gabriels, D., & Kowsar, S. A. (2016). Assessment of groundwater recharge influenced by floodwater spreading: An integrated approach with limited accessible data. *Hydrological Sciences Journal,* 1–18. https://doi.org/10.1080/02626667.2016.1183164

48. Rafiei-Sardooi, E., Azareh, A., Choubin, B., Mosavi, A. H., & Clague, J. J. (2021). Evaluating urban flood risk using hybrid method of TOPSIS and machine learning. *International Journal of Disaster Risk Reduction, 66,* 102614.

49. Ramachandra, T., & Mujumdar, P. P. (2009). Urban floods: Case study of Bangalore. *Disaster Dev, 3*(2), 1–98.

50. Rincón, D., Khan, U. T., & Armenakis, C. (2018). Flood risk mapping using GIS and multi-criteria analysis: A greater Toronto

area case study. *Geosciences, 8*(8), 275.

51. Scheuer, S., Haase, D., & Meyer, V. (2011). Exploring multicriteria flood vulnerability by integrating economic, social and ecological dimensions of flood risk and coping capacity: From a starting point view towards an end point view of vulnerability. *Natural Hazards, 58,* 731–751.

52. Scholz, M., & Grabowiecki, P. (2007). Review of permeable pavement systems. *Building and Environment, 42*(11), 3830–3836. https://doi.org/10.1016/j.buildenv.2006.11.016

53. Shabalala, A. N. (2021, June). *Utilisation of Pervious Concrete for Removal of Heavy Metals inContaminated Waters: Opportunities and Challenges.* The 6th World Congress on Civil, Structural, and Environmental Engineering. https://doi.org/10.11159/iceptp21.lx.302

54. Shafique, M., Kim, R., & Kyung-Ho, K. (2018). Rainfall Runoff Mitigation by Retrofitted Permeable Pavement in an Urban Area. *Sustainability, 10*(4), 1231. https://doi.org/10.3390/su10041231

55. Shuaibu, A., Hounkpè, J., Bossa, Y. A., & Kalin, R. M. (2022). Flood risk assessment and mapping in the Hadejia River Basin, Nigeria, using hydro-geomorphic approach and multi-criterion decision-making method. *Water, 14*(22), 3709.

56. Singh, H., Nielsen, M., & Greatrex, H. (2023). Causes, impacts, and mitigation strategies of urban pluvial floods in India: A systematic review. *International Journal of Disaster Risk Reduction,* 103751.

57. Sowmya, K., John, C., & Shrivasthava, N. (2015). Urban flood vulnerability zoning of Cochin City, southwest coast of India, using remote sensing and GIS. *Natural Hazards, 75,* 1271–1286.

58. Srinivasa Rao, G., Surwase, T., Begum, A., Reddy, K., & Rao, P. (2019). *2D Flood Simulation and Development of Flood Hazard Map by using Hydraulic Model. 8,* 3096–3105. https://doi.org/10.23953/cloud.ijarsg.424

59. Sudhira, H. (2008). Studies on urban sprawl and spatial planning support system for Bangalore, India. *Published Doctorate Thesis, Indian Institute of Science Department of Management Studies.*

60. T. V. Ramachandra, Shivamurthy, V., & Bharath H. Aithal. (2017). *Frequent Floods in Bangalore: Causes and Remedial Measures.* https://doi.org/10.13140/RG.2.2.17517.90088

61. Tang, Y., Leon, A. S., & Kavvas, M. L. (2020). Impact of Size and Location of Wetlands on Watershed-Scale Flood Control. *Water Resources Management, 34*(5), 1693–1707. https://doi.org/10.1007/s11269-020-02518-3

62. Tingsanchali, T. (2012). Urban flood disaster management. *Procedia Engineering, 32,* 25–37. https://doi.org/10.1016/j.proeng.2012.01.1233

63. Todeschini, S. (2016). Hydrologic and Environmental Impacts of Imperviousness in an Industrial Catchment of Northern Italy. *Journal of Hydrologic Engineering, 21*(7), 05016013. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001348

64. *Transforming our world: The 2030 agenda for sustainable development.* Home .:. Sustainable Development Knowledge Platform. https://sustainabledevelopment.un.org/post2015/transformingourworld/publication

65. Twohig, C., Casali, Y., & Aydin, N. Y. (2022). Can green roofs help with stormwater floods? A geospatial planning approach. *Urban Forestry & Urban Greening, 76,* 127724. https://doi.org/10.1016/j.ufug.2022.127724

66. UNESCO (2009). Global trends in water-related disasters: an insight for policymakers. UNESCO. Available at: https://unesdoc.unesco.org/ark:/48223/ pf0000184137_eng.

67. Varghese, V. R. R. (2022). Bengaluru flood woes are a recent phenomenon. The Hindu. https://www.thehindu.com/data/data-deluge-in-bengaluru-flood-woes-are-a-recent-phenomenon-in-karnataka/article65919247.ece

68. Wang, J., & Guo, Y. (2020). Dynamic water balance of infiltration-based stormwater best management practices. *Journal*

of Hydrology, 589, 125174. https://doi.org/10.1016/j.jhydrol.2020.125174

69. Wang, J., Zhang, P., Yang, L., & Huang, T. (2016). Cadmium removal from urban stormwater runoff via bioretention technology and effluent risk assessment for discharge to surface water. *Journal of Contaminant Hydrology, 185–186,* 42–50. https://doi.org/10.1016/j.jconhyd.2016.01.002

70. Yousaf, A., Khalid, N., Aqeel, M., Noman, A., Naeem, N., Sarfraz, W., Ejaz, U., Qaiser, Z., & Khalid, A. (2021). Nitrogen Dynamics in Wetland Systems and Its Impact on Biodiversity. *Nitrogen, 2*(2), 196–217. https://doi.org/10.3390/nitrogen2020013

71. Zevenbergen, C., Fu, D., & Pathirana, A. (2018). Transitioning to Sponge Cities: Challenges and Opportunities to Address Urban Water Problems in China. *Water, 10*(9), 1230. https://doi.org/10.3390/w10091230

72. Zhai, H., Gu, B., & Wang, Y. (2023). Evaluation of policies and actions for nature-based solutions in nationally determined contributions. *Land Use Policy, 131,* 106710. https://doi.org/10.1016/j.landusepol.2023.106710

Annexure

Workshop on "Co-creating strategy and action plan for Bengaluru in the context of urban flooding"

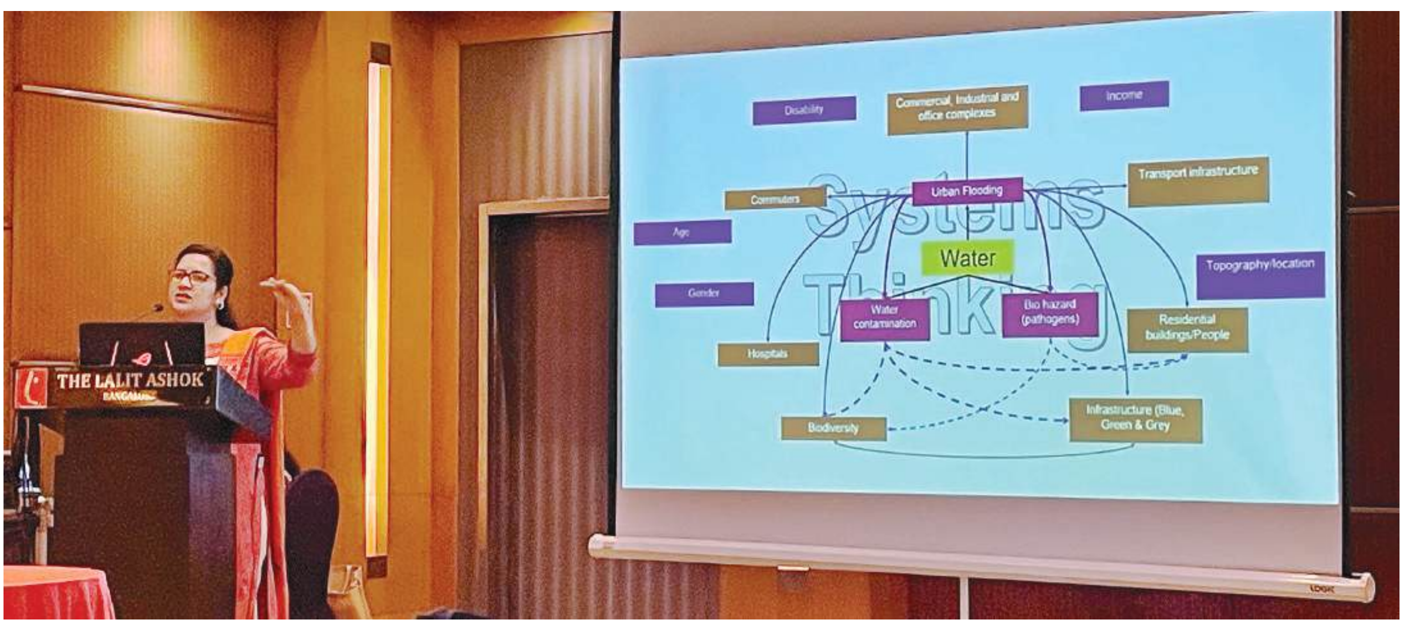
A one-day workshop was organised titled 'Co-creating strategy and action plan for Bengaluru in the context of urban flooding' at Lalit Ashok on 09/01/2024. The workshop engaged diverse participants, including NGOs, academicians, researchers and practitioners. The focus was to co-create a strategy and action plan to tackle urban flooding in Bengaluru.

There were technical sessions on the study of the impact of Nature-based Solutions (NbS) on flood inundation by Dr Priyanka Jamwal and Hymavathi P from ATREE. Following this, Mr. Ari Daman from the Public Landscape and Urbanism Studio (PLUS), provided insights on his efforts to integrate NbS into urban planning by presenting case studies from the United States of America.

Later, participants split into three groups and delved into the intricacies of the problem, employing a systems elements approach laying the groundwork for exploring effective solutions, particularly the role of nature-based approaches in mitigating the risk to urban flooding.

A comprehensive summary by the rapporteurs from each group encapsulated the day's discussions, and the synthesis of that information serves as the backbone in formulating this strategy and action plan.

The below pictures are a few glimpses of the workshop



Dr. Priyanka Jamwal delved into the intricacies of the complex and wicked urban flood problem, employing a systems elements approach laying the groundwork for exploring effective solutions, particularly the role of Nature-based Solutions in mitigating the risk.

Dr. Soubadra Devy provided a comprehensive introduction to ATREE, offering a detailed background and highlighting key aspects of its establishment and evolution.

Ms. Hymavathi P presented the impact of Nature-based Solutions on flood inundation using scenario-based modelling.

Mr. Ari Daman from the Public Landscape and Urbanism Studio (PLUS), provided insights on his efforts to integrate NbS into urban planning.

Participants actively engaged by asking insightful questions and seeking further clarification.

Three groups were formed to focus on seven critical areas related to the implementation of NbS in the context of urban flooding

Summary of the group discussion

Agenda: Three groups were formed to focus on seven critical areas related to the implementation of NbS in the context of urban flooding. Their objectives included assessing the feasibility of deploying nature based interventions, tackling challenges in existing policies, addressing social and economic vulnerabilities, and identifying subsequent data gaps.

Group 1 was tasked with assessing the feasibility of implementing Blue Roofs and Green Roofs. They thoroughly explored the intricacies involved and devised innovative solutions to promote the deployment of these interventions and explored the scope for incentives. Additionally, they provided insights into the appropriate methods for prioritising between the two interventions and identified key design specifications to guarantee their suitability for different urban demographics.

Group 2 concentrated on delineating the existing challenges associated with conventional Lake Dredging/Desilting, a commonly chosen solution for enhancing the capacity of the lake to capture floodwater. Furthermore, they explored innovative approaches for the efficient management of stormwater drains with a particular emphasis on enhancing monitoring capabilities. Additionally, they identified the direction for further scientific research to determine the optimal locations for installing recharge wells.

Group 3 delved into an in-depth exploration of the challenges present in existing policies and formulated subsequent actions to ensure their effective implementation and improve accountability. Moreover, they conducted a thorough analysis of the technological, economic, and social constraints, emphasising on highlighting the resulting data gaps. They proposed various actions to overcome these gaps in a timely manner by leveraging the capacities of stakeholders.

The details of the members in each group are provided in Table A-1 and the reports from the group discussion elaborating on each group's strategy, problem delineation, corresponding actions, identified stakeholders, and an estimated timeline are in Table A-2.

Table A-1: Group members details

Name	Organization
Group 1	
Dr. Shivakumar J Nyamathi	University of Visvesvaraya College of Engineering, Bengaluru
Mr. Nagesh Aras	Federation of Bengaluru Lakes
Mr. Ramprasad	Federation of Bengaluru Lakes
Dr. Priya Narayanan	WRI India
Ms. Jessy Sharoon	Vellara Bengaluru
Dr. Priyanka Jamwal	Ashoka Trust for Research in Ecology and the Environment
Mr. Arun Kumar G. P	Ashoka Trust for Research in Ecology and the Environment
Group 2	
Dr. Harini Santhanam	Manipal Academy of Higher Education, Bengaluru
Dr. M. Inayathulla	University of Visvesvaraya College of Engineering, Bengaluru
Mr. Santosh Sutar	Vanalok Ventures Pvt Ltd
Ms. Vishnupriya Hathwar	Vanalok Ventures Pvt Ltd
Dr.Soubadra Devy	Ashoka Trust for Research in Ecology and the Environment
Dr. Priyadarshan Rajan Dharma	Ashoka Trust for Research in Ecology and the Environment
Dr. Ashish Kumar	Ashoka Trust for Research in Ecology and the Environment
Ms. Vardhini Suresh	Ashoka Trust for Research in Ecology and the Environment
Ms. Samhitha D	Ashoka Trust for Research in Ecology and the Environment

Name	Organisation
Group 3	
Dr. A. S. Ravikumar	University of Visvesvaraya College of Engineering, Bengaluru
Mr. Sahil Mathew	Center for Study of Science, Technology and Policy (C-STEP)
Ms. Rashmi Kulranjan	Ashoka Trust for Research in Ecology and the Environment
Mr. Sourabh	Consortium for DEWATS Dissemination Society (CDD India)
Ms. Swati J M	Janaagraha
Dr. Shrinvas Badiger	Ashoka Trust for Research in Ecology and the Environment
Ms. Hymavathi P	Ashoka Trust for Research in Ecology and the Environment
Ms. Aishwarya N	Ashoka Trust for Research in Ecology and the Environment

Table A-2: Group discussion report

S.No	Strategy	Problem Definition	Actions	Stakeholder (Actors)	Timeline
1	Blue Roofs	1.There is no common definition that distinguishes between green roofs and blue roofs. Hence, Lack of awareness needs to be addressed.	1. Interventions to create more awareness via social media and integrating education and capacity building at school level for long-term effectiveness. For maximum impact, the communication must be made in Kannada.	BBMP, BWSSB, CREDAI, BREDAI (URBAN), Local Rural Water Supply, Builders construction companies, and residential welfare associations (RWAs)	Should be integrated with the National Education Policy
		2. Challenges in importing wholesome water to places like Bengaluru and the unequal distribution of water still need to be addressed.	2. A site-specific water balance should should be done, promoting a Zero Runoff strategy along with water metering for all consumers.		
		3. Perception of people on groundwater recharge not bringing benefits to them is a major challenge structures in deep aquifers in scaling up blue-green infrastructure.	3. Incentives should be given for implementing recharge with a focus on identification of discharge zones and permeable surfaces.		
		4. Per capita supply and consumption of freshwater is highly variable within the city, for example slums use around 55-60 lpcd and urban areas use 260 lpcd.	4. Household and community-level recharging in open layouts or garden areas, should be done based on geological conditions supported by town planning policies to meet the additional demands of the areas promoting secondary use of water.		
2.	Green Roofs	1. In general, people are not aware of the implementation and benefits of the green roof infrastructure as they are of Rain water harvesting, which is the blue roof method.	1. Create awareness via social media. Introduce the topic in the school syllabus, for long-term effectiveness the communication must also be done in Kannada.	BBMP SWD, BBMP-Slum board, BWSSB, RWAs	
		2. Requires high maintenance and is water-intensive, which poses a significant challenge especially during dry periods.	2. Separation of greywater and blackwater for household reuse in future constructions, to cater to the water demand.		

S.No	Strategy	Problem Definition	Actions	Stakeholder (Actors)	Timeline
2	Green Roofs	3. There is not enough data to determine the limitations of the water-holding capacity of the plant layer. The thin soil layer on the rooftop may not slow down the subsurface flow significantly enough to impact the hydrograph at the catchment level.	3. Using mathematical models to assess the water holding capacity based on soil moisture scenarios (field capacity), and re-assessing the effect to validate the hypothesis under various scenarios.	BBMP, BWSSB, CREDAI, BREDAI (URBAN), Local Rural Water Supply, Builders construction companies, and residential welfare associations (RWAs)	Should be integrated with the National Education Policy
		4. Risk of groundwater and surface water contamination due to the use of fertilisers/pesticides on green roofs and a chance of ornamental plants being used as vegetation due to lack of awareness and its aesthetic appeal.	4. Normalise the use of appropriate native vegetation and application of organic fertilisers/household compost for the plant growth.		
		5. Can be seen as a space constraint on terraces which accommodate several other infrastructures such as solar panels for water heating and electricity generation.	5. Prioritise the implementation of blue roofs as the foundational solution with green roofs as a supplementary measure. Also, integrating with solar panels to efficiently utilise space for various purposes.		
		6. Implementing such solutions in slum housing areas is challenging due to structural limitations of roofs, which are not designed to support vegetation, and legal issues stemming from the lack of formal demarcation and notification of the area.	6. Identifying the needs of stakeholders based on the water-related challenges they face and designing site specific interventions - for slums rather than blue green roof, community runoff holding/ recharge structures can be implemented.		
3.	Lake Dredging /Desilting	1. By definition the intended use for for the lake in the city is always ignored, raising questions about the purpose of dredging: whether it aims to restore the lake for recharge and storage purposes or to enhance its capacity to effectively capture floodwaters.	1. a) Integrated micro-watershed Water balance/ Planning report (within sub-catchments; Whole to part method than part to whole)	Karnataka Tank Conservation & Development Authority	6 months
			b) Conducting Lake specific Micro stakeholder assessment and conducting local stakeholder's stewardship training.		
			c) An Integrated PPP and CSR Model for Lake ownership to avoid private entities commercialising the lakes.		
		2. Engineering interventions result in soup bowls that impact the surface water connectivity via the cascading system, i.e the "rajakaluves", disregarding its impact downstream .	2. Dredging should be Site/Context specific, which takes into consideration; • Groundwater potential • Quantifications of treated Waste Water generated • Lake Ecology • Higher resolution DEM • Tertiary SWD's		

S.No	Strategy	Problem Definition	Actions	Stakeholder (Actors)	Timeline
3.	Lake Dredging /Desilting	3. Due to lack of planning in appropriately siting the STPs, maximum water bodies become perennial, subsequently flash flooding results from not having enough time to infiltrate.	3. a) When STP exists upstream, a tertiary water treatment plant can be installed downstream at catchment level, and augmented for advanced treatment of water which can be further supplied for secondary use.		
			b) Installation of sluice gates to handle all lake outflows as already mentioned in the new DPR.		
4.	Stormwater drains	Lack of integrating stormwater with STP planning and monitoring - the negligence of illegal connections by public, shortsighted solutions by the government (eg: slum dwellings).	Crowd Based Data Sourcing to improve Social Accountability by engaging Academic Institutions for storm water surveillance and mapping. Perks 1. Addresses NEP 2. Schools can be standardised and certified to validate their achievements 3. Projects and Internships for Universities Model relies on a chain of stakeholders which has proved to be most effective to increase social accountability and ownership. Teacher ➔ Child ➔ Parent ➔Community ➔Teacher	BBMP SWD, BBMP-Slum board, BWSSB, Resident Welfare Associations	
5	Recharge Wells	Notional implementation of recharge wells in unconfined aquifers is failing to improve the groundwater situation, thereby exacerbating the reduction in infiltration capacity of flood water. Additionally, recharge wells linked to stormwater drains contaminate freshwater with discharges, resulting in public health concerns.	Aquifer Mapping: Wells to be dug up only to recharge confined aquifers after scientific aquifer Mapping	Central Ground Water Board, State Ground Water Board, Citizens, Research Institutions	
6.	Policies and challenges	1. Lack of proper planning in policy making with regards to urban flood	1. Ward level hyperlocal plans with respect to urban flooding	BWSSB, BBMP, KSNDMC, KSPCB, CWC, Citizen Groups, Builders, Planners	6 months
		2. Lack of monitoring over the implementation of existing policies by city-level boards.	2. Implementation of monitoring committees composed of members who are not part of the government.		
		3.Lack of regulatory policies.	3. Strengthening regulatory policies with a renewal time period.		
		4. Lack of an apex body to monitor the responsible government bodies and implementation of policies.	4. Bringing experts from different departments together to compose an apex body to monitor the interrelationships and data transparency inside/among the government organisations.		

S.No	Strategy	Problem Definition	Actions	Stakeholder (Actors)	Timeline
6.	Policies and challenges	5. Lack of capacity building among the decision makers and planners.	5. Bi-annual/Annual intensive workshops for government employees to cope up with new emerging issues in city planning and technological advancements.		
		6. Lack of government participation in MoU where community participation and external funding is available.	6. An open floor meeting organised yearly in the presence of the press including citizens, builders, planners and government officials with a predefined agenda to address with MoUs.		
		7. Lack of proper and transparent distribution of monetary resources as well as lack of human resources.	7. Proper resource delivery for the government and [ublicly available.		
7	Technological/ Economic/ Social constraints and Data Gaps	1. Lack of data availability	1. a) Each government organisation engaged in data collection and research should have an updated website with data resources.	KSNDMC, Karnataka State Remote Sensing Applications Centre	6 months
			b) An active cell in each organisation engaged in making data easily available and regularly updated, also with an active contact detail to address any discrepancy in the data.		
		2. Lack of quality or high-resolution data	2. a) Updating the data collection method with technical advancements	KSNDMC, Karnataka State Remote Sensing Applications Centre	
			b) Transparency in allocation of monetary resources assigned for research activities		
			c) Along with making this data available to others online for future research prospects.		
		3. Lack of proper demarcation of vulnerable populations regarding urban floods	3. A detailed study should be carried out in the whole city which would delineate the vulnerable population and vulnerable locations. These findings should be published for laymen in local language with statements clarifying the reason behind flooding for each location, with a follow-up immediate action plan backed up case study evidence, which can help decision makers to take action immediately.	KSNDMC, BBMP	
		4. Lack of awareness about the incentives provided by the government among citizen	4. a) Ward wise awareness programs arranged bi-annually/quarterly in local language with proper Flood Information Education and Communication materials (IEC)	Citizen Groups, NGOs	

S.No	Strategy	Problem Definition	Actions	Stakeholder (Actors)	Timeline
7.	Technological/ Economic/ Social constraints and Data Gaps		b) Explanation about the organisational structure of government and who is also which authority is accountable for what kind of issues along with proper explanation about the communication channel to address the issues faced by citizens.		
		5. Lack of citizen participation from different age groups and different genders	5. A proper setup of grievance a cell for different age groups and different gender with, addressed by people who are qualified to address the issues with sensitivity and in the local language.	BBMP	

Sir. M. Vishweshwaraya rain water harvesting theme park visit

ATREE team visited Sir. M. Vishweshwaraya rain water harvesting theme park to gather firsthand information and insights into the practical implementation of rainwater harvesting techniques within a small-scale setting. The various models showcased were crucial to the understanding of the feasibility of the Nature-based Solutions that we had proposed in our strategy and action plan. The idea behind the establishment of this theme park is to encourage the adoption of rainwater harvesting practices by providing information on different models and technologies, including borewell recharge systems, wall-mounted filters, and sloping roof designs.

Following are images depicting; the borewell recharge model, the wall mounted filters shown for rain water harvesting which helps in removing the dirt and unwanted solid materials from rainwater collected at the roof and flowing towards the storage tank and how the use of sloping roof can help in rain water harvesting, respectively.

The borewell recharge model

The wall mounted filters for rain water harvesting

Depicting the use of sloping roof for rain water harvesting