https://doi.org/10.64211/oidaijsd191108

Urban Liveability and its De-Linkages with Climatic Stress - The Case of Degradation of Urban Blue Infrastructure in Bangalore

Swathikka S [1], Ayon Kumar Tarafdar [*2]
[1] AMRUT Centre of Urban Planning for Capacity Building (ACUPCB-SPAV), School of Planning and Architecture, Vijayawada, India
[2] Department of Planning, School of Planning and Architecture, Vijayawada, India
*Corresponding author: swathikka07@gmail.com

© Author (s)
OIDA International Journal of Sustainable Development, Ontario International Development Agency, Canada.
ISSN 1923-6654 (print) ISSN 1923-6662 (online) www.oidaijsd.com
Deposited in SSRN repository: https://www.ssrn.com/ssrn/

Abstract: Loss of urban blue infrastructure is a troubling trend for cities, particularly in rapidly urbanizing metropolitan regions that face accelerating climate risks like urban heat islands (UHI) and urban flooding. This study explores the spatial relationship between climate-related vulnerabilities and degradation of blue infrastructure in Bangalore, a rapidly urbanizing Indian city. This study performs spatial analysis using Analytic Hierarchy Process (AHP) in Geographic Information System (GIS) platforms to identify climate-related vulnerability zones using several spatial indicators, with a focus on urban flood risk and heat stress. It also studies the degradation of blue spaces and examines the linkages between their degradation and hazard vulnerabilities. This analysis evidences successive increase of impervious surfaces and a rapid contraction of blue infrastructure networks that historically facilitated the city's hydrological functions. A critical finding confirmed by Moran's I analysis and spatial autocorrelation is the significant spatial overlap and clustering of high flood risk zones with degradation of blue infrastructure patches, which scientifically establishes the implications of destruction of wetlands with increasing flood vulnerability. The study indicates that the sub-region of Bellandur Lake is of high criticality and notices that urban hotspots have emerged as points of intersection between stress due to climate and structural degradation around the lake. This study concludes with certain thoughts on an actionable nature-based solutions using urban blue into smart enabling frameworks, and to call for action to build resilient urban environments with a focus on blue infrastructure.

Keywords: Climatic Hazard Mapping; Liveability, Spatial Autocorrelation; Urban Blue Infrastructure

Introduction

The history of Bangalore as the 'Garden City of India' is seemingly a contradiction for many in present times. Various cities in the Global South, like Bangalore, are facing conflicting challenges of rapid economic development and pressures of increased and uncontrollable population, leading to a substantial change of urban climatic conditions. The coverage of land with impervious surfaces, the removal of natural buffers, and the fragmentation of ecosystems affect not only environmental sustainability but also expose people to the extremes of climate (Ganguli & Tarafdar, 2025). In this situation, Bangalore is both a typical and warning case, as the city's famous character of a series of networked lakes has been unfortunately diminished by urban sprawl. Sustainable development in Bangalore faces three main hurdles: overlapping city agencies, continuous building on lake beds, and planning frameworks that ignore climate risk data. The city has the technical expertise to build resilience, but political and economic priorities continue to sideline ecological needs. To effectively handle climate hazards, urban planning must move beyond quick engineering fixes and treat natural water systems as essential public infrastructure. This paper is

an attempt to showcase how we can integrate the knowhow of hazrd risk identification with urban planning and development strategies.

The Paradox of the "Garden City": Historical and Ecological Transformation

Bangalore, known proudly in history as "The Garden City of India" because of its accessible parks and interconnected lakes, is now situated in the state of stark vulnerability associated with climate change, experiencing factors directly related to urbanization and the lack of planning. Urbanization has threatened the ecological and hydrologic functions of the city, taking the spatial ecology that was very much an integrated part of nature to a drastically fragmented arrangement of built form and concrete (Kumar & Shreya, 2025). The loss of the lakes as part of blue infrastructure of the city illustrates this vividly. Historical records show that Bangalore may have contained over 1,450 lakes in 1800, to only 194 functioning lakes in 2016 (Unnikrishnan et al., 2017), which is nearly 87% loss of water bodies as water storage declined from 35 thousand million cubic feet (TMC) to 5 TMC.

This degradation relates to an accelerated period of natural as well as demographic growth. The population of the city increased (Sourav, 2024) from 1 million sixty years ago to 14 million today. The population density of the Bangalore Urban (BBMP) limits increased from 7,881 persons per square kilometre, to 11,664 persons per square kilometre (48%) from 2001 to 2011. The area of concrete at this density increased to 88% of the city (Czyża & Kowalczyk, 2023). The increase in density and population were accompanied with development of concrete, but this is not new trend. For many decades unplanned transitional growth patterns followed a trajectory of development which completely obscured the natural topography of the city and its historical water systems. The result of that unplanned growth is transforming the lakebeds into residential and commercial areas which has eroded the ability of Bangalore to now perform environmental functions (World Resources Institute India, 2023). The consequences now are the predictable, yet rapidly worsening outcomes of a systematic failure to embed ecological parameter in the original urban planning process.

Vulnerability to Climate Change and the Role of Blue Infrastructure in Urban Resilience

The rapid growth of the city aggravates Urban Heat Island (UHI) effects and urbanized floods, primarily caused by climate change, and documented through the Indian Meteorological Department (IMD) records. Urban floods in Bangalore have occurred seventy-three times between 1969-2019, making it the most flood-prone district in Karnataka (Indian Meteorological Department, 2023). Between 1969 and 2019, temperature averages rose by approximately 1.5 °C in Bangalore-indeed worsening UHI (Wang *et al.*, 2024). Such climate indicators are not simply numbers and indicators, these climate issues have an impact on the lives of individuals living in a city. Recent news articles from Bangalore and the surrounding area from 2023 and 2024 confirm the continued occurrence of flooding events, resulting in public infrastructure water-logging-which in turn contributes to heavy traffic congestion, while also exposing members of the public to lethal events such as electrocution and drowning in flooded basements and under-passes.

The continual occurrence of flooding events demonstrates the possible inadequacies of the municipal systems, or infrastructure, to address the changing circumstances at the hands of environmental impacts and foot traffic in the context of volunteerism in a city. Each day these climate problems present public inconveniences, such as bad commutes and shortages of water, but it also poses serious questions for the public safety and stability of the economy (Tarafdar & Bjønness, 2010). Economically, the great city of Bangalore, otherwise known as "India's Silicon Valley" is experiencing foundational failures of infrastructure related to water and heat. The city has reached a point where it must restore and protect its blue infrastructure. Hence, it is imperative to think of an assessment process or framework that identifies areas under threat in terms of degrading and transforming blue infrastructure. This paper attempts to build a spatial for the same.

The deterioration of blue infrastructure in Bangalore is not simply a case study of localized challenge; this is seen as an indication of the challenge on a national level. Urban flooding is well recognized to be a serious threat in India, with flood risk designated as more than 40 million hectares of land classified as flood prone areas (Indian Meteorological Department, 2023). A rapidly growing city can be a significant indicator of wider climatic vulnerabilities, where the impact of unanchored or infrastructural solutions that unhinges the support of ecological infrastructure become minimal in importance and preparation. This study will serve as document suggesting integrated nature-based solutions on the city of Bangalore in the urban spatial basis.

Materials and Methods

Literature Review: The Nexus of Blue Infrastructure, Climatic Hazards, and Geospatial Analysis

Within urban climate resilience discussions, blue infrastructure is defined as the array of natural, or engineered, aquatic systems (lakes, rivers, wetlands, canals, ponds, etc) in cities, which generate important ecosystem services relevant for water management and climate preparations. Blue infrastructure is often conceptually linked to green infrastructure as part of nature-based solutions (NBS) in cities, which are approaches that protect, restore, or replicate natural systems for addressing social challenges while simultaneously providing benefits to human health and biodiversity. The Intergovernmental Panel on Climate Change (IPCC) noted in its Sixth Assessment that nature-based solutions – including urban blue and green space conservation – have become mainstream urban adaptation solutions, albeit optimizing their use is not realized (Intergovernmental Panel on Climate Change [IPCC], 2022). In rapidly urbanizing areas, the loss of blue infrastructure (i.e., loss of lakes and wetlands) is accompanied by heightened climate hazards. This section reviews literature on the loss of urban blue infrastructure and climate hazards (flooding and heat), and how geospatial analysis methods have been used to consider hazards and remediation.

Degradation of Blue Infrastructure

The decline of urban water bodies is a global issue, and results from various stressors including pollution, encroachment, and mismanagement. These stressors sufficiently diminish the capacity of blue infrastructure to carry out vital ecological functions including flood mitigation, groundwater recharge, and microclimate cooling. Silva et al.'s (2023)'s research from a semi-arid region of Northeast Brazil, which may be a useful comparative study for Bangalore, identifies a reduction in both water bodies and vegetation cover over a 19-year period. The authors note that the reduction of water bodies in Brazilian cities was primarily a function of agricultural expansion and climate variability. They further noted that a shift to sustainability and integrated water management is a necessary precondition to achieving resilience. Additional studies in Romania (Avram, Cipu, Corpade, Gheorghe, & Manta, 2021), Malaysia, Siberia, and Nainital (Sourav, 2024) reflected similar negative outcomes and demonstrate that poor regulatory practice, combined with rapid urban development, has contributed to declines in lake ecosystems and water quality. Collectively, these studies further demonstrate that restoring urban water bodies is not merely an aesthetic or conservationist response to the issue of development, but a precondition for ecological and urban resilience. Collectively, the studies outlined provide an academic rationale for the main position of this report, which is that the degradation of urban blue infrastructure contributes to exacerbate climate hazards, such as flooding.

This situation of degraded blue infrastructure is not an isolated event in India's urban areas, and across multiple cities in the world, urban development over decades has led to the loss and/or modification of natural waterways. For instance, London lost many of its tributary rivers and wetlands – a process that has put the city in increased risk of surface water flooding when these tributary rivers were encased in culverts or drained (Wild et al., 2017). North American cities have either paved over or contaminated urban streams leading to reduced capacity for retaining stormwater run-off and decline in water quality (Kaushal et al., 2012). In rapidly urbanizing cities in Asia, the fast infill of wetlands and conversion of lakes for development has similarly compromised natural drainage – similar trends were noted in metropolitan areas in China which spurred the recent "sponge city" initiative to restore wetland functionality (Chan et al., 2018). It may be understood that urban resiliency is tied to the potential status of urban blue infrastructure. Cities that have acknowledged this relationship are deliberately starting to invest in blue infrastructure restoration or conservation as a first-step for climate adaptation. For example, Singapore is restoring concrete canals back into semi-natural waterways or creating new ponds through their Active, Beautiful, Clean (ABC) Waters program to regain lost hydrological function (PUB, 2015). Such situations reinforce that Bangalore's obstacles in conserving and restoring blue assets, in hindsight, are part of a grander scheme of urban resiliency.

Therefore, the depletion of blue infrastructure extends beyond India, mirroring a global pattern where decades of urbanization have systematically altered natural aquatic networks. This paper attempts to look into this aspect where the depletion is not merely looked upon as a loss of biodiversity by a key tenet in making cities less liveable and hence less investment-friendly.

Urban Floods

Urban flooding is an inevitable byproduct of urbanization processes that have disrupted the natural water regulation and drainage systems operating in cities. Urbanization increases impervious substrates, overwhelming the capacity of urban drainage systems to absorb excess water. As Kaur and Gupta (2022) articulates, blue infrastructure made up of lakes, ponds, wetlands, and rivers is a resource sponge that functions to regulate and control flood and excess stormwater runoff. The research regarding flood resilience in Peshawar City, by Tayyab et al. (2021) found that

structures that were observed to have the highest relative flood risk had the lowest relative coping mechanisms, and that integrating blue infrastructure into their resilience planning would greatly increase the management of flood risk. This finding aligns with widespread global literature reviews analyzing GIS based hazard mapping and hazard modelling studies assessing flood hazards.

The effectiveness of these nature-based solutions can, and has been empirically verified. A 2022 meta-analysis of green-blue infrastructure outcomes in 50 cities around the world demonstrated clear evidence that green-blue infrastructure classified studies experienced a 30% average decrease in stormwater runoff volume in areas deploying green-blue infrastructure (Almaaitah *et al.*, 2021). This is certainly empirical evidence that endorses the position that integrated blue infrastructure can provide a viable and cost-effective ecological alternative to built infrastructure-based flood control systems. The causal relationship is made easily and clearly in the literature; where natural water system, or green-blue infrastructure, has been removed or damaged, the hydraulic water regulation of the city has subsequently and consequently been diminished, and an increase in flood risk to the city ensues.

Across the globe, cities are changing their flood management strategies to include the re-introduction of blue infrastructure. In the Netherlands, for instance, the Room for the River program explicitly reconceives floodplain and wetland restoration on rivers, accepting that accommodating water in the landscape is more effective than containing it within the confines of higher levees. In the UK, sustainable drainage systems (SuDS) have seen an increase in interest in a more green or blue-green approach to urban development - London, in particular, has tested a series of rain gardens, swales, detention ponds within their drainage network to complement grey drainage. An analysis of adaptation pathways for a London borough has demonstrated that integrating blue-green infrastructure (bioretention cells, permeable pavements, and retention ponds) with grey-infrastructure can improve flood risk management, while also delivering multiple co-benefits. New York City has developed a Green Infrastructure Plan, which includes constructing thousands of curb side rain gardens, green roofs, and other forms of green infrastructure which catch stormwater prior to draining into the sewer system, thereby reducing combined sewer overflow and local flooding (New York City Department of Environmental Protection, n.d.).

Singapore has implemented blue-green approaches even in its dense urban areas - retrofitting the Bukit Timah stormwater canal with wetlands and rain gardens improved flood flow conveyance, while also generating new recreational spaces for public use. These examples from the global landscape are revealing a significant pivot: flood resilience now needs to be strengthened by restoring, or creating, opportunities for water (Public Utilities Board, 2010).Peer-reviewed literature has shown and documented the rationale for these cases with the recent case study in Belgium demonstrating that a nature-based flood control remedy (restoring wetlands) could show equal to or improved effectiveness of a technical remedy (concrete flood barrier) to mitigate peak flows, which in a powerful way captures the mindset of the working group. On a global scale, the IPCC advocates for the use of nature-based solutions (urban wetlands, bioswales, retention basins) as an adaptation strategy to flood risk in urban settings. Bangalore's situation, therefore, is not a singular occurrence, rather happens to be a part of a larger narrative where cities are re-learning to coexist with water.

Urban Heat Island

Urban heat islands (UHI) are an unavoidable effect of densification of built-up areas, where materials capture heat and raise temperatures at the local scale. The cooling effects of blue and green infrastructure as part of urban planning mitigates this locally increased temperature through processes such as evapotranspiration and retention of water. Pritipadmaja et al. (2023) in Bhubaneswar, India, looked at Land Surface Temperature (LST) maps in conjunction with the Normalized Difference Water Index (NDWI), to demonstrate the areas with abundant water and vegetation cover, having a lower surface temperature than adjacent areas at the normal condition of no water or vegetation cover.

The function of urban blue infrastructure for thermal cooling is being globally acknowledged. Water bodies (i.e., lakes, rivers, and even decorative pools or fountains) serve as heat sinks due to the thermal nature of water, in addition to the evaporative cooling added by the water source. Wu and Zhang (2019) found that in an urban context, water bodies can lower surface temperatures throughout the day to varying degrees, and offer a meaningful ecosystem service of heat cooling ability. Cities with large blue networks, like Amsterdam and Copenhagen, have shown city microclimates adjacent to canals and water features are cooler than built-up areas without water.

Other studies provide better quantitative understanding of this effect. For example, a study of blue green spaces in Changsha, China, (Cai *et al.*, 2018) concluded that blue green spaces cool the surrounding local temperature, and that the cooling effect was correlated to increased area and shape complexity. The study provided some specific thresholds, finding that a certain size and complex shape blue space would create a localized cooling magnitude of 5.17°C, and

at 413.46 meters of cooling distance. This evidence is significant because it changes how the benefits of BGI are understood from being a general documentation of observational understanding with observed local cooling, to principles based on measurable outcomes and design approaches. The research points out that merely having profit of localized temperature cooling is not sufficient, the design and placement of these water bodies are needed to comprehend measurable impacts to the microclimate of a localized area and thermal stress across a city.

Some cities are intentionally using water for cooling during extreme heat events: Paris is utilizing cooling fog mist units and open water features as part of its extreme heat response plan and Barcelona has created "climate shelters," which usually feature some water as a design element to cool public spaces. In tropical cities, like Singapore, water features are included by urban planners as not only drainage, but also a cooling feature or benefit – tropical water features (ponds, waterfront parks, and vertical water features) all contribute to reducing ambient temperatures and improving comfort as components of Singapore's urbanism. Ultimately, blue infrastructure can function as the city's "thermostats." The peer-reviewed literature across climates finds that a system of ponds, reservoirs, and wetlands can mitigate UHI by cooling adjacent air by evaporation and enhance airflow paths to dissipate heat. For Bangalore, which we know suffers from extreme levels of UHI effects, restoring its lake systems and conserving its water bodies are not about just water resource management – they are an essential strategy for heat adaptation. By enlarging, expanding, and connecting blue spaces, Bangalore will be able to take advantage of these cooling services from nature, according to local findings in India, and international institutional research on microclimatic benefits of blue infrastructure.

Benefits of Blue Infrastructure in Climatic Hazards

Urban blue infrastructure functions as single use with flood and heat mitigation purposes for a given blue infrastructure deployment. It offers a number of ecosystem services, such as, improved aesthetic values, biodiversity increases, and water purification, that contribute to a city's capacity to build resilience to climate related hazards. Furthermore, the significance of blue elements in urban areas design for public health, social cohesion, and consideration of alternative engineering hydrological practices. Again, while Almaaitah, et al., (2021) show BGI as an implementation indeed had successful intertwining based outcomes, it may also be prohibitive to have barriers, effectively shown in the evidence. The hurdles are often multi-level governance; budgets; and lack of risk reduction frameworks in place.

With this as the backdrop, the topic about climate resilience has made important inroads on blue infrastructure as a critical form of nature-based climate solution. High profile agencies and frameworks have indicated widespread uptake of the concept. The United Nations through its World Water Development Report 2018, outlined that working with natural systems (like restoring urban wetlands and rivers) is a "crucial way to move from business-as-usual" in water management and disaster risk reduction, suggesting a shift in thinking, where ecosystem services can serve as protective assets in an urban setting. World Resources Institute (WRI) has also reached for the potential of nature-based solutions; WRI India (2023) has proposed wetlands and urban watersheds into planning as a solution to resilience in flooding and drought. Also, various benefits associated to blue infrastructure link directly to sustainable urban development: by mitigating climate hazards in ways that also can support liveability and equity, blue infrastructure can advance overlapping Sustainable Development Goals (SDGs 6,11, 13, etc.). Thus, investments made to keep a lakeshore clean or designing a new urban wetland will ultimately be realized in less disaster losses, greater urban biodiversity, and higher quality of life for residents. These wider benefits strengthen the argument for blue infrastructure especially in resource-challenged contexts – they are not simply environmental amenities, but foundational elements of a resilient urban tapestry (Lamond & Everett, 2019).

Objectives of the Study

Once recognized as the 'Garden City,' Bangalore now faces considerable ecological strain due to uncoordinated development, and its extensive lake system, vital for stormwater management and groundwater recharge, that is significantly degraded. Restoring blue infrastructure could provide a huge opportunity for building urban resilience through flood abatement, cooling, and ecological restoration. This study as presented herewith, has an overall intention of analysing the spatial dynamics of climatic hazards (flood and heat risks) in relation to the degradation of urban blue infrastructure in Bangalore. In order to achieve that, it sets forth a few objectives. Firstly, the study understands the existing urban blue infrastructure and determines the nature and degree of its transformation. Thereafter, it identifies and delineates potential areas of climate risks within the city, focusing on heat accumulation zones and flood accumulation zones using several factors. After that the study analyses the overlap between urban heat accumulation zones, flood accumulation zones, and the Urban Blue Transformation Index. Finally, it takes up areas where urban blue infrastructure is deteriorating and are also having climatic risks of flooding and heat accumulation to propose a planning framework that rejuvenates these areas and also mitigates the climatic hazards of flood or heat.

Methodological Framework: A Multi-Criteria Geospatial Approach

The study uses a multi-criteria spatial analytical tool based on the Analytic Hierarchy Process (AHP) and Geographic Information Systems (GIS) to identify and assess climate hazard areas and visualize. AHP is used in this study to assign relative weights to a series of biophysical and environmental factors that were identified as factors proven to escalate or mitigate climate hazard incidences such as heat accumulation, surface runoff, and local flooding in areas of rapid and variable urbanization.

Combining AHP and GIS allows for the spatial distribution of a weighted index to be calculated over the study area to produce composite hazard layers that are analytically meaningful, and visually interpretable. The weighted linear combination produced maps of relative vulnerability that showed the most vulnerable areas in Bangalore. By combining the structured judgment of AHP and the spatial ability of GIS, this transpired into a method that has ensured the knowledge of experts and empirical geospatial data are integrated appropriately providing planners with a defensible basis for climate resilience planning for priority areas.

The Analytic Hierarchy Process (AHP) in Environmental Decision-Making

In this research, we are employing a multi-criteria spatial analysis technique using AHP and GIS together to identify and map potential climate hazard-prone areas. AHP, a multi-criteria decision-making (MCDM) tool, provides a systematic and objective way to analyse complex decisions. AHP can transform a multi-dimensional problem, such as urban vulnerability, which involves multiple dimensions into a one-dimensional priority ranking.

For this study, the AHP was used to generate weights for different indicator aspects of heat stress and flooding risk, e.g., Land Surface Temperature (LST), and flow accumulation (refer Table 1). The AHP process is capable of providing a transparent assessment that employed a scientifically defensible rationale in order to be able to end up with a shared geospatial assessment or evaluation that was derived from quantitative data and expert judgment. The AHP is an additional step that brings robustness to the analysis because it provides rationale to demonstrate that we deemed some criteria more important than others in the final maps for vulnerability.

The use of AHP in environmental planning is well established. Originally developed by Saaty in the 1980s, AHP has been used extensively for mapping hazard and vulnerabilities because it provides consistency to expert evaluations of a complex set of criteria. By checking the consistency of pair-wise evaluations, AHP allows for weight assignment to be trustworthy and not haphazard. In urban locales, each trend utilized GIS more recently to model maps of flooding susceptibility, urban heat vulnerabilities and socio-environmental indices. GIS enabled local expert knowledge to be measured and synchronized with spatial data layers. In this study we utilized best practices and computed a consistency ratio of the AHP pair-wise comparison matrix to ensure expert input was relatively consistent. The total weights we generated (refer Table 1) portray the relative weight of each criterion. In heat stress mapping, LST generated the largest weight as it indirectly aids proximate measures of surface heat retention, followed by PM10 concentrations (inferred from urban activity and pollution which may be associated with trapped heat), Normalized Difference Built-up Index (NDBI) and the paved-to-unpaved surface ratio. This is consistent with findings in the literature - for example studies in other Indian cities have identified land surface temperature and built-up intensity to be top contributors to UHI risk (Pritipadmaja et al., 2023; Sourav, 2024). Likewise, for flood risk mapping, flow accumulation, elevation (from DEM), and slope received top weight categories because of the high role of runoff and pooling water. Proximity to road or water borrowings received lower weight categories (refer Table 2) due to more localized nature. The AHP measures allow for them to presumably provide trustworthy bridges to qualitative-quantified data products that contribute to the validity of generated hazard maps beyond the stakeholders' technical expertise.

Next page

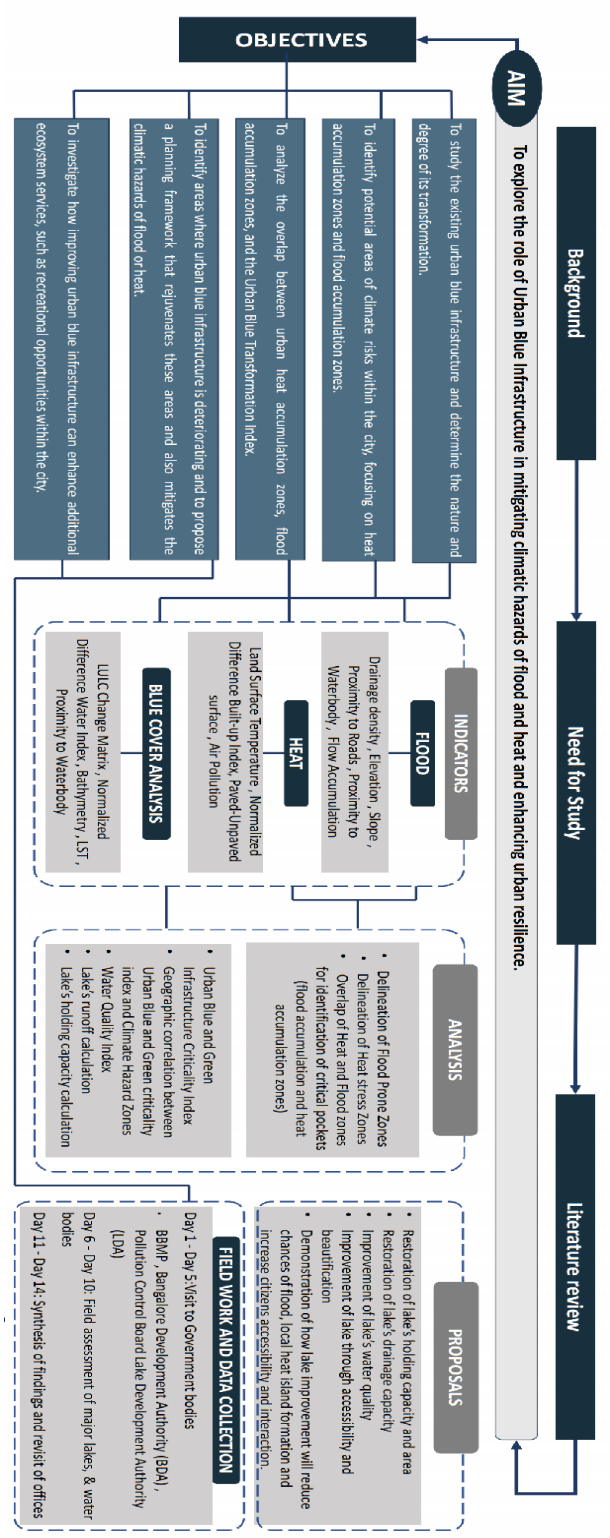

Fig 1. Methodological framework for assessing the role of urban blue infrastructure in mitigating climatic hazards.

Source: Output of this Research

Geographic Information Systems (GIS): Data Integration and Spatial Modeling

The specific software platform for the integration, spatial modelling, and visualization of this research study was Geographic Information Systems (GIS). In this research, GIS was utilized to pre-process the remote sensing data and produce thematic maps for a number of environmental and urban parameters. It had the capacity to allow various layers of the data to be overlaid, which enables formal assessments of increasing vulnerability and identifying areas of higher risk. Through GIS, we can address the spatial heterogeneity of urban settings. Each criterion (in our case, LST or flow accumulation) were basically a map by themselves, and GIS has the capability to execute map algebra and overlay analysis once you apply the AHP weights. The use of AHP and GIS is a powerful integration – it generates spatial composite indices for multi-criteria decision-making. Others have demonstrated the same: flood risk zones (Tayyab et al., 2021); heat stress distributions using GIS-based multi-criteria analysis and validated using prior event data or field assessments.

For our process, we entered the weights using the AHP process; then we reclassified and weighted each raster layer, producing a continuous surface of vulnerability to both heat and flood hazards. The GIS platform also allowed for accuracy assessments and sensitivity ranges; we could change a weight and instantly visualize what the vulnerability map would be, an effective way of estimating robustness of the results. Furthermore, spatial statistical capabilities in GIS (e.g., hotspot analysis and clustering) allowed to evaluate the map patterns beyond visual overlay. This AHP–GIS methodology is inter-disciplinary – it employs knowledge of human actors and processes with computerized data methods. This is beneficial for urban climate resilience research given the social factors (using expert opinion on what is valuable to vulnerability) and physical factors (using all of the geospatial data layers) of climate risks. GIS was not only used as a mapping system, but as a decision-support system that formulated the complexity of possible data into spatial actionable information for the planners of Bangalore.

Analysis and Findings

Historical Land Use and Land Cover (LULC) Change

The urban environment of Bangalore has undergone serious alterations and at speed over the 10-year period that has been the subject of prior LULC and area of water surface investigations. The LULC change in land surface area was spatially produced using NDWI and showed a general decline of the area of water surface values between 2014 and 2024. Furthermore, there was a marked increase of water surface values between 0 and 0.2 (flooding and/or wet conditions), as well as even larger areas of the index between -0.3 and 0 (medium drought conditions). Permanent water bodies have not only been reduced but also retention capacity has been reduced, which has contributed to dry conditions in some areas and flooding episodically in other areas, none of which bode well for sustainable presence.

These trends were also supported in several other studies that have shown historic declines in landforms and contributed to the impacts associated with climate, weather and environment. In 2014, land cover was 1% water, 20% vegetation and 79% built surface in Bangalore. The 2025 forecast indicates continued vegetation loss and even greater urban built space. The indices referenced were quantitative and have hard numbers, and consequently leads one to ponder the degree of trauma to the natural environment where natural land cover was converted by urban impervious surfaces characterized by their permanence and allocated mostly as a zone for commerce. This is the primary driver of the city's climatic vulnerabilities, as the land has lost its natural ability to absorb and thermoregulate for water.

Next page

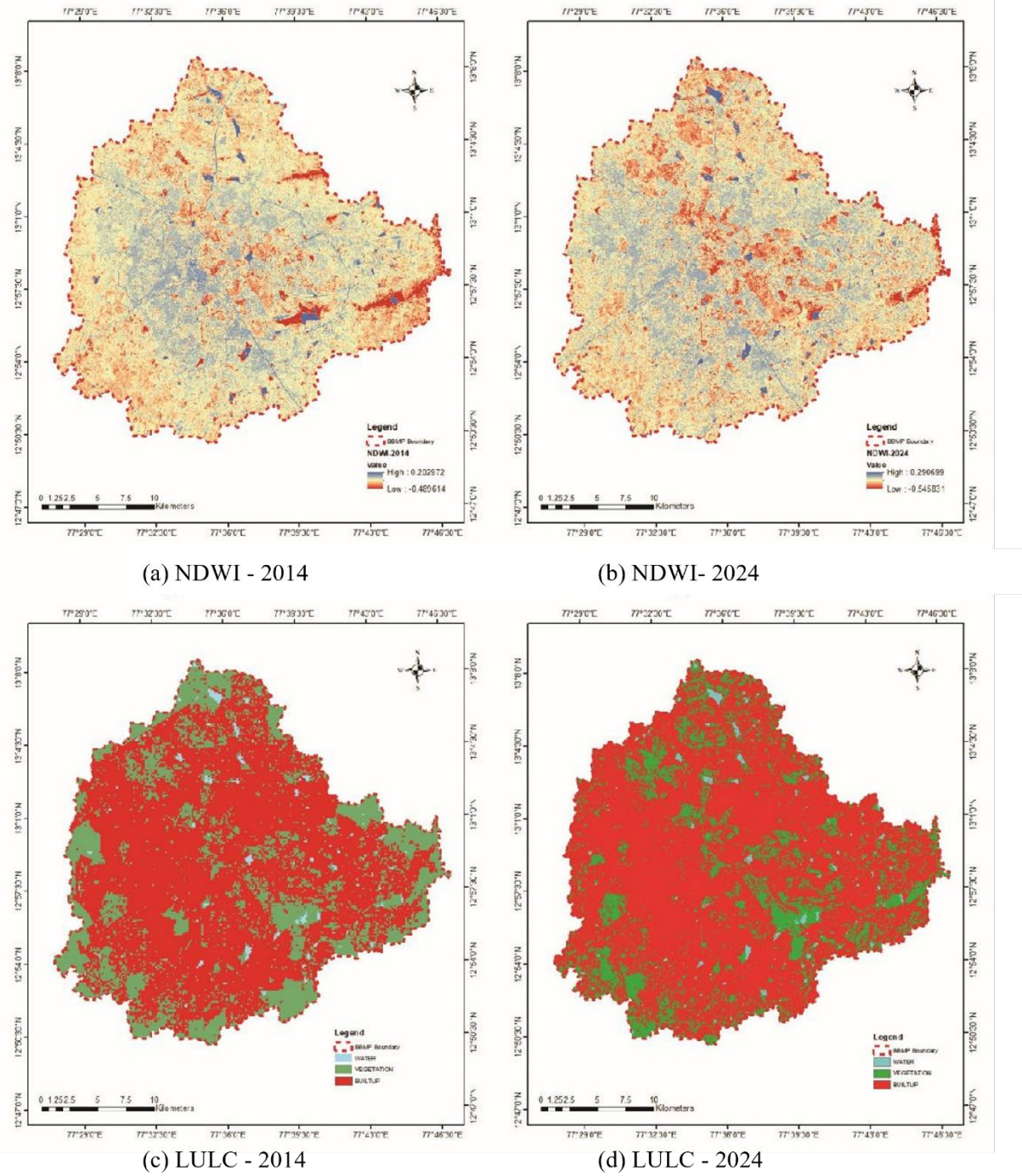

Fig 2. Spatio - Temporal analysis of Normalized Difference Water Index (NDWI) and Land Use Land Cover (LULC) transformation between 2014 and 2024 (a) NDWI – 2014 (b) NDWI – 2024 (c) LULC – 2014 and (d) LULC -2024.

Source: Output of this Research

Heat Accumulation Zones: Analysis of Key Indicators

Spatial vulnerability zones to the UHI phenomenon were assessed via AHP weights of primary criteria in a multi criteria spatial analysis. The assessment utilized four indicators of change, LST, NDBI, PM10 concentration, and the ratio of paved to unpaved surfaces. The AHP process established weights which were applied and assigned to each of the criteria and the results are presented in the following Table 1. LST was given the greatest weight, as it was the

most direct measure of heat retention at the ground surface. PM10 concentrations were weighted the second highest, as they are considered as proxy indicators for urban air pollution, and vehicle density km, both of which are covariates to urban temperature elevations. NDBI and the paved to unpaved surface ratio indicated density of built, impervious surfaces which absorb and hold heat. The overlapping and spatially weighed UHI layers of Bangalore has provided identification of density hotspots which are centred principally in built, densely- populated areas which were not only confirmed spatially, but in a direct correlated pattern of density, in relation to thermal stress.

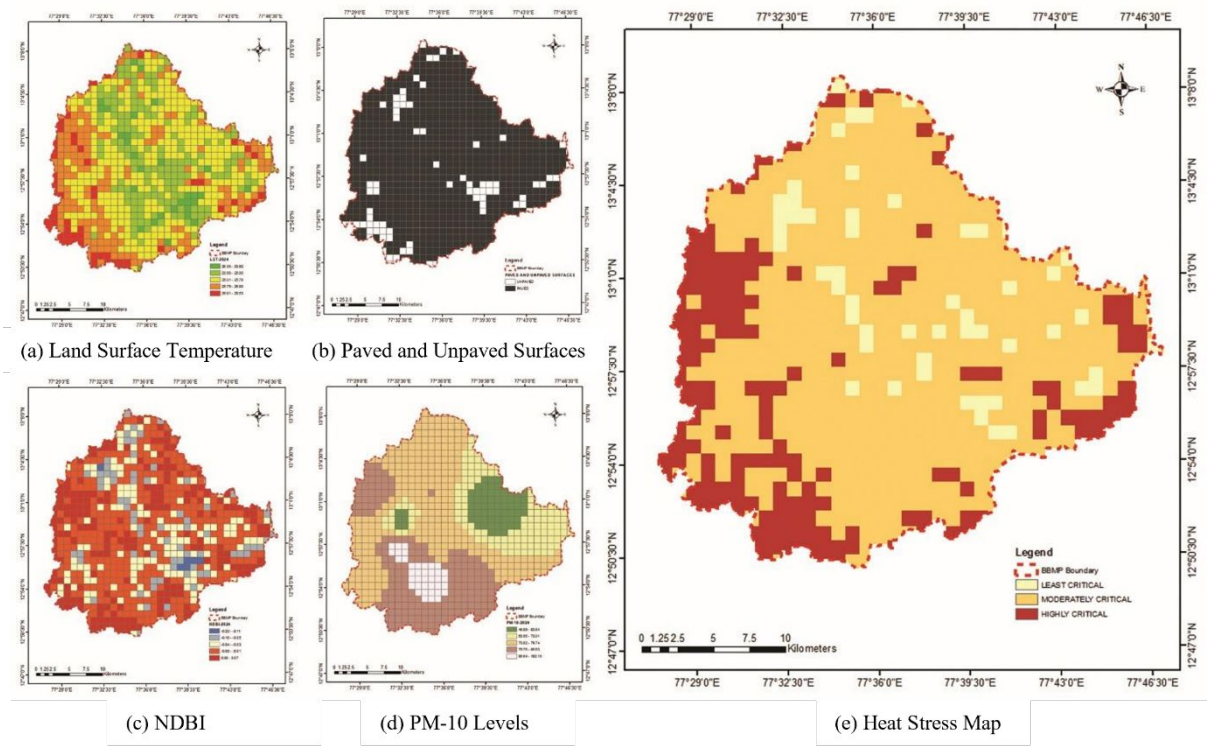

Fig 3. Spatial distribution of heat related parameters and the resultant heat stress map (a) Land Surface Temperature (b) Paved and Unpaved Surfaces (c) Normalized Difference Built-up Index (d) PM-10 levels and (e) Heat Stress Map.

Source: Output of this Research

Table 1. Relative weight distribution of parameters in heat stress mapping using Analytic Hierarchy Process (AHP).
Source : : Output of this Research (AHP Method)

Criteria	Weightage (%)
Land Surface Temperature (LST)	47.0
Normalized Difference Water Index (NDBI)	16.0
Paved-Unpaved Ratio	10.0
Particulate Matter (PM)-10	27.0

Flood Accumulation Zones: Hydrological and Topographic Assessment

Urban flood awareness zones were devised in the same manner of assessment. It utilized six indicators of change, DEM, Drainage Density, Flow Accumulation, Proximity to Roads, Proximity to Waterbodies and Slope. The AHP process established weights which were applied and assigned to each of the criteria based on total contribution

potential to urban flooding, and the results are presented in the following Table 2. The criteria with most weightage was Flow Accumulation, followed by DEM and Slope. Flow Accumulation had weightage as it directly represents the natural course, flow, and accumulation of surface runoff, the leading factor towards flooding. Similarly, the DEM and Slope layers had weightages relative to how land is defined topographically, with shallow slopes being more likely to experience flooding. Proximity information to both waterbodies and roads were incorporated into the directional model with comparatively less weightage assigned, as they could potentially impact localized flooding events. The result of the flood-risk map indicates a high-risk zone in a low-lying area that was associated with low drainage and was highly proximate to a degraded waterbody.

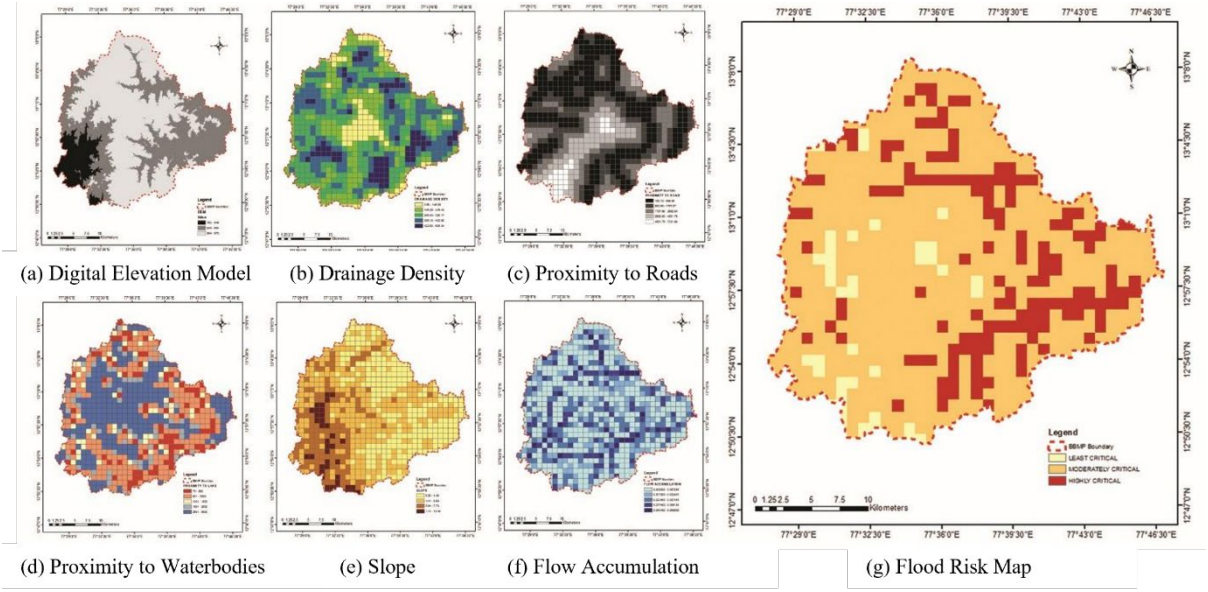

Fig 4. Spatial distribution of flood related parameters and resultant flood risk map (a) Digital Elevation Model (b) Drainage Density (c) Proximity to Roads (d) Proximity to Waterbodies (e) Slope (f) Flow Accumulation and (g) Flood Risk Map.

Source: Output of this Research

Table 2. Relative weight distribution of parameters in flood risk mapping using Analytic Hierarchy Process (AHP).
Source : : Output of this Research (AHP Method)

Criteria	Weightage (%)
Proximity to Roads	6.0
Flow Accumulation	26.0
Slope	21.0
Proximity to Waterbody	10.0
Digital Elevation Model (DEM)	21.0
Drainage Density	16.0

The Spatial Relationship Between Infrastructure and Hazards: An Autocorrelation Assessment

A quantitative description of the relationship between climate hazards and green infrastructure was performed spatially by assessing spatial autocorrelation using the Global Moran's I statistic. The conclusion of this assessment is an

important piece of evidence concerning the presence of ecological buffers throughout the city and their relationship to outcomes.

For urban planners and policymakers, understanding the significant clustering of flood risk with blue infrastructure deterioration is not a trivial consideration. It implies that solutions, such as the restoration of wetlands, expanding culverts around lakes or the establishment of new retention basins in selected areas, could yield a disproportionate impact at dismantling these vulnerability clusters. Many global cities have performed similar types of spatial analysis to identify priority investments. For example, New York City identified combined sewer overflow "hotspots," and subsequently built green infrastructure in those catchments (NYC DEP, n.d.). Cities in China have also identified stormwater inundation areas to develop Sponge City measures (Ruangpan et al., 2020).

Moran's I analysis offers evidence to identify "hotspots" of compounded risk in Bangalore (e.g. Bellandur lake region discussed below), this would lend support for similarly targeting nature-based solutions. Additionally, the lack of spatial correlation between existing green cover and heat stress correlatively suggests that having green cover is insufficient, in that existing green spaces need to be thoughtfully located, and of an adequate size to reduce UHI impacts. This reinforces the idea that there is potential in developing a city-wide green-blue infrastructure network plan, so that green parks and lakes are connected and positioned for maximal cooling, and it would allow for heat and flood mitigation.

Moran's I is a statistical tool used to examine spatial autocorrelation; that is, whether similar values spatially cluster or not. Moran's I identify whether a pattern is:

- Clustered (similar values are in close proximity),
- Dispersed (dissimilar values are in close proximity), or
- Random (indicating no spatial pattern)

Formula:

$$I = \frac{N}{W} \cdot \frac{\sum_i \sum_j w_{ij}(x_i - \underline{x})(x_j - \underline{x})}{\sum_i (x_i - \underline{x})^2} \quad (1)$$

N = number of spatial units (e.g., pixels, wards)
xi = value at location i
$\bar{x}$ = mean of all x
wij = spatial weight between location i and j
W = sum of all spatial weight

Next page

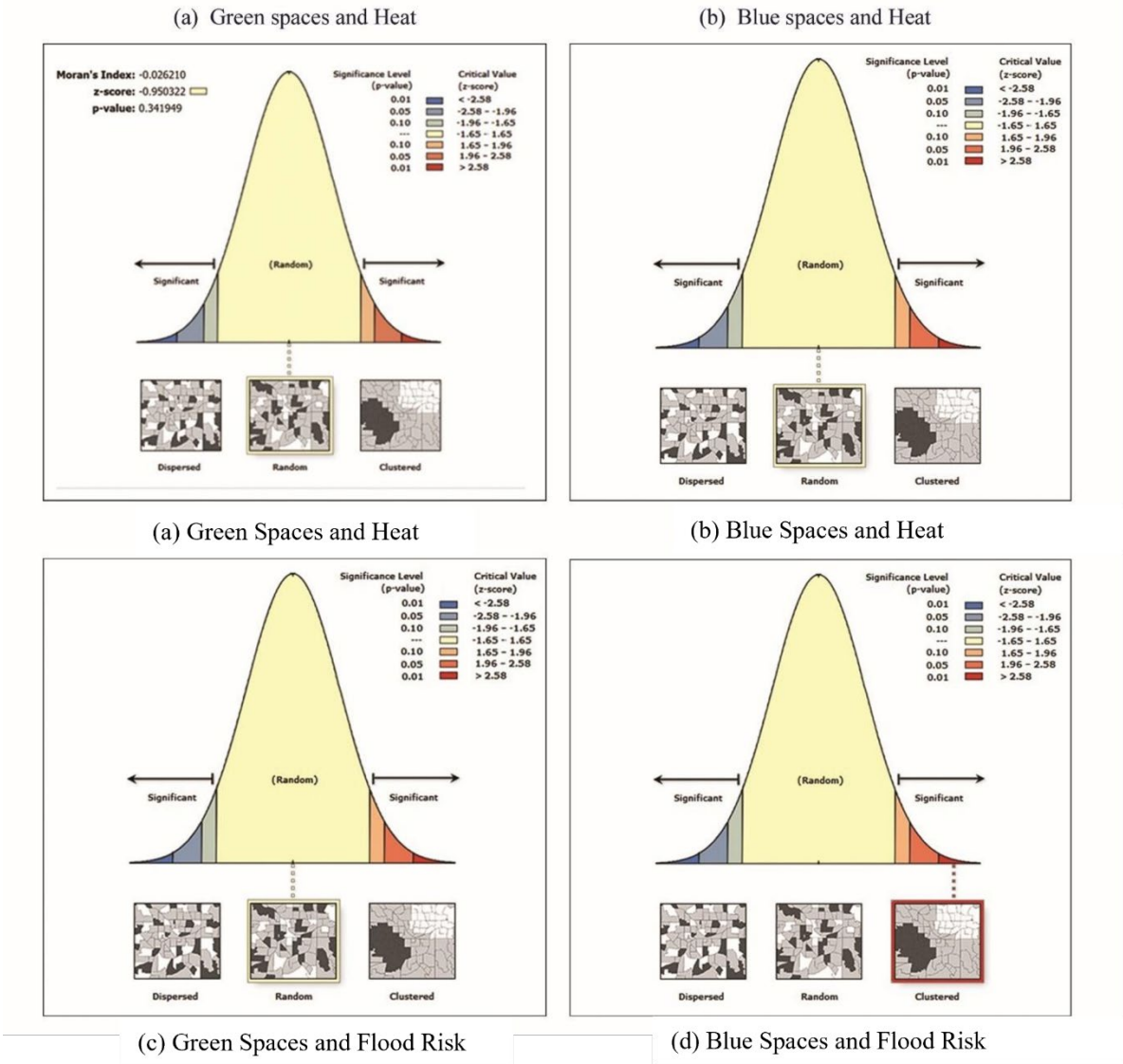

Fig 5. Moran's I Analysis of Spatial Relationships between blue-green infrastructure and climatic hazards (a) Relation between green spaces and heat (b) Relation between blue spaces and heat (c) Relation between green spaces and flood risk and (4) Relation between blue spaces and flood risk

Source : : Output of this Research

The analysis concluded that there was a weak and insignificant spatial relationship between the green space concentration and heat stress zones (Moran's I: -0.026210, p-value: 0.341949), while similar weak negative relationships were evident between blue infrastructure and heat stress (Moran's I: -0.152870, p-value: 0.192556). Statistical insignificant results indicate that the current greenspace and blue space are distributed randomly in relation to heat stress zones and they are either too small or insufficiently connected to effectively reduce UHI. The incautious suggested distributions reinforce that there is absolute disregard for ecological networks in the history of the city's development.

The analysis concluded the presence of a weak positive spatial autocorrelation (Moran's I: 0.039437, p-value: 0.121967) between green spaces and flood risk as green spaces may slightly cluster in areas with similar values, likely due to their natural ability to retain water. The analysis unambiguously showed a high significant spatial cluster between flood-prone zones and blue infrastructure (Moran's I: 0.033021, p-value: 0.000000). This finding is of high importance. The value of Moran's I returned plenty high and the p-value of zero indicates a propensity that confirms there is a strong statistically significant overlap between flood risk locations of higher risk, and water bodies in

degraded states, if not the catchments or absence of nearby water bodies. The results of the analysis presented in Table 3 provides a strong empirical basis for the central inquiry of this study.

Comprehensive Criticality Mapping

A conceptual process was made that leads to the Comprehensive Criticality Map. The Comprehensive Criticality Map is a merger of four thematic datasets layered and evaluated as they interact with one another: Heat Stress Zones, Flood-Prone Zones, Green Infrastructure Concentration, and Blue Infrastructure Concentration. Each was reclassified and given a weight that reflects how relevant the data is particularly to assist with urban vulnerability. The map classifies the study area into three levels of criticality based on a synthesis of the data-sets contained in the analysis.

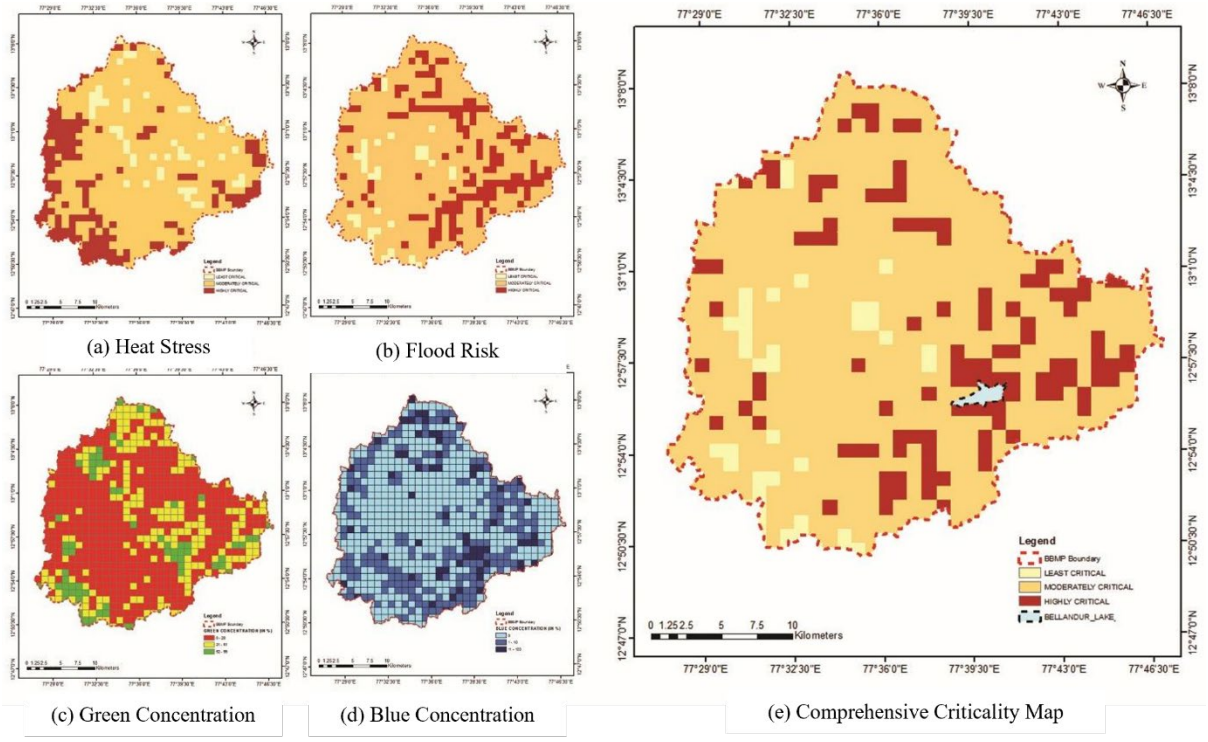

Fig 6. Comprehensive criticality mapping of climatic hazards and ecological infrastructure and its parameters (a) Heat stress (b) Flood risk (c) Green concentration index and (d) Blue concentration index

Source: : Output of this Research

Most importantly, the analysis identifies the Bellandur Lake area as one of the most critical area in the city, which lies in the interface of manifestations of climate change and challenges of urban blue infrastructure. It represents a perfect case of overlapping vulnerabilities as it relates to the wastefulness around, significant heat stress, extreme flooding, and unacceptable levels of degrading of blue and green infrastructure. The map offers a comprehensive, data-based mandate for selection of the case area and for the development of specific resilience interventions and an immediate need for spatial planning, to address and come up with a qualified climate adapted living strategy.

Lack of Integration of Climate Hazards and Urban Liveability

At this juncture, it is Urban "Liveability," or how well an urban area meets the needs for people to lead happy, healthy lives within their urban environments, has become a core component of urban research and planning. However, there is an enormous divide, both theoretically and practically, between the aspirational goals of urban liveability and the reality of the physical stresses placed on cities due to environmental degradation and climatic hazards (Murali & Pradhan, 2025), (Reis et al., 2015). In fact, most metrics developed to measure liveability do not account for these shocks, and therefore, are fundamentally unable to measure the impacts of climate change on urban liveability. The consequences of this disconnection can have far-reaching implications for the long-term viability of many of the world's largest metropolitan areas. This disconnect has been clearly illustrated in major urbanizing centers of the Global South, such as Bangalore. As Bangalore continues to grow economically at unprecedented rates, it also appears

to be losing its ability to buffer itself against extreme climatic events. This has occurred while the natural ecological systems of the area continue to be degraded. (Ramanath Jha, 2024).

Urban Liveability and its De-Linkages with Climatic Stress – Theoretical aspect

The concept of liveability is complex, and represents a wide-ranging, evolving, and inclusive picture of the condition of the urban human settlement environment. Liveability is a term that evolved out of early urban ecosystem theory. For example, Doxiadis (1970) viewed the city as a living entity and considered the quality of the "anthropocosmos" was dependent upon how harmoniously people interacted with their physical surroundings (Doxiadis, 1970). Modern research divides liveability into two categories: objective liveability, which includes the tangible environmental qualities found within cities including accessible community amenities, health care services, and available basic infrastructure; and subjective liveability, which is based upon the way individuals perceive their local urban environment through their feelings of happiness, comfort, and well-being generated by their interactions with their environment. (Chen et al., 2023).

Although there are good examples of both the definition and application of liveability, the theoretical framework of liveability remains fuzzy and flexible and is subject to varying degrees of disagreement among disciplines and geographic locations. (Economist Intelligence Unit, 2025). Due to the flexibility of the definition of liveability, the use of commercially developed liveability indices (e.g. the Global Liveability Index, published by the Economist Intelligence Unit (EIU); and the Ease of Living Index, published by the Indian government) have dominated the assessment of urban environments. Both indices were created to provide a commercial-based tool to assess the living conditions of expatriates relocating to another country for work purposes and to determine the level of hardship allowance. Thus, the criteria used to assess the living conditions are biased towards the needs of expatriates (i.e. politically stable country, international transportation network, etc.). A significant disconnection exists between the commercially produced liveability indices and climatic stress. The reason is that both indices statically define the "environment" category. For example, the EIU defines the environment through indicators such as humidity, temperature, and comfort levels. However, the EIU does not account for the frequency and severity of extreme climate events (e.g. urban floods, heat waves). Therefore, a city can be evaluated as having a high degree of livability because of its infrastructure and stability, but not be prepared at all to respond to a climate-related disaster. Additionally, the indices rely heavily on expert opinion and do not represent the lived experience of the broader urban population. The population most affected by climate-related disasters, i.e. those living in informal settlements, are often underrepresented in the development of the indices. (Chen et al., 2023)

In response to the increasing impacts of the climate crisis, protecting the ability to participate in society requires a safe, non-hazardous environment and secure housing. When the commercially developed liveability indices view environmental quality as an additional "perk" to be received as opposed to a fundamental need, they disguise the widening "capabilities gap" being caused by climate change. Capabilities such as working during extreme heat or losing one's house to a flood directly undermine the core capabilities necessary for social participation, however, these types of climate-related stressors are rarely accounted for when assessing urban liveability using standardized indices. (Shakya et al., 2025). Therefore, the absence of a common framework results in urban managers often pursuing liveability scores that are disconnected from ecological sustainability. An example of this is if a city improves its "infrastructure" score by adding more paved roads. While this would increase the number of impervious surfaces, thereby increasing the Urban Heat Island (UHI) effect and the likelihood of urban flooding, ultimately reducing the city's long-term liveability. (Chen et al., 2023). The ongoing cycle of developing smart, but unliveable cities clearly demonstrates the immediate need to close the gap between quality-of-life perceptions and environmental risk assessments.

Need for Integrating Climate Stress with Liveability: Bangalore

There exists a very important and ominous case study in the city of Bangalore which is referred to as "India's Silicon Valley" and illustrates the disconnection between economically driven livability and climatically based realities. Prior to the massive urbanization of the last couple of decades, Bangalore was historically referred to as the "Garden City", due to the fact that the city's liveability was directly related to the natural ecological principles of semi-arid systems, a large inter-connected network of 1,450 lakes and large expanses of canopy cover that functioned as the city's hydrologic and thermal "thermostat". However, the rapid urbanization of the last couple of decades has essentially eliminated this natural topography. (Ganguli & Tarafdar, 2025). In terms of land use/land cover, Bangalore experienced an exponential increase of 1055% in built up area from 1973 to 2023, and at the same time experienced an equivalent increase in the percentage of surface coverage with impervious surfaces. Impervious surface coverage reached 93.3% of the total surface area by 2023. (Murali & Pradhan, 2025).

This explosive growth has resulted in a drastic decline in the city's "blue infrastructure". As of 2016, there were only 194 functional lakes, representing an 87% reduction. (Unnikrishnan et al., 2017). At the same time, the amount of available water storage capacity decreased from 35,000 million cubic feet (TMC) to only 5 TMC. The lack of integration between the ecological indicators (e.g. lake functionality, land surface temperature, green and blue concentration etc.) and liveability assessments has created vulnerability to "creeping disasters" in Bangalore. Although Bangalore continues to be one of the most attractive locations for investments, the residents of Bangalore continue to experience extreme temperatures and recurrent flooding. (Kumar et al., 2025). Land Surface Temperatures (LST) have increased by 7.9 °C in the city between 1992 and 2017. Core areas of the city have experienced LST values as high as 41°C. During the 2024 heat wave, LST values in some hot spots exceeded 47°C. These values are not represented in the city's global ranking in international reports on "livability" (Murali & Pradhan, 2025).

Bangalore has experienced an increasing trend of urban flooding in recent years. Bangalore is the most flood prone district in Karnataka. A review of major flood events occurring in Bangalore between 1969 and 2019 indicates that the city has experienced 73 major flood events. The loss of wetlands which previously provided resource sponge functions was the primary cause of this trend. (Jennath & Singh, 2024). Because the hazards associated with flooding are typically not included in liveability indices, the "infrastructure failures" (i.e. the electrical shock hazard present in flooded underpasses or the collapse of the water supply system) resulting from flooding are frequently reported as anecdotal inconvenience rather than as indicators of unlivability.

The inclusion of climatic factors such as heat stress, flood risk, and green and blue concentration into liveability assessments will enable the development of "actionable nature-based solutions" (NBS). Spatial analysis using the Analytic Hierarchy Process (AHP) (Bagyaraj et al., 2023) shows that statistical clusters of high flood risk and heat accumulation occur near degraded blue infrastructure patches, specifically in the Bellandur Lake sub-region. The criticality mapping demonstrates that liveability can no longer be achieved solely through grey infrastructure; therefore, it is necessary to restore the ecological principles of the "Garden City". The Bengaluru Climate Action and Resilience Plan (BCAP), launched in 2023 (Bruhat Bengaluru Mahanagara Palike (BBMP, 2023), is a marked departure from previous efforts and aims to achieve net zero emissions and inclusive adaptation. However, the success of BCAP will depend on whether climate risk data is incorporated into the core urban management and development frameworks of the city.

Lack of Integration of Climate Hazards and Urban Liveability

Urban "Liveability," or how well an urban area meets the needs for people to lead happy, healthy lives within their urban environments, has become a core component of urban research and planning. However, there is an enormous divide, both theoretically and practically, between the aspirational goals of urban liveability and the reality of the physical stresses placed on cities due to environmental degradation and climatic hazards (Murali & Pradhan, 2025), (Reis et al., 2015). In fact, most metrics developed to measure liveability do not account for these shocks, and therefore, are fundamentally unable to measure the impacts of climate change on urban liveability. The consequences of this disconnection can have far-reaching implications for the long-term viability of many of the world's largest metropolitan areas. This disconnect has been clearly illustrated in major urbanizing centers of the Global South, such as Bangalore. As Bangalore continues to grow economically at unprecedented rates, it also appears to be losing its ability to buffer itself against extreme climatic events. This has occurred while the natural ecological systems of the area continue to be degraded. (Ramanath Jha, 2024).

This study empirically validates its core premise: urban liveability and climate stress are indistinguishably tied together through their mutual dependency on blue infrastructure. Spatial autocorrelation analysis confirms that deteriorating water bodies directly reduce urban liveability, proving this is far more than a basic conservation issue. The Comprehensive Criticality Map illustrates this by locating spatial clusters-most notably around the Bellandur Lake sub-region-where heat stress, flood risk, and ecological degradation overlap. This spatial convergence offers empirical proof that liveability indices incorrectly condone liveability from climate stress, overlooking how residents experience these hazards simultaneously. Ultimately, the study bridges urban ecology, climate adaptation, and liveability research by demonstrating that ecological infrastructure is fundamental-not supplementary-to urban quality of life.

Urban Liveability and its De-Linkages with Climatic Stress – Theoretical aspect

The concept of liveability is complex, and represents a wide-ranging, evolving, and inclusive picture of the condition of the urban human settlement environment. Liveability is a term that evolved out of early urban ecosystem theory. For example, Doxiadis (1970) viewed the city as a living entity and considered the quality of the "anthropocosmos"

was dependent upon how harmoniously people interacted with their physical surroundings (Doxiadis, 1970). Modern research divides liveability into two categories: objective liveability, which includes the tangible environmental qualities found within cities including accessible community amenities, health care services, and available basic infrastructure; and subjective liveability, which is based upon the way individuals perceive their local urban environment through their feelings of happiness, comfort, and well-being generated by their interactions with their environment. (Chen et al., 2023).

Although there are good examples of both the definition and application of liveability, the theoretical framework of liveability remains fuzzy and flexible and is subject to varying degrees of disagreement among disciplines and geographic locations. (Economist Intelligence Unit, 2025). Due to the flexibility of the definition of liveability, the use of commercially developed liveability indices (e.g. the Global Liveability Index, published by the Economist Intelligence Unit (EIU); and the Ease of Living Index, published by the Indian government) have dominated the assessment of urban environments. Both indices were created to provide a commercial-based tool to assess the living conditions of expatriates relocating to another country for work purposes and to determine the level of hardship allowance. Thus, the criteria used to assess the living conditions are biased towards the needs of expatriates (i.e. politically stable country, international transportation network, etc.). A significant disconnection exists between the commercially produced liveability indices and climatic stress. The reason is that both indices statically define the "environment" category. For example, the EIU defines the environment through indicators such as humidity, temperature, and comfort levels. However, the EIU does not account for the frequency and severity of extreme climate events (e.g. urban floods, heat waves). Therefore, a city can be evaluated as having a high degree of livability because of its infrastructure and stability, but not be prepared at all to respond to a climate-related disaster. Additionally, the indices rely heavily on expert opinion and do not represent the lived experience of the broader urban population. The population most affected by climate-related disasters, i.e. those living in informal settlements, are often underrepresented in the development of the indices. (Chen et al., 2023)

In response to the increasing impacts of the climate crisis, protecting the ability to participate in society requires a safe, non-hazardous environment and secure housing. When the commercially developed liveability indices view environmental quality as an additional "perk" to be received as opposed to a fundamental need, they disguise the widening "capabilities gap" being caused by climate change. Capabilities such as working during extreme heat or losing one's house to a flood directly undermine the core capabilities necessary for social participation, however, these types of climate-related stressors are rarely accounted for when assessing urban liveability using standardized indices. (Shakya et al., 2025). Therefore, the absence of a common framework results in urban managers often pursuing liveability scores that are disconnected from ecological sustainability. An example of this is if a city improves its "infrastructure" score by adding more paved roads. While this would increase the number of impervious surfaces, thereby increasing the Urban Heat Island (UHI) effect and the likelihood of urban flooding, ultimately reducing the city's long-term liveability. (Chen et al., 2023). The ongoing cycle of developing smart, but unlivable cities clearly demonstrates the immediate need to close the gap between quality-of-life perceptions and environmental risk assessments.

Need for Integrating Climate Stress with Liveability: Bangalore

There exists a very important and ominous case study in the city of Bangalore which is referred to as "India's Silicon Valley" and illustrates the disconnection between economically driven livability and climatically based realities. Prior to the massive urbanization of the last couple of decades, Bangalore was historically referred to as the "Garden City", due to the fact that the city's liveability was directly related to the natural ecological principles of semi-arid systems, a large inter-connected network of 1,450 lakes and large expanses of canopy cover that functioned as the city's hydrologic and thermal "thermostat". However, the rapid urbanization of the last couple of decades has essentially eliminated this natural topography. (Ganguli & Tarafdar, 2025). In terms of land use/land cover, Bangalore experienced an exponential increase of 1055% in built up area from 1973 to 2023, and at the same time experienced an equivalent increase in the percentage of surface coverage with impervious surfaces. Impervious surface coverage reached 93.3% of the total surface area by 2023. (Murali & Pradhan, 2025).

This explosive growth has resulted in a drastic decline in the city's "blue infrastructure". As of 2016, there were only 194 functional lakes, representing an 87% reduction. (Unnikrishnan et al., 2017). At the same time, the amount of available water storage capacity decreased from 35,000 million cubic feet (TMC) to only 5 TMC. The lack of integration between the ecological indicators (e.g. lake functionality, land surface temperature, green and blue concentration etc.) and liveability assessments has created vulnerability to "creeping disasters" in Bangalore. Although Bangalore continues to be one of the most attractive locations for investments, the residents of Bangalore continue to

experience extreme temperatures and recurrent flooding. (Kumar et al., 2025). Land Surface Temperatures (LST) have increased by 7.9 °C in the city between 1992 and 2017. Core areas of the city have experienced LST values as high as 41°C. During the 2024 heat wave, LST values in some hot spots exceeded 47°C. These values are not represented in the city's global ranking in international reports on "livability" (Murali & Pradhan, 2025).

Bangalore has experienced an increasing trend of urban flooding in recent years. Bangalore is the most flood prone district in Karnataka. A review of major flood events occurring in Bangalore between 1969 and 2019 indicates that the city has experienced 73 major flood events. The loss of wetlands which previously provided resource sponge functions was the primary cause of this trend. (Jennath & Singh, 2024). Because the hazards associated with flooding are typically not included in liveability indices, the "infrastructure failures" (i.e. the electrical shock hazard present in flooded underpasses or the collapse of the water supply system) resulting from flooding are frequently reported as anecdotal inconvenience rather than as indicators of unlivability.

The inclusion of climatic factors such as heat stress, flood risk, and green and blue concentration into liveability assessments will enable the development of "actionable nature-based solutions" (NBS). Spatial analysis using the Analytic Hierarchy Process (AHP) (Bagyaraj et al., 2023) shows that statistical clusters of high flood risk and heat accumulation occur near degraded blue infrastructure patches, specifically in the Bellandur Lake sub-region. The criticality mapping demonstrates that liveability can no longer be achieved solely through grey infrastructure; therefore, it is necessary to restore the ecological principles of the "Garden City". The Bengaluru Climate Action and Resilience Plan (BCAP), launched in 2023 (Bruhat Bengaluru Mahanagara Palike (BBMP, 2023), is a marked departure from previous efforts and aims to achieve net zero emissions and inclusive adaptation. However, the success of BCAP will depend on whether climate risk data is incorporated into the core urban management and development frameworks of the city.

Results and Discussion

The spatial analyses show a city where ecological collapse and climate threats mutually reinforce one another. The intention of this paper is to demonstrate the strong linkages between urban blue transformation index and the rising vulnerabilities related to flood and heat. It demonstrates an analytical hierarchical spatial process of systematic overlay that can help city authorities delineate and identify specific risk zones for further study and analysis at the zone or sub-city level.

Land use change in the city has resulted in a disconnection of blue infrastructure, wherein the previously existing network of lakes and wetlands have been changed into separate or dysfunctional patches that cannot evoke ecological functions of flood control or natural drainage. The shrinkage of Bangalore’s blue network and increase of impervious area has compromised natural hydrological abilities. Areas that used to depend on adjacent waterbodies for stormwater retention now have a greater risk of flooding, meaning that loss of aquatic ecosystems equals increased flood risk. In short, the natural hydrological buffers of the city have been lost, encased in a patchworked set of waterbodies that cannot absorb heavy rainfall or recharge groundwater.

UHI mapping further demonstrates a spatial disconnection of green space and UHI zones. The hottest neighbourhoods, almost all characterized by dense built environment and little-to-no vegetation, have almost no overlap to the areas identified by parks and blue cover. Autocorrelation (Moran’s I) statistically confirms that green infrastructure clusters are not found in the highest temperature zones, implying that there is a reduction of green space between green infrastructure and high temperature areas where cooling is the most need. This trend suggests that Bangalore’s green infrastructure is either too little or badly placed to cool heat stress in hotspots. In practical terms, natural thermal balance is out of sync with thermal risk, pointing to a disconnection for integrated heat resiliency.

Importantly, degradation blue areas show spatial clustering with flood risk. Flood risk areas cluster around missing or impaired water bodies, a statistically significant observation that illuminates the role of lakes and wetlands in attenuation of urban flood risk. Wherever blue infrastructure is neglected or eliminated, rainfall run-off continues behaved, which results in frequent flooding in urban areas. The Bellandur Lake example shows the compounding risk: the interplay of extreme heat stress, flooding, and degradation show in this one urban hot zone. Examples of co-occurring risk show the nature of Bangalore’s ecological collapse – an environment where broken natural networks exacerbate climate risks. Such information is pertinent knowledge for resiliency. That restoring and reconnecting blue infrastructure (to re-attain flood attenuation functions) and selectively increasing green cover in heat stressed areas are important steps to increasing Bangalore’s climate resiliency.

Contributions Aligned With Sustainable Development

The findings of this study have important implications for translating sustainable development in rapidly urbanized areas of Global South. The study demonstrates how the theory of sustainable development can be interpreted in urban scale by identifying areas of multi-hazard zone relevant to urban context and then use that zoning as an input for spatial planning. Traditional spatial planning practices followed in the cities are mostly aligned with economic proliferation and utilisation of socio-economic and transportation principles and rarely take environmental hazards as a determinant of spatial planning decisions.

The spatial mapping of climate hazard zones, especially the statistically significant clustering of flood risk around patches of degraded blue infrastructure, emphasizes the importance of incorporating eco-system based planning into sustainable urban development. Quantitatively establishing the loss of hydrological functions-i.e., the reduction in water storage function from approximately 35,000 million cubic feet (TMC) to about 5 TMC-the study illustrates the tangible consequences of development trajectories that continuously neglect ecological criteria. The study shows that nature-based solutions -specifically restoring/conserving urban blue infrastructure - can be used to achieve several Sustainable Development Goals (SDGs): SDG 6 (Clean Water and Sanitation); SDG 11 (Sustainable Cities and Communities); and SDG 13 (Climate Action). The fully integrated criticality mapping framework established in this study allows urban planners to develop actionable tools to select priority actions that will support both climate adaptation and ecological restoration, while contributing to advancing the agenda for sustainable urban transformations.

However, the study has highlighted significant obstacles to implementing sustainable development contributions in the city. The fragmented governance structure across municipal agencies (such as BBMP, BDA, and BMRDA); continued invasion of informal and formal developments onto lake beds; and the absence of climate risk data within the core urban management/development frameworks combine to present challenges to developing resilient cities. These obstacles indicate that while there may be sufficient technical knowledge and analytical capability to implement sustainable development in Bangalore, it is being prevented by failing to incorporate ecological resilience into the political economy of urban planning. As such, the study posits that addressing climatic hazards necessitates moving beyond simply engineering remedies, and instead adopting a fundamentally new orientation for planning priorities toward ecosystem based adaptation that treats blue infrastructure as essential urban infrastructure rather than expendable environmental amenity.

In terms of conceptual validation, the results provide empirical support for the central theme of this research: i.e., that urban livability and climatic stress are inextricably linked via their mutual mediation by blue infrastructure. The results from the spatial autocorrelation analysis confirm that the deterioration of urban blue infrastructure represents a more than mere environmental conservation issue, but is directly related to declining urban liveability. The Comprehensive Criticality Map operationalizes this thematic relationship by visually illustrating where heat stress, flood risk and ecological degradation coincide in identifiable spatial clusters - most notably in the vicinity surrounding the Bellandur Lake sub region. The coincidence of these stresses provides empirical evidence of what was theoretically argued elsewhere - namely, the "de-linking" between livability and climate stress as represented in commercial liveability indices - occurs spatially as a compounding form of vulnerability for residents who experience concurrent exposures to extreme temperatures, flooding and reduced environmental quality. In doing so, the study connects conceptually three previously disparate thematic areas: urban ecology, climate adaptation, and liveability studies - by providing geospatial proof that ecological infrastructure is foundational to urban quality-of-life rather than supplementary.

Conclusion and Directions for Future Research

The present research provided a spatially explicit assessment of climate hazard zones, specifically heat stress and flooding risk, in relation to the degradation of urban blue infrastructure in Bangalore city. Through a multi-criteria assessment framework driven by the Analytical Hierarchy Process (AHP), this study merged remote sensing datasets, environmental indices, and urban morphology parameters in high-resolution maps of heat accumulation and flood prone areas.

This research further provides an analytical framework and a method that can help measure and use empirical evidences that provide significance to the concept of sustainable development in urban environments. It documents evidence that ecological infrastructure (e.g., lakes) serves not only as an aesthetically pleasing feature, but as a key resource in addressing climate resilience and ensuring long term sustainability for urban areas. Findings illustrate that sustainable urban development will require more than just continued gray infrastructure investments; instead, they must include a comprehensive restoration of the natural hydrologic systems that were disassembled due to the

uncontrolled and haphazard manner of urbanization over many decades. The case of Bangalore exemplifies an enduring impediment to sustainable development within the Global South – the continuing conflict between accelerated economic activity and protecting vital ecosystem functions. In addition, the research shows that this conflict can be resolved through a coordinated approach of incorporating nature based solutions into decision-making processes while mitigating flooding, reducing urban heat, recharging groundwater aquifers, and rehabilitating biodiversity in urban ecosystems. Furthermore, the research identifies specific "vulnerability clusters" (i.e., the Bellandur Lake sub-region), which provide actionable and geographically targeted sites where interventions could be implemented consistent with principles of inclusive adaptation, climate justice, and the United Nations' Sustainable Development Goals.

The investigations revealed accelerations in impervious surface morphology, losses in green cover, and fragmentation of blue infrastructure networks, which compounded simultaneously and expanded both the intensity and spatial area of urban climate hazards. In conclusion, city-wide results indicate a fragmented ecological network in Bangalore. Bellandur Lake is one example of the most vulnerable areas of the city – an area now being stressed by heat, flooding, and poor infrastructure. The condition of Bellandur Lake exemplifies the identified urban paradox: when an integrated blue-green system becomes degraded an extent where it magnifies rather than mitigates climate risk. Global lessons learned indicate that these are not insurmountable challenges. Cities like London, New York, Singapore, and Amsterdam demonstrate that nature-based solutions and blue-green infrastructure can be a simultaneous solution to both urban flooding and heat, while also delivering co-benefits for urban liveability (Global Facility for Disaster Reduction and Recovery [GFDRR], 2022). For Bangalore, this means restoring (repairing) its blue infrastructure – restoring lakes, conserving wetlands, and daylighting streams wherever possible – should grow from Bangalore's climate resilience agenda. The results of the spatial analysis provide strong support for that avenue of localised further action. The study builds an analytical framework to take up such areas for local action plans (LAPs) by the urban planning and development agencies, which are driven by the principle of being urban climate informed and environmentally sensitive. The findings support the need for cities to pursue climate-resilient development pathways that utilize local ecosystem services.

A significant conceptual contribution of this research was to explicitly articulate the relationship between blue infrastructure, liveability, and climate stress. The study demonstrated that the degradation of urban water bodies has become a major driver of increased flood vulnerabilities and increasing urban heat islands. Thus, blue infrastructure represents a crosscutting element for assessing liveability and developing sustainable urban plans. The findings from this research are mandating a paradigmatic shift among policy makers, urban planners, and development authorities from merely reacting to disasters to proactively using ecosystem-based adaptations. The AHP–GIS analytical framework also presents a replicable interdisciplinary methodological tool for assessing climate risks and integrating them with spatial planning and implementing nature based solutions in rapidly urbanizing cities in the Global South. Therefore, restoring Bangalore's blue infrastructure (rejuvenating lakes, conserving wetlands, daylighting streams, and creating ecological corridors) is considered a strategic investment toward a sustainable future for the city.

The study also highlights that ecological integrity with social and economic growth is a fundamental component of the concept of sustainable urban development for enhancing urban liveability. Liveable urban areas are not only spaces which help us connect socially and earn livelihoods but also spaces that are environmentally safe, non-compromised and hazard free. If we are unable to identify the challenged spaces due to climate risks and only focus on socio-economic proliferation, it shall be leading to urban crises in the long term.

Therefore, there needs to be a linkage established between climatic stress and liveability measures, with liveability assessment incorporating hazard vulnerability, blue-green infrastructure status and ecosystem services. It is essential that the ecological and climatic components are embedded within the primary frameworks for decision-making in order to ensure that cities transitioning toward greater levels of vulnerability will do so to levels of increased resilience, thereby preventing future generations from paying the price of unsustainable environmental practices, as a result of current economic growth and improved human well-being.

Acknowledgements

The work in this paper is an outcome of ongoing Doctoral level research conducted at the Dept. of Planning, School of Planning and Architecture Vijayawada, wherein the first author is the doctorate thesis student candidate, and the second author is the supervisor. The authors express their gratitude to officials of BBMP, BMRDA and other Government Departments who provided crucial data and insights.

Authors' Contribution

Swathikka S: Conceptualization, Visualization, Writing – original draft.

Ayon Kumar Tarafdar: Conceptualization, Visualization, Writing – review & editing, Supervision.

Funding: The authors did not receive support from any organization for the submitted work.

Author Biographies:

Swathikka S is a Research Officer working with the "Centre of Urban Planning for Capacity Building at SPA Vijayawada", which works as a Centre of Excellence in the domain of Climate Sensitive Urban Development and Planning and is funded by Ministry of Housing and Urban Affairs, Government of India. She is also Doctoral Research Scholar at the School of Planning and Architecture Vijayawada, which is an Institute under the Ministry of Education, Government of India. She holds Master's degree in Environmental Planning and Management from SPA Vijayawada and a B.Arch degree from Kongu School of Architecture, Anna University. Her research interests include multi-hazard risk assessments, sustainable development, environmental planning and GIS-based planning.

Prof. Dr. Ayon Kumar Tarafdar is a Professor in the Department of Planning at the School of Planning and Architecture Vijayawada and Head of the AMRUT Centre of Urban Planning for Capacity Building. He holds a Bachelor's degree in Planning from SPA Delhi, an MS in Urban Ecological Planning and PhD from NTNU, Norway. He was the former Dean of Academics and Dean of Planning and Development at SPA Vijayawada. His research interests include climate-sensitive spatial planning, resilience, environmental planning, livelihood analysis, and urban carrying capacity.

Declarations

Ethics approvals: All procedures involved in conducting the surveys and discussions as a part of the research were in accordance with ethical standards in the organisations, where the authors work and maintains the standards as per the rule of the land of the study area. The paper does not entail use of any personal details or opinions and hence do not infringe upon any individual's' integrity or personal space.

References

1. Almaaitah, T., Appleby, M., Rosenblat, H., Drake, J., & Joksimovic, D. (2021). The potential of blue-green infrastructure as a climate change adaptation strategy: A systematic literature review. *Blue-Green Systems, 3*(1), 223–248. https://doi.org/10.2166/bgs.2021.016
2. Avram, S., Cipu, C., Corpade, A. M., Gheorghe, C. A., & Manta, N. (2021). GIS-based multi-criteria analysis method for assessment of degradation of lake ecosystems: A case study in Romania. *International Journal of Environmental Research and Public Health, 18*(11), 5915. https://doi.org/10.3390/ijerph18115915
3. Bagyaraj, M., Senapathi, V., Chung, S. Y., Gopalakrishnan, G., Xiao, Y., Karthikeyan, S., Nadiri, A. A., & Barzegar, R. (2023). A geospatial approach for assessing urban flood risk zones in Chennai, Tamil Nadu, India. Environmental Science and Pollution Research, 30(45), 100562–100575.
4. Bruhat Bengaluru Mahanagara Palike. (2023). Bengaluru Climate Action and Resilience Plan (BCAP). Government of Karnataka. https://apps.bbmpgov.in/bcap/PDF/BCAP_FullReport_091224.pdf
5. Chen, W., Yi, L., Wang, J., Zhang, J., & Jiang, Y. (2023). Evaluation of the livability of arid urban environments under global warming: A multi-parameter approach. Sustainable Cities and Society, 99, 104931. https://doi.org/10.1016/j.scs.2023.104931
6. Cai, Z., Han, G., Chen, M., (2018). Do water bodies play an important role in the relationship between urban form and land surface temperature? Sustain. Cities Soc. 39, 487–498. https://doi.org/10.1016/j.scs.2018.03.021
7. Chan, F.K.S., Griffiths, J.A., Higgitt, D., Xu, S., Zhu, F., Tang, Y.T., Xu, Y., Thorne, C.R., 2018. "Sponge City" in China - a breakthrough of planning and flood risk management in the urban context. Land Use Policy 76, 772–778. https://doi.org/10.1016/j.landusepol.2018.03.005
8. Czyża, S., Kowalczyk, A.M., (2023). GIS and geodata contribution to the cartographic modelling of Blue-Green infrastructure in urbanised areas. Geod. Cartogr. 59, 183–194. https://doi.org/10.24425/jwld.2023.147243
9. Doxiadis, C. A. (n.d.). *The Anthropocosmos model*. Constantinos A. Doxiadis. https://www.doxiadis.org/Downloads/The%20Anthropocosmos%20model.pdf
10. Economist Intelligence Unit. (2024). The Global Liveability Index 2025.

11. Ganguli, B., Tarafdar, A.K., (2025). An integrated framework for assessment of coastal vulnerability in the Sunderban Delta Region. J. Coast. Conserv. https://doi.org/10.1007/s11852-025-01130-0
12. Jennath, A., & Singh, C. (2024). Bengaluru floods spotlight unequal risk on migrant settlements. Nature India. https://doi.org/10.1038/d44151-024-00209-1
13. Jha, R. (2024). *Why cities experience 'livability atrophy': The case of Bengaluru and Pune*. Observer Research Foundation. https://www.orfonline.org/expert-speak/why-cities-experience-livability-atrophy-the-case-of-bengaluru-and-pune
14. Flood, H.A., (2018). Green to gray: Silicon Valley of India. Environ. Monit. Assess. 206, 1287–1295. https://doi.org/10.1007/s10661-018-6598-2
15. Ganguli, B., Tarafdar, A.K., (2025). An integrated framework for assessment of coastal vulnerability in the Sunderban Delta Region. J. Coast. Conserv. https://doi.org/10.1007/s11852-025-01130-0
16. Global Facility for Disaster Reduction and Recovery (GFDRR), (2022). A catalogue of nature-based solutions for urban resilience. The World Bank, Washington, DC. https://documents1.worldbank.org/curated/en/502101636360985715/pdf/A-Catalogue-of-Nature-based-Solutions-for-Urban-Resilience.pdf
17. Indian Meteorological Department (IMD), (2023). Bengaluru rainfall from 1901. https://data.opencity.in/dataset/bengaluru-rainfall
18. Intergovernmental Panel on Climate Change (IPCC), (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the IPCC (H.-O. Pörtner, D.C. Roberts, M. Tignor, et al., Eds.), Cambridge University Press, Cambridge. https://doi.org/10.1017/9781009325844
19. Kaushal, S.S., Belt, K.T., Stack, W.P., (2012). Watershed urbanization and the evolution of water quality management in the Baltimore region. J. Am. Water Resour. Assoc. 48, 876–895. https://doi.org/10.1111/j.1752-1688.2012.00658.x
20. Kaur, R., Gupta, K., (2022). Blue-Green infrastructure (BGI) network in urban areas for sustainable storm water management: A geospatial approach. Sustain. Cities Soc. 6, 100087. https://doi.org/10.1016/j.scs.2022.100087
21. Kumar, P., Shreya, K.A., (2025). Beyond the thermometer: Bengaluru's race to modernise ignored climate - now its residents are paying the price. Down To Earth. https://www.downtoearth.org.in/climate-change/beyond-the-thermometer-bengalurus-race-to-modernise-ignored-climate-now-its-residents-are-paying-the-price
22. Lamond, J., Everett, G., (2019). Sustainable Blue-Green infrastructure: A social practice approach to understanding community preferences and stewardship. Landsc. Urban Plan. 191, 103639. https://doi.org/10.1016/j.landurbplan.2019.103639
23. Murali, J., & Pradhan, A. (2025). Urban heat island in Bengaluru: Built-up growth and temperature trends. E3S Web of Conferences, 648, 02019. https://doi.org/10.1051/e3sconf/202564802019
24. Public Utilities Board (PUB), (2010). Active, Beautiful, Clean Waters (ABC Waters) design guidelines. PUB, Singapore. https://www.pub.gov.sg/-/media/PUB/PDF/ABC_Waters_Design_Guidelines.pdf
25. Public Utilities Board (PUB), (2015). The Active, Beautiful, Clean Waters Programme: Water as an environmental asset (Vol. 1). PUB, Singapore. https://isomer-user-content.by.gov.sg/50/7a481fd0-e545-417e-a14efee6694/rb172978-mnd-abc-water.pdf
26. Pritipadmaja, R., Garg, R.D., Sharma, A.K., (2023). Assessing the cooling of Blue-Green spaces: An implication for urban heat island mitigation. Water 15, 2983. https://doi.org/10.3390/w15162983
27. Ruangpan, L., Vojinović, Z., Di Sabatino, S., Leo, L. S., Capobianco, V., Oen, A. M. P., McClain, M. E., & Lopez-Gunn, E. (2020). Nature-based solutions for hydro-meteorological risk reduction: A state-of-the-art review of the research area. *Natural Hazards and Earth System Sciences*, 20, 243-270. https://doi.org/10.5194/nhess-20-243-2020
28. Reis, S., Morris, G., Fleming, L. E., Beck, S., Taylor, T., White, M., Depledge, M. H., Steinle, S., Sabel, C. E., Cowie, H., Hurley, F., Dick, J. McP., Smith, R. I., & Austen, M. (2015). Integrating health and environmental impact analysis. Public Health, 129(10), 1383–1389. https://doi.org/10.1016/j.puhe.2013.07.006
29. Shakya, R., & Khan, S. (2025). Assessing nexus of spatio-temporal livability and various contemporary factors: A case of Central India from 2001 to 2021. Science of the Total Environment, 972, 179117. https://doi.org/10.1016/j.scitotenv.2025.179117
30. Silva, J.L.B., Moura, G.B.A., Silva, M.V., Oliveira-Júnior, J.F., Jardim, A.M.R.F., Refati, D.C.C., Lima, R.C.C., (2023). Environmental degradation of vegetation cover and water bodies in the semiarid region of Brazil Northeast via cloud geoprocessing techniques applied to orbital data. J. South Am. Earth Sci. 121, 104164. https://doi.org/10.1016/j.jsames.2022.104164

31. Sourav, S.K., (2024). Urbanization and seasonal dynamics of the lake ecosystem during the years 2002–2022 in Bengaluru, South India. Environ. Adv. 15, 100944. https://doi.org/10.1016/j.envadv.2024.100944
32. Tarafdar, A.K., Bjønness, H.C., (2010). Environmental premises in planning for sustainability at the local level in large southern cities: Case study – Calcutta, India – suggesting the PRETAB planning process model. Int. J. Sustain. Dev. World Ecol. 17, 24–38. https://doi.org/10.1080/13504500903481581
33. Tayyab, M., Zhang, J., Hussain, M., Ullah, S., Khan, S.N., Baig, M.A., Hassan, W., Al-Shaibah, B., (2021). GIS-based urban flood resilience assessment using urban flood resilience model: A case study of Peshawar City, Khyber Pakhtunkhwa, Pakistan. Remote Sens. 13, 1864. https://doi.org/10.3390/rs13101864
34. Unnikrishnan, H., Mundoli, S., Nagendra, H., (2017). Making water flow in Bengaluru: Planning for the resilience of water supply in a semi-arid city. J. Sustain. Urban Plan. Prog. 2, 1–14. https://doi.org/10.18063/JSUPP.2017.01.002
35. Wang, W., Shi, K., Wang, X., Zhang, Y., Qin, B., Zhang, Y., Woolway, R.I., (2024). The impact of extreme heat on the warming of lakes in China. Int. J. Environ. Res. Public Health 15, 70. https://doi.org/10.3390/ijerph20032642
36. Wild, T., Bernet, J.F., Westling, E.L., Lerner, D.N., (2017). Deculverting: Reviewing the evidence on the 'daylighting' and restoration of culverted rivers. Water Environ. J. 31, 350–358. https://doi.org/10.1111/wej.12259
37. Wu, Z., Zhang, Y., (2019). Water bodies' cooling effects on urban land daytime surface temperature: Ecosystem service reducing heat island effect. Sustainability 11, 787. https://doi.org/10.3390/su11030787
38. World Resources Institute India (WRI India), (2023). Urban water resilience strategies for Indian cities. WRI India, New Delhi