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Utilizing Remote Sensing for Sponge City Development: Enhancing Flood Management and Urban Resilience in Karachi

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Abstract: Rapid urbanization in Karachi, Pakistan, has resulted in increased impervious surfaces, leading to significant challenges, such as frequent flooding, urban heat islands, and loss of vegetation. These issues pose challenges to urban resilience, livability, and sustainability, which further demand solutions that incorporate urban greening and effective water management. This research uses remote sensing technologies and Geographic Information Systems (GISs), to analyze current surface treatments and their relationship to Karachi's blue-green infrastructure. By following this approach, we evaluate flood risk and identify key flood-conditioning factors, including elevation, slope, rainfall distribution, drainage density, and land use/land cover changes. By utilizing the Analytical Hierarchy Process (AHP), we develop a flood risk assessment framework and a comprehensive flood risk map. Additionally, this research proposes an innovative Sponge City (SC) framework that integrates nature-based solutions (NBS) into urban planning, especially advocating for the establishment of green infrastructure, such as green roofs, rain gardens, and vegetated parks, to enhance water retention and drainage capacity. The findings highlight the urgent need for targeted policies and stakeholder engagement strategies to implement sustainable urban greening practices that address flooding and enhance the livability of Karachi. This work not only advances the theoretical understanding of Sponge Cities but also provides practical insights for policymakers, urban planners, and local communities facing similar sustainability challenges.

Keywords: flood; risk management; sponge city; Karachi

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1. Introduction

The rapid urbanization of recent decades has quickly transformed urban landscapes around the world. This transformation has generated complex challenges, specifically in the Global South, where urban growth is often unplanned and haphazard [1]. One of the most visible consequences of this growth is the widespread increase in impervious surfaces, including roads, buildings, and pavements, which prevent natural water absorption. Consequently, urban areas are increasingly facing severe environmental issues, such as frequent flooding, urban heat islands, and the loss of green spaces [2]. These challenges not only put pressure on existing infrastructure but also compromise urban resilience, livability, and sustainability. To address these concerns, we need innovative and effective

solutions that can integrate water management, climate adaptation, and urban greening into city planning.

One such promising approach is the idea of Sponge Cities (SC), which uses nature-based solutions (NBS) to manage water sustainably while enhancing urban resilience [3]. Originating from the traditional gray infrastructure (roads and buildings), which often struggles to accommodate the complexities of hydrological systems, the SC framework integrates green infrastructure elements such as wetlands, parks, and urban forests to absorb, retain, and filter extra rainwater [4]. By imitating the natural hydrological cycles, Sponge Cities are designed to maintain, slow down, and purify stormwater, which helps cities grow in more sustainable and better ways for the environment [5]. Despite the potential of Sponge Cities to reduce surface runoff, mitigate flood risks, and enhance overall environmental quality [6], their adoption remains underexplored in many regions of the Global South [7]. Rapid urban expansion, socio-economic constraints, and institutional challenges further hinder the implementation of sustainable urban planning solutions [8].

Karachi, Pakistan, a megacity described by its dense population, unregulated urban growth, and weak infrastructure, is a prime example of a city facing these challenges [9,10]. The overreliance on impermeable surfaces, combined with poor water management practices, has led to frequent urban flooding, especially throughout the monsoon period. The city also experiences the urban heat island effect, which raises high temperatures, and increases energy consumption and health risks [11]. Furthermore, while there are some efforts to add urban greening to the city, they are not well integrated into broader flood management and climate adaptation strategies [12]. This shows the urgent need for a holistic and innovative approach, such as the SC model, which can transform Karachi's urban planning paradigm by integrating water-sensitive design principles. Therefore, this research aims to assess the flood risk in Karachi, Pakistan, arising from fast urban growth and the environmental issues that come with it. By utilizing an SC framework and employing remote sensing and Geographic Information Systems (GIS) techniques, this study seeks to identify vulnerable areas to flooding and propose NBSs that will contribute to sustainable urban planning and climate adaptation. This aim will be achieved by the following: (1) evaluating the extent of impervious surfaces and their role in worsening flood risks. (2) Identifying flood-prone areas by analyzing key flood-conditioning factors, such as elevation, slope, rainfall distribution, drainage density, proximity to rivers, and land use/land cover changes. (3) Developing a flood risk assessment framework by using the Analytic Hierarchy Process (AHP) that quantifies the influence of various flood-conditioning factors and produces a comprehensive flood risk map for Karachi. (4) Assessing the effectiveness of the SC model and NBSs, which can be integrated into existing urban planning frameworks in Karachi to enhance urban resilience, maintain sustainable water management, and reduce flood risk.

In contrast to past flood risk analyses, the current research combines AHP-based risk mapping and the newly emerging sponge city (SC) approach, providing context-specific nature-based solutions for Karachi, an application context in which such dual efforts have not been rigorously examined. Through adapting flood risk zoning outputs to support SC interventions, this research presents a new operational connection between geospatial risk assessment and practical urban resilience actions.

2. Literature Review

In recent years, sustainable approaches such as the sponge city (SC) concept as part of nature-based solutions (NBS) aim to improve stormwater management in urban settings. The SC framework focuses on the absorption, retention, and utilization of stormwater runoff to improve urban water resource management and resilience [13] by integrating

natural, semi-natural, and engineered elements [14]. By incorporating permeable surfaces and vegetated green spaces, SC initiatives not only facilitate effective water storage but also help to capture water during dry periods [15]. Researchers are continuously working to evaluate the feasibility and overall impact of SC initiatives that highlight their potential to serve as a paradigm for resilient infrastructure and sustainable stormwater management [16,17]. However, some critiques and limitations of the SC approach need attention. For instance, the effectiveness of SC interventions is highly context-dependent, requiring careful consideration of local climate, geography, and socio-economic conditions. While SC methods promise innovation and adaptability, there is a significant challenge in identifying suitable locations in densely populated urban areas. Specifically, areas with insufficient available space for implementing green infrastructure struggle to realize the full potential of SC implementation [18]. Flooding continues to pose significant risks in urban environments, with recent reports indicating that it endangers more people than any other natural disaster, accounting for 41% of global flood incidents in South Asia particularly [19]. Despite the recognized need for innovative interventions, current efforts to retrofit urban environments with SC concepts in the Global South, such as the region of Pakistan, remain limited [8]. Furthermore, while multiple studies have demonstrated the effectiveness of SC concepts for stormwater management [20], these studies often fail to focus on unique challenges presented by dense urban areas, where rapid urbanization complicates flood risk management.

The reliance on RS data for monitoring flood risks emphasizes its importance in contemporary research, particularly in managing urban water systems and identifying potential water sources [21–23]. While adoption of hydrological models has been more widely applied for stormwater management [24,25], they often have high costs and require comprehensive input data that may not always be easily available [26]. Thus, the use of RS has helped the development of geographically and temporally related datasets for accessing, preserving, and monitoring water resources, while also helping to reduce financial burdens [27,28]. RS data combined with Geographic Information System (GIS) technology and several statistical and mathematical techniques can be utilized for flood risk assessments and the affecting parameters [29–32]. When other information, such as soil, topography, and land use/land cover (LULC) is combined with these techniques, it can efficiently and accurately delineate potential areas for urban water management [33]. These techniques, such as the Analytical Hierarchy Process (AHP), can yield high resolution and strong predictive performance to form an expert-based model for flood susceptibility [34–36]. Multi-Criteria Decision Analysis (MCDA) is also an established technique for analyzing potential zones for water resources with a strong efficiency and achievement rate [37,38]. Numerous empirical studies have used spatial datasets of rainfall, slope, land use and land cover, soil and drainage components with GIS-based AHP techniques [27,39–41].

Studies that incorporate both MCDA and GIS for selecting suitable sites for SC implementation are very promising [14]. Such practices can be valuable for assessing and comparing alternative strategies for flood risk management [42]. Several recent studies have successfully utilized GIS-based AHP to identify various target areas for implementing the SC approach. [43–46]. Other studies have used GIS modelling techniques to simulate the efficiency and performance of the SC concept applied to cities to combat flood risk [47–49]. Mubeen et al. [50] explored spatial suitability for large-scale sponging initiatives by using RS methods with Synthetic Aperture Radar (SAR) data for effective water resource management in various contexts, including the Tamnava River basin in Serbia [21,51]. Guerrero et al. [52] determined the geographic extent of current and prospective locations in Germany that could function as sponge areas, testing for floodplain-based solutions particularly. Chen et al. [53] developed a GIS-based inundation model to simulate urban

flooding in Memphis, Tennessee. Topal and Baykal (2022) [54] determined different measurable platforms for developing sponginess in cities by using thematic map layers and evidence-based GIS urban maps. Nguyen et al. [55] developed a model to enhance various SC practices by evaluating stormwater drainage capacity using Multi-Criteria Decision Analysis (MCDA) within urban water systems. Luo et al. [56] constructed a GIS-based stormwater model to evaluate 100-year rainfall scenarios to target flood risk reduction in the Shenzhen–Shantou special cooperation zone. A study simulated future land use and climate scenarios to evaluate the impact on the Ravi River in Pakistan, with the help of GIS, RS, and hydrological modelling [57]. Kumar et al. [41] demonstrated that integrating RS, GIS, AHP, MCDA, and field surveys can effectively map and model both current and future flood events, even at the local scale. This approach also holds significant potential for generating datasets that support long-term flood preparedness, risk assessment, and relief management.

In addition, an integrated approach to assessing flood susceptibility requires evaluating the impact of flood-inducing factors and understanding their interrelationships with flood occurrence [58–61]. The key factors influencing flood susceptibility include the slope, elevation, curvature, drainage density, topographic wetness index, stream power index, land use and land cover (LULC), normalized difference vegetation index, and rainfall. These factors have been widely applied in various studies to analyze the relationship between flood-causing elements and flood occurrence across different regions, including the study area [62–64].

3. Case Study Area

Karachi is situated on the southeastern coast of Pakistan and is the main economic and industrial hub of the country (Figure 1). It holds significant geographical importance due to its proximity to the Arabian Sea, making it the country's largest seaport. The city spans approximately 3527 square kilometers and has a massive population that exceeds 20 million, making it one of the most populous cities in the world [65]. The built-up area in Karachi has expanded significantly, while open bare land decreased by more than 76.76% over the same period. Concurrently, vegetation cover increased by 68.35%. These land use and land cover changes have substantially reshaped the spatial distribution and intensity of the surface urban heat island effect across the city [66].

Karachi has a hot desert climate (BWh) according to the Köppen climate classification system, marked by extremely hot summers and relatively mild, dry winters. In summer, from March to June, temperatures often soar to between 30 °C and 40 °C (86 °F to 104 °F). June is the hottest month in Karachi, with temperatures occasionally soaring above 40 °C (104 °F). Winters in Karachi are generally mild from November to February, with temperatures rarely dropping below 10 °C. January is the coldest month. Karachi receives limited annual rainfall, approximately 10 inches, primarily concentrated during the short monsoon season from July to September. Rainfall is not evenly distributed throughout the year, as most precipitation occurs in these monsoon months, leading to potential flooding and waterlogging in certain areas [67,68].

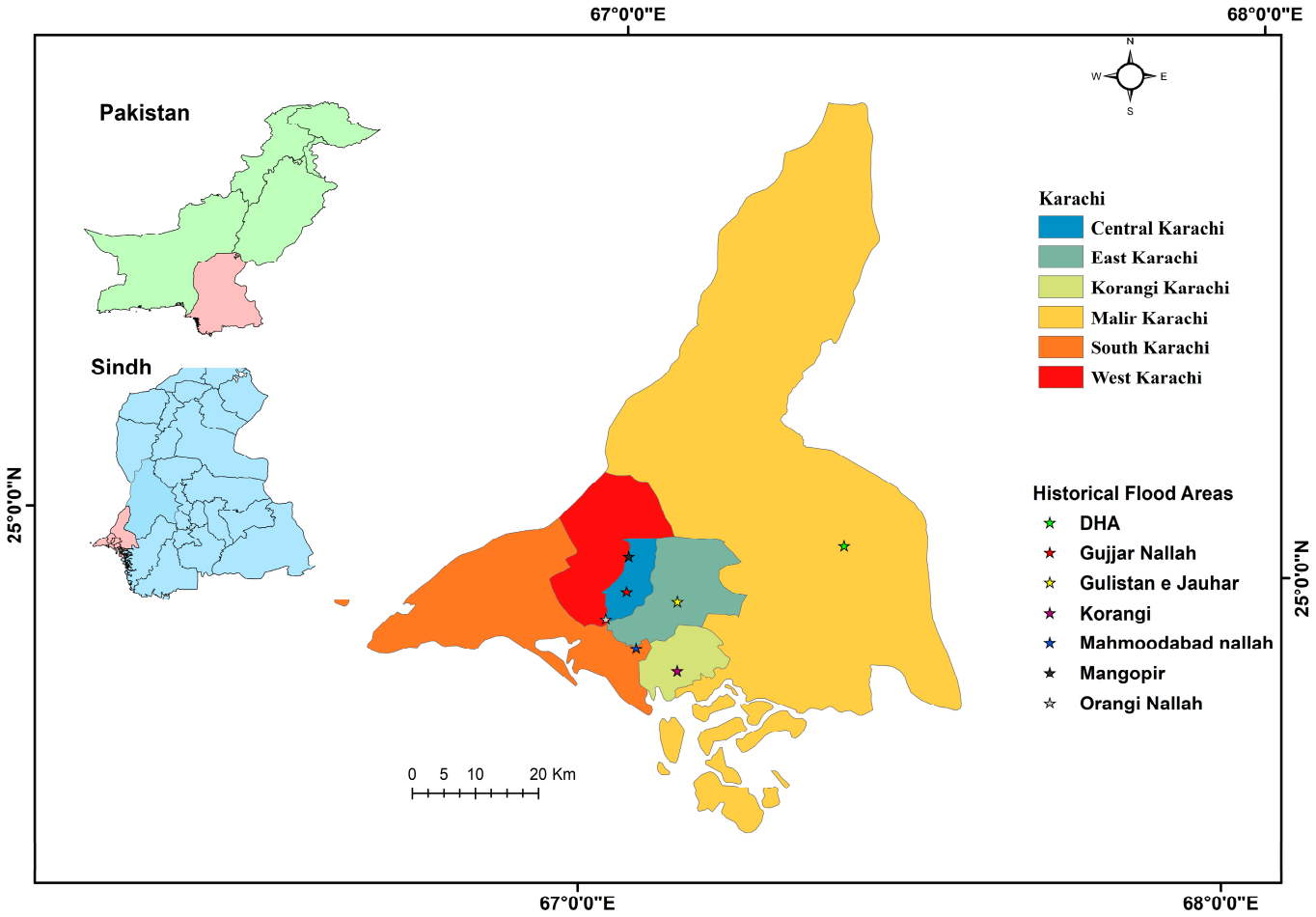

Figure 1. Map of Karachi showing spatial distribution of historically flooded areas (Source: authors).

4. Materials and Methods

This study employed a comprehensive approach integrating RS and GIS techniques to assess Karachi's urban conditions and hydrological characteristics while facilitating the development of an SC framework. The methodology was structured to identify flood-prone areas and evaluate key flood-conditioning factors critical for effective urban planning in the context of increasing flooding risks.

Selection of Flood-Conditioning Factors

The identification of appropriate flood-conditioning factors is important for achieving accurate and reliable flood risk assessments. Each region has unique flood susceptibility characteristics, and careful selection of influencing parameters is necessary for effective flood hazard mapping [69]. For this study, a comprehensive GIS and remote sensing-based analysis was conducted to identify the key flood-prone areas within the research zone. The selection of flood risk factors was guided by their critical role in flood dynamics, which ensured the inclusion of the most relevant and influential variables in the analysis (see Figure 2).

In any given watershed, the identification of flood-prone zones starts with selecting appropriate variables. Challenges arise in susceptibility mapping when researchers fail to integrate critical hydrological and topographical parameters. Therefore, eight key flood-conditioning factors were selected, including elevation, slope, aspect, drainage density, rainfall, distance from roads, distance from rivers, and LULC. These parameters are widely recognized in flood risk assessments [58–61] due to their direct impact on surface runoff,

water accumulation, and overall flood vulnerability (Table 1), thus informing the design of SC interventions.

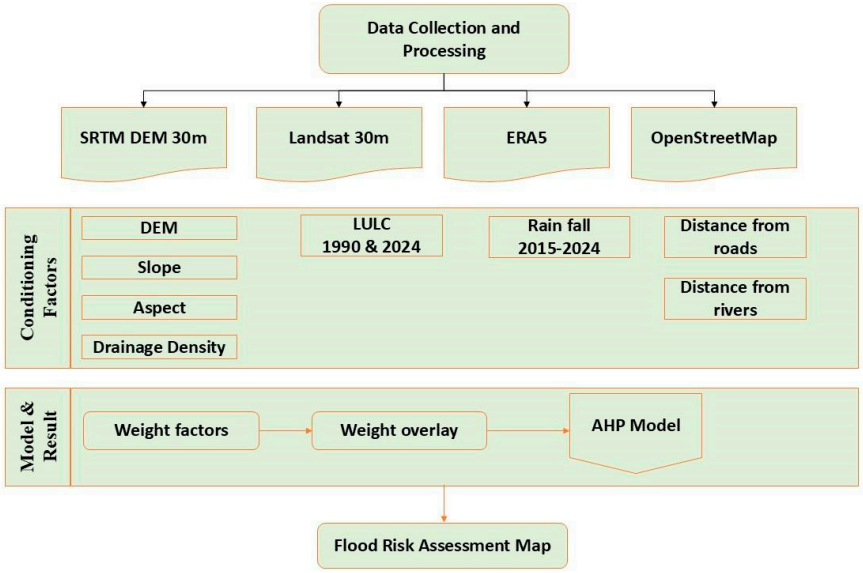

Figure 2. Framework of research methodology.

Table 1. Hydrological and geospatial variables for flood risk assessment.

Variable	Data Source	Description
Elevation	DEM (SRTM)	Represents the terrain height, influencing water accumulation
Slope	Derived from DEM	Determines the rate of surface runoff
Aspect	Derived from DEM	Indicates the direction of slope exposure, affecting water flow
Rainfall	ERA 5	Represents precipitation intensity, a key factor in flooding
Drainage Density	Hydrography datasets	Indicates the concentration of rivers/streams in an area
Distance from the River	Hydrography datasets	Proximity to rivers increases flood susceptibility
Distance from Road	Road network data	Areas near roads may have altered drainage patterns
Land Use/Land Cover (LULC)1990 & 2024	(Landsat 5 and 8)	Represents land cover types affecting runoff and infiltration

Topographic features significantly affect flood susceptibility, as they determine water flow patterns and drainage efficiencies [70]. The Digital Elevation Model (DEM) is a critical tool in flood forecasting, as it provides a 3D representation of terrain elevation. For this study, a 30 m resolution DEM from NASA's Shuttle Radar Topography Mission (SRTM) was used to extract the elevation and create slope maps. The slope data, represented in degrees, were generated using spatial analysis tools in ArcGIS.

Rainfall data, a key factor influencing flood events, were obtained from the ERA5 dataset for the period of 2015–2024 to analyze historical precipitation trends. ERA5, developed by the European Centre for Medium-Range Weather Forecasts, provides high-resolution global climate reanalysis data. It offers hourly estimates of various atmospheric

and land-surface parameters, including precipitation, temperature, and wind speed, at a spatial resolution of 30 km. Utilizing ERA5 ensured the integration of reliable and consistent rainfall data, which are crucial for understanding precipitation patterns and assessing flood risk in the study area. Drainage density maps were generated in ArcGIS using the raster calculator, based on drainage networks derived from the DEM.

To analyze LULC, Landsat imagery was used. The ArcGIS Pro was employed for supervised classification of different LULC types, ensuring accurate classification of built-up areas, vegetation, water bodies, and bare land. The classification results were further validated via ground truthing and visual interpretation.

These flood-conditioning factors were integrated into a multi-criteria evaluation framework, in which each factor was assigned a relative weight using the AHP. The weighted factors were combined to generate a flood risk assessment map, identifying high, moderate, and low flood-prone zones within the study area.

Each dataset was preprocessed to ensure consistency and accuracy. Four key steps were performed, as follows. (1) Reprojection: all spatial layers were projected to the same coordinate reference system (CRS WGS1984); (2) Resampling: raster datasets were resampled to a common resolution for uniform analysis, (3) Extraction: Study area boundaries were used to clip datasets to the region of interest. The last step, (4) Derivation of Variables, involved the following four variables: (a) slope and aspect were derived from the Digital Elevation Model (DEM), (b) drainage density was calculated using the line density tool based on river networks (c) distance from rivers and distance from roads were computed using the Euclidean distance tool, (d) the LULC classification was performed using supervised classification in the Google Earth Engine.

Further, the Analytical Hierarchy Process (AHP) methodology, developed by Saaty [71], was employed in this study to rank multiple flood risk factors and facilitate Multi-Criteria Decision-Making (MCDA). AHP has been extensively applied in flood risk assessment to evaluate the relative importance of flood-conditioning variables [72]. To quantify the relative influence of flood-contributing factors, a pairwise comparison matrix was constructed. The matrix was normalized, and weights were assigned to each factor based on their significance in flood risk determination. The selected factors—elevation, slope, aspect, drainage density, rainfall, distance from roads, distance from rivers, and LULC—were reclassified before assigning weights. A consistency check was performed to validate the reliability and coherence of the assigned weights.

The AHP weight calculation adhered to Saaty's structured approach [73]. We initially built a pairwise comparison matrix through a 1–9 scale of importance, comparing each factor with others based on expert judgment and the literature. The matrix was later normalized by dividing the elements by their column total, and the final weights were achieved by averaging the normalized values over each row (Table 2). To guarantee consistency, we calculated the maximum eigenvalue, Consistency Index (CI), and Consistency Ratio (CR), which resulted in a CR of 0.0097, thereby validating the reliability of the weight allocations.

Although the AHP process is based on established principles, the weightings for this study were also determined through consultations with local experts, hydrological specialists, and urban planners. This provided a measure of customizability to ensure that the factor prioritization reflected Karachi's unique hydrological, infrastructural, and socio-ecological conditions, departing from the conventional applications found in the AHP literature. Also, the integration of these context-specific weights helped to inform the SC intervention recommendations directly, providing a new applied avenue of connecting MCDA outputs with urban adaptation strategies.

Table 2. Normalized pairwise comparison.

Factors	Elevation	Slope	Aspect	Drainage Density	Rainfall	Distance from Rivers	Distance from Roads	LULC
Elevation	0.0323	0.0435	0.0314	0.036	0.0279	0.0305	0.0317	0.0286
Slope	0.0323	0.0435	0.0519	0.036	0.0423	0.0388	0.0452	0.0571
Aspect	0.1613	0.1304	0.1572	0.1092	0.1691	0.1385	0.2262	0.1714
Drainage Density	0.0968	0.1304	0.1572	0.1092	0.0845	0.0914	0.1131	0.1143
Rainfall	0.0968	0.087	0.0786	0.1092	0.0845	0.0914	0.0747	0.0571
Distance from Rivers	0.2903	0.3043	0.3145	0.3275	0.2536	0.277	0.2262	0.2857
Distance from Roads	0.2258	0.2174	0.1572	0.2183	0.2536	0.277	0.2262	0.2286
LULC	0.0645	0.0435	0.0519	0.0546	0.0845	0.0554	0.0566	0.0571

To ensure the accuracy and validity of the weight assignments, the Consistency Index (CI) and Consistency Ratio (CR) were computed using Saaty's equations [71]. The computed CR value was 0.0097, which is significantly lower than the acceptable threshold of 0.1, confirming the consistency and reliability of the comparisons.

$$\mathrm{CI} = \frac{(\lambda_{\max} - \mathrm{n})}{(\mathrm{n} - 1)} \quad (1)$$

where CI is the Consistency Index, λ_{max} is the maximum eigenvalue of the comparison pairwise matrix, and n is the number of elements being studied [74]. The comparison pairwise matrix's maximum eigenvalue (λ_{max}) was calculated using the procedures shown below [71].

In addition, the priority vector (eigenvector) was computed by averaging the normalized values across each row. The final weights assigned to each variable are given in Table 3.

Table 3. Weights assigned to each variable.

Variable	Weight	Rank
Rainfall	0.2849	1st
Drainage Density	0.2255	2nd
Elevation	0.1579	3rd
Slope	0.1121	4th
LULC	0.0849	5th
Aspect	0.0585	6th
Distance from Rivers	0.0434	7th
Distance from Roads	0.0327	8th

Lastly, to generate a flood risk map, the Weighted Overlay Method was used, and a Flood Risk Index (FRI) was computed:

$$\mathrm{FRI} = (W1 \times X1) + (W2 \times X2) + \cdots + (W8 \times X8)$$

where:

Wn = weight assigned to each variable;

Xn = normalized raster value for each variable;

The overlay operation was performed in ArcGIS (Raster Calculator).

5. Results

This study identified potential regions vulnerable to flooding in Karachi by analyzing eight flood-controlling elements: elevation, slope, aspect, rainfall, drainage density, and distance from roads and rivers as well as land use/land cover. These factors not only inform flood risk assessments but align closely with SC principles aimed at enhancing urban resilience through effective water management. The applied methodology, which integrated remote sensing, GIS-based flood risk assessment, and multi-criteria analysis, effectively supported the study's objectives by identifying flood-prone areas, evaluating key flood-conditioning factors, and informing data-driven recommendations for SC implementation in Karachi.

5.1. Elevation

The elevation map (Figure 3) shows variations in Karachi's height above sea level, detecting areas of low elevation more susceptible to flooding. The elevation map depicts the topographical variations of the study area, ranging from below sea level to over 400 m. The low-lying coastal regions (0–100 m, shown in black and purple) are highly vulnerable to coastal flooding, storm surges, and urban waterlogging, particularly in Karachi and its surroundings. The 101–200 m zone (peach) serves as a transition area, where moderate elevation reduces but does not eliminate flood risks. Farther inland, higher elevations (201–300 m in orange and 301–400 m in yellow) consist of foothills and undulating terrain, which experience rapid runoff that can lead to flash floods in downstream areas. The northernmost regions (>400 m, green) are characterized by hilly landscapes, which contribute to surface runoff and potential downstream flooding during heavy rainfall.

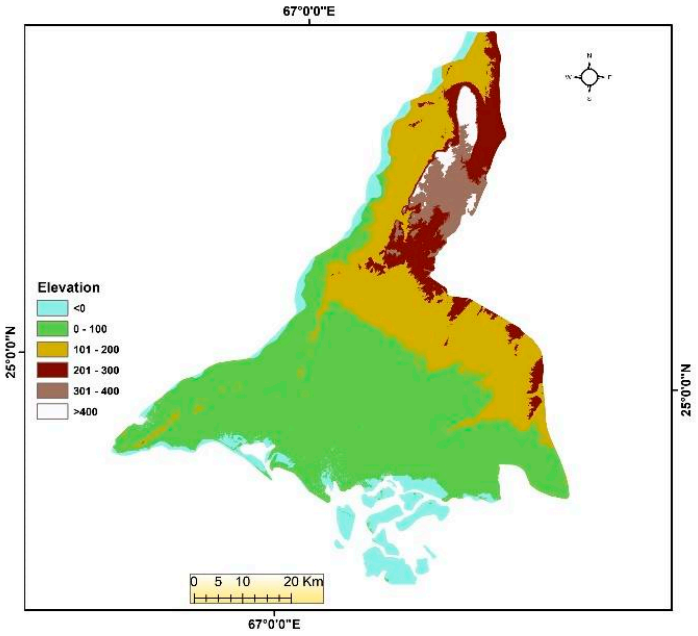

Figure 3. Variations in Karachi's height above sea level. Source: authors.

5.2. Rainfall

Figure 4 shows the average annual rainfall in Karachi from 2016 to 2023, highlighting the spatial distribution of average annual precipitation throughout the region, with a color gradient ranging from green to red indicating variations in rainfall levels. The northern areas, characterized by higher elevations, received more rainfall, reaching as high as 577 mm, likely due to orographic effects. In contrast, the southern and coastal regions experienced lower precipitation, with values as low as 442 mm, possibly influenced by marine conditions and the lower elevation. This variation has significant implications for hydrology, agriculture, and urban planning. Higher rainfall zones play an important role in water resource management, groundwater recharge, and vegetation growth, whereas drier areas may require irrigation strategies as well as drought resilience measures.

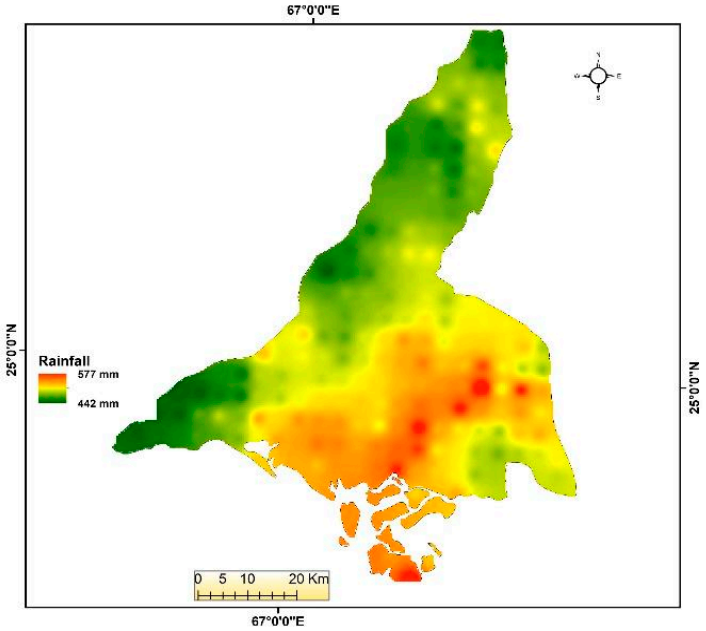

Figure 4. Annual rainfall between 2016 and 2024. Source: authors.

5.3. Land Use/Land Cover (LULC)

The LULC transformation from 1990 to 2024 (Figures 5 and 6) reveals substantial changes in the spatial distribution of various land cover types. In 1990, barren land was the most dominant feature, particularly in the northern and central regions, which indicate minimal vegetation cover due to arid conditions or water scarcity. Agricultural land was scattered across the region, with a greater concentration in the southern regions, suggesting active farming activities supported by irrigation. Built-up areas were mainly confined to the southern coastal region, showing the early stages of urbanization. Forests were relatively limited, primarily appearing in coastal and deltaic zones, likely consisting of mangroves or vegetation adapted to coastal conditions. Water bodies, including rivers, lakes, and coastal zones, remained essential for sustaining ecosystems and human settlements.

By 2024, significant transformations in land use are evident. The most notable transformation has been the rapid growth of built-up areas, which have spread inland, replacing large portions of agricultural and barren land. This indicates population growth, infrastructure development, and industrialization, leading to major shifts in land utilization. The once-dominant barren land has decreased significantly, converted into urban areas, agricultural land, or forests, which reflects increased human activity, afforestation efforts, and land reclamation projects.

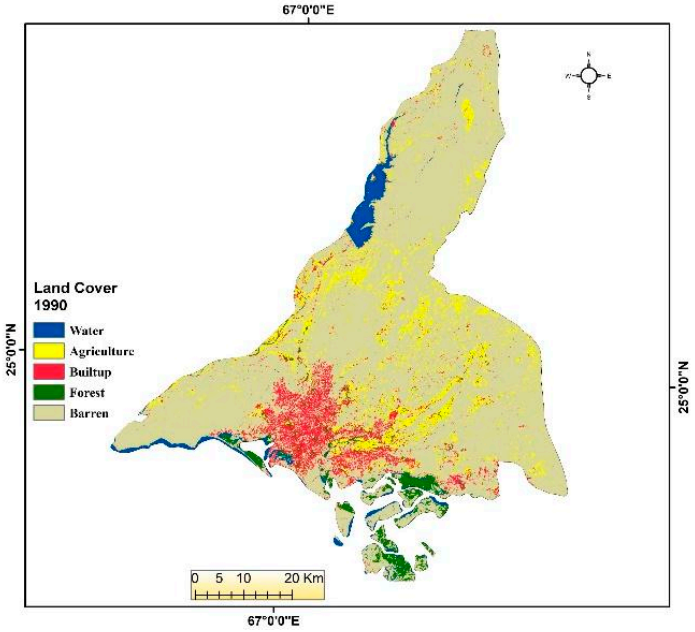

Figure 5. Land cover transformations 1990. Source: authors.

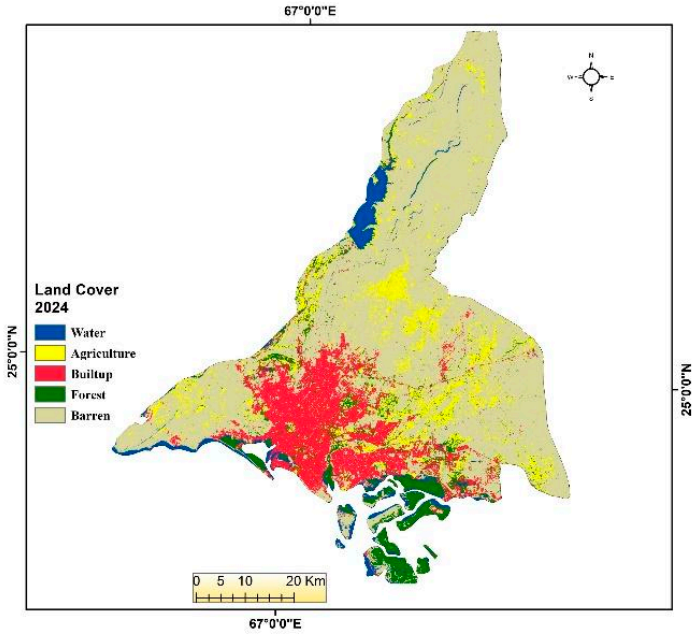

Figure 6. Land cover transformations 2024. Source: authors.

Despite its continued presence, agricultural land is under pressure from expanding urbanization. The fragmentation of farmland, particularly in the southern and central regions, suggests that productive agricultural zones are being encroached upon. This trend has potential long-term implications for food security and rural livelihoods, necessitating policies that balance urban expansion with sustainable agricultural practices. A positive development is the increase in forest cover, especially in coastal and deltaic regions, which indicates successful afforestation efforts as well as mangrove restoration projects. This expansion contributes to biodiversity conservation, carbon sequestration, and climate resilience, helping to mitigate climate change impacts. Meanwhile, the distribution of water bodies has remained stable, though the rise of urban settlements near water sources may pose risks to water quality and ecosystem health. Increased human activity could lead to

pollution and habitat degradation, which highlights the need for effective water resource planning and management strategies.

Overall, the LULC changes from 1990 to 2024 highlight the dominance of urbanization and the reshaping of land use patterns. While the reduction of barren land and forest regeneration are positive developments, the loss of agricultural land and increased pressure on natural ecosystems highlight the need for sustainable land use policies. To address these challenges, integrated urban planning, conservation efforts, and climate adaptation strategies are essential for ensuring environmental sustainability while accommodating development needs.

5.4. Aspect

The aspect map (Figure 7) represents the directional orientation of the terrain, ranging from 0° (north) to 359.8°, indicating the slope direction across the study area. The varied color gradients highlight different slope orientations, which play a crucial role in determining sunlight exposure, wind patterns, and water drainage. The northern and northeastern slopes (blue-green) receive less direct sunlight, making them cooler and more prone to moisture retention, whereas southern and southwestern slopes (yellow-red) receive higher solar radiation, leading to drier conditions. The rugged terrain in the northern and central parts of the map suggests significant topographical variation, impacting water runoff and soil erosion dynamics. Coastal and low-lying regions exhibit minimal aspect variation, indicating relatively flat terrain. This understanding aspect is essential for hydrological modeling, land use planning, and climate impact assessments, particularly for managing water resources and identifying areas susceptible to erosion or changes in vegetation.

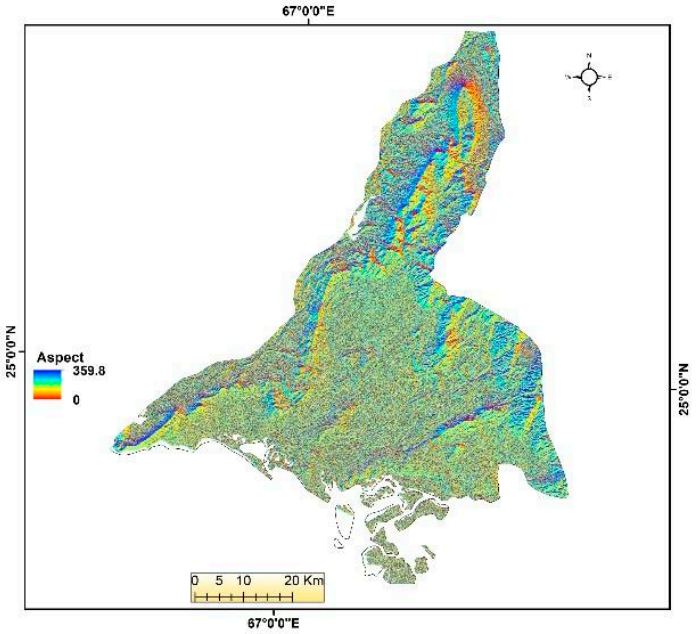

Figure 7. Aspect. Source: authors.

5.5. Slope

The slope map (Figure 8) illustrates the steepness of the terrain, with values ranging from 0° (flat) to 65.4° (steepest areas). The gradient from red to yellow highlights varying slope intensities, where flat and low-lying areas, such as coastal regions and river plains, exhibit minimal slope (yellow), while steeper slopes (blue) are concentrated in the northern and central hilly terrain. The presence of steep slopes suggests a higher susceptibility to erosion, landslides, and rapid water runoff, which are key factors in urban planning, watershed management, and infrastructure development.

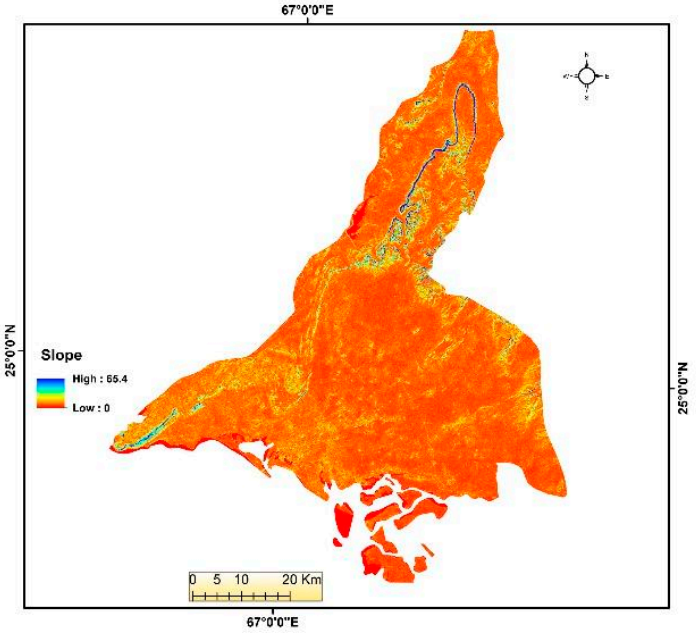

Figure 8. Slope. Source: authors.

5.6. Distance from Rivers

The distance from rivers map (Figure 9) highlights the spatial distribution of areas based on their proximity to river networks. A color gradient, ranging from light green to dark brown, indicates increasing distances from the rivers, with lower values (light green) representing areas close to the river and higher values (dark brown) showing areas farther away. The riverine zones, particularly in the southern and coastal regions, are characterized by closer proximity to water bodies, making these more prone to flooding and sediment deposition. In contrast, inland areas, particularly in the northern and elevated zones, exhibit greater distances from rivers, which may lead to challenges in water accessibility for agriculture and human settlements.

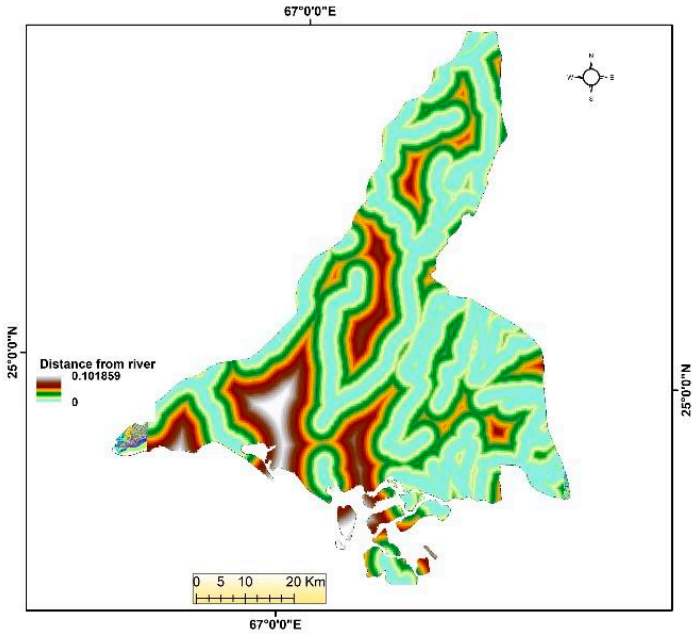

Figure 9. Distance from rivers. Source: authors.

5.7. Distance from Roads

The distance from roads map (Figure 10) provides a visual representation of how far different areas are from the road network. Using a color gradient ranging from purple to green, the map effectively illustrates accessibility variations across the region. The areas marked in purple indicate proximity to roads, signifying improved connectivity and ease of transportation. These regions are likely to have more infrastructure, economic activities, and easier access to essential services. In contrast, the yellow and green areas represent regions that are farther away from roads, highlighting potential accessibility challenges. Higher distances suggest transportation difficulties, which can impact the movement of goods and services, emergency response times, and overall economic development. Such areas may experience lower infrastructure investments and logistical constraints in accessing markets and essential services.

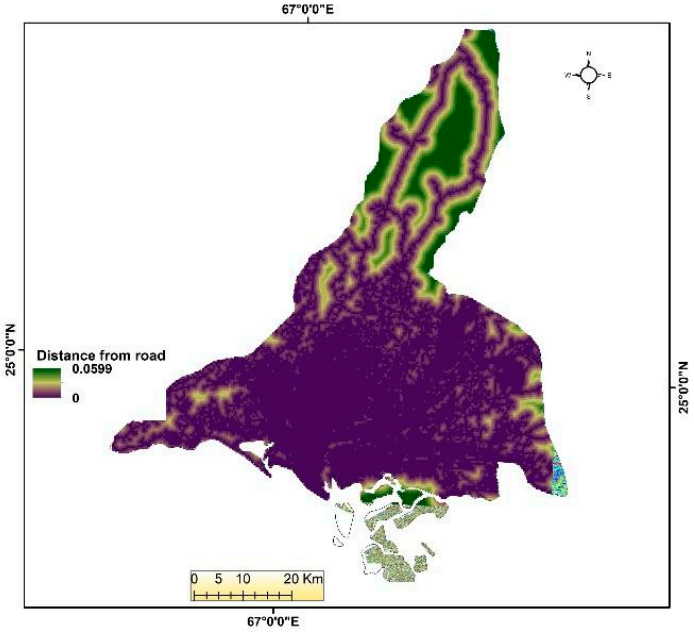

Figure 10. Distance from roads. Source: authors.

5.8. Drainage Density

The drainage density map (Figure 11) shows the concentration of drainage features, such as rivers and streams, within a given area. Different colors on the map indicate varying levels of drainage density, which can provide insights into hydrological and geomorphological characteristics. Areas with higher drainage density, represented in darker shades, suggest regions with a well-developed network of streams and rivers, which may indicate higher runoff potential, lower infiltration rates, and possibly steeper slopes or impervious surfaces. Conversely, areas with lower drainage density, represented in lighter shades, signify regions that have fewer drainage channels. These areas often have more permeable soil, lower runoff, and higher infiltration, making them less prone to surface water accumulation and subsequent flooding.

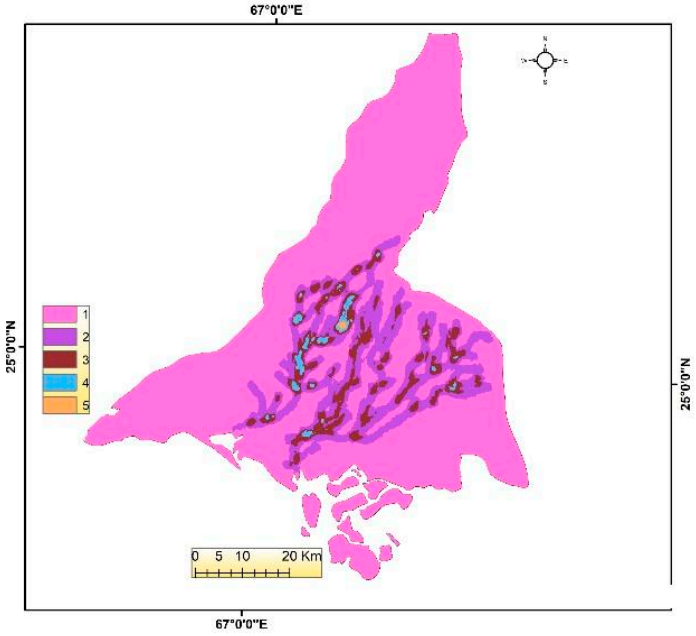

Figure 11. Drainage density: Source: authors.

5.9. Flood Risk Assessment Map of Karachi

The Flood Risk Assessment Map of Karachi (Figure 12) provides a comprehensive spatial representation of flood vulnerability across Karachi, generated using the AHP and multiple contributing factors, including elevation, slope, LULC, rainfall intensity, drainage network proximity, and soil type. The map categorizes flood risk into five classes: very low, low, moderate, high, and very high, offering insights into the most flood-prone areas.

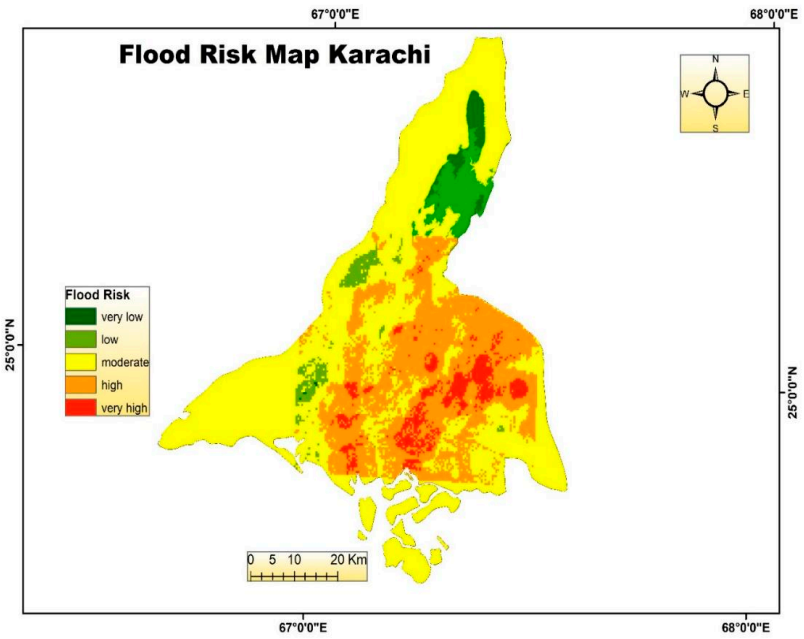

Figure 12. Flood risk assessment map of Karachi.

The central and southeastern regions of Karachi show high to very high flood risk, represented in orange and red. These areas are highly urbanized with dense built-up land, which reduces natural infiltration and increases surface runoff. In addition, poor drainage infrastructure and rapid urban expansion have exacerbated flood susceptibility in these regions. Moderate-risk zones, marked in yellow, dominate most of the city, indicating areas

with mixed land use. These regions experience occasional flooding due to their moderate slope, partial drainage coverage, or a combination of factors that neither fully mitigate nor significantly exacerbate flood risk.

The low-risk areas, represented in light green, are found in patches across the northern and western parts of the city. These regions generally have higher elevations and better natural drainage, reducing their susceptibility to flooding. The very low-risk zones, marked in dark green, are concentrated in the northern parts of Karachi, where natural topography and vegetation contribute to effective water absorption and runoff management. These areas benefit from higher elevations and relatively less urban development.

The flood risk map integrates multiple weighted factors assessed through AHP, where expert judgment and pairwise comparison helped in determining their influence. Higher elevations, particularly in the northern regions, correspond to lower flood risk, whereas lower-lying, flat areas in central Karachi are more prone to water accumulation. Urban areas with extensive impervious surfaces (roads and buildings) have reduced permeability, increasing surface runoff and flood risk. Green spaces and undeveloped land in the north help mitigate flood hazards.

Areas with high rainfall accumulation and poor drainage infrastructure are significantly at risk. The city's stormwater system struggles under high-intensity rainfall, leading to frequent urban flooding. Regarding soil type, sandy and permeable soils in some regions help absorb excess water, whereas clay-dominated and compacted urban soils contribute to increased runoff and flood potential.

6. Discussion

Karachi faces significant flood risks, particularly in densely populated and low-lying areas. For example, the Defense Housing Authority (DHA), a prominent residential and commercial area, has experienced severe urban flooding, especially during the August 2020 monsoon season, due to poor drainage networks and extensive land encroachments [75]. Similarly, Korangi, an industrial and residential hub in southeastern Karachi, faces high flood vulnerability. Flood risk assessment mapping indicates that areas within Korangi, as well as the West, Central, and East districts, show high to very high flood susceptibility, highlighting the urgent need for comprehensive flood mitigation strategies, as shown in Figure 12. The eastern part of Karachi, particularly Gulistan-e-Jauhar, also contends with flooding during the monsoon season, disrupting daily life and causing property damage [76]. Furthermore, major stormwater drains, such as Orangi Nullah, Gujjar Nullah, and Mahmoudabad Nullah, despite annual cleaning efforts, remain vulnerable to overflowing during heavy rains. Encroachments and solid waste accumulation worsen the risk of urban flooding in adjacent neighborhoods [77,78].

The risk of flooding in Karachi is intricately linked to elevation, with lower-lying areas being more vulnerable to flood events. These areas are more likely to flood during heavy rainfall events, when large volumes of water flow rapidly and rivers discharge more quickly [79]. Figure 3 shows the elevation distribution in Karachi, highlighting the need for effective flood mitigation measures in low-lying urban and coastal areas, while recognizing the influence of higher-altitude regions on flood dynamics. Such areas can benefit significantly from SC interventions like constructed wetlands and permeable surfaces, aiming to absorb excess stormwater and enhance local drainage capabilities.

To effectively address these flooding concerns, integrating the SC framework is a viable solution for Karachi. SC principles promote the incorporation of nature-based solutions, such as green infrastructure, that can mitigate flood risks by enhancing water retention and improving drainage capacity. Integrating urban greening into this framework is particularly crucial. By using the flood risk map, urban planners can strategically place

vegetation corridors, rain gardens, and permeable pavements in areas identified as high-risk, thus optimizing water absorption and reducing surface runoff. Establishing green roofs, rain gardens, and urban parks can significantly reduce the impact of urban flooding in vulnerable areas such as DHA and Korangi by capturing and managing stormwater more efficiently. Such interventions improve soil absorption, reduce surface runoff, and provide essential ecological benefits, including enhanced biodiversity and improved air quality.

Additionally, understanding rainfall distribution is important for effective flood risk assessment and urban drainage design. Comparative analysis of rainfall data with factors such as slope, land use, and soil moisture can further inform sustainable development and climate adaptation strategies. Research has shown that heavy or prolonged rainfall events are primary flood triggers, generating significant runoff that overwhelms existing drainage systems [80]. Moreover, land use and land cover significantly impact the chance of flooding. Areas with high vegetation density are generally less prone to floods due to improved water infiltration. In contrast, urbanization leads to increased impermeable surfaces that contribute to greater runoff and elevated flood risks [81]. In light of the above considerations, the aspect, or slope orientation of the land, affects surface runoff patterns, thus playing an important role in urban flood dynamics and necessitating customized flood mitigation measures [82]. The degree of slope influences water flow rates, with lowlands and flatter regions being more susceptible to flooding due to slower water movement and accumulation [83]. Understanding these factors is important for integrated urban planning and flood risk management in Karachi, particularly as SC initiatives allow for more adaptive responses to unique urban landscapes. These results support the need for implementing SC strategies that can transform urban spaces by enhancing vegetation cover and stormwater management capabilities. However, reliance on RS data for monitoring environmental risks highlights its importance in contemporary research [21].This approach may be constrained by the quality and temporal resolution of the input data used, which can affect the accuracy of flood risk assessments [84]. While various studies have effectively applied geospatial techniques and modelling frameworks, they often fail to account for the complex societal dynamics involved in implementing NBS, including governance and community engagement challenges [84].

Implementing the SC approach in Karachi also involves considering the proximity to river systems, which impacts both flood risk and water resource management [85]. Identifying areas near rivers and integrating drainage density metrics can further enhance urban planning, helping to pinpoint flood-prone regions and optimize land use strategies. Furthermore, the spatial distribution of drainage density plays a critical role in flood risk assessment and is a key consideration in effective land use planning [86]. A comprehensive understanding of drainage networks can inform infrastructure decisions and highlight the need for conservation measures, reinforcing the importance of incorporating SC principles to improve ecological balance and manage urban water flows. However, the successful implementation of urban greening initiatives within the SC framework faces various challenges. The limited availability of space for green infrastructure in highly urbanized areas can hinder the successful implementation and effectiveness of sponge city (SC) strategies [18].

Moreover, while the SC approach promotes green infrastructure as a solution for urban flooding, it may overlook other critical issues, such as socio-economic inequities in access to urban resources and the maintenance of green spaces [55]. This can lead to uneven benefits, often privileging wealthier neighborhoods while marginalized communities continue to bear the impact of flooding risks. Therefore, the promotion of justice and inclusivity in SC interventions is needed to ensure equitable outcomes. It is also very important to establish a balanced perspective that acknowledges both the potential and limitations of

the SC framework, particularly in the context of rapidly urbanizing cities like Karachi. This includes encouraging discussions on adaptive management, community involvement, and the integration of diverse stakeholder perspectives to optimize the implementation of SC strategies. These nature-based solutions are based on the flood-prone areas outlined by our GIS-AHP analysis. For instance, the inclusion of permeable pavements, rain gardens, and green roofs in the most at-risk neighborhoods (like DHA, Korangi, and Gulistan-e-Jauhar) is suggested to minimize surface runoff and improve water absorption. Vegetated swales and bioswales may also be used strategically to address drainage density where infrastructure is substandard. By setting the SC framework explicitly against the spatial patterns based on our evaluation, we ensure that SC is not just a theoretical discourse but an evidence-based and focused intervention strategy.

Engaging local communities, policymakers, urban planners, and environmental organizations in the design and execution of urban greening initiatives can enhance public acceptance and support for SC concepts. Methods for stakeholder engagement might include public workshops, surveys to gather input on community needs, and participatory planning processes that involve residents in decision-making.

This research expands the SC idea by using it for the megacity Karachi, where few empirical SC implementations exist. Our contributions include the following: (1) integrating GIS-AHP flood risk zoning with SC design recommendations tailored to local conditions, (2) expanding the SC framework's operational relevance to a new regional context with distinct hydrological and urbanization patterns, and (3) offering a context-specific SC intervention plan that addresses Karachi's unique challenges, thereby improving the adaptability and applicability of the SC model.

By systematically combining RS, GIS, MCDA, and hydrological modeling, this methodology provides a comprehensive, data-driven framework that supports each of the study's objectives, ensuring that SC principles are applied effectively to mitigate urban flooding in Karachi. The accuracy and reliability of flood risk assessments in this study are closely associated with the quality and spatial resolution of RS and geospatial data. The satellite imagery used provides valuable perceptions into land cover changes and hydrological patterns; however, its spatial resolution may limit the precise identification of small-scale urban features necessary for flood modeling. Furthermore, the temporal relevance of the data is important, as rapid urbanization and climate variability may make older datasets less reflective of current flood risk conditions. While high-resolution datasets and multi-temporal analyses enhance the strength of flood risk predictions, challenges such as cloud cover, sensor limitations, and data processing constraints can impact accuracy. Additionally, the reliance on secondary datasets, such as historical flood records and digital elevation models, may introduce uncertainties, particularly if these datasets are outdated or inconsistent across different sources. Future studies should incorporate near-real-time monitoring and high-frequency RS data to improve flood prediction accuracy and adaptive urban planning strategies. While this study relied on AHP-based multi-criteria analysis, which does not simulate physical water flow dynamics, it remains reliable due to its structured weighting process, consistency validation, and alignment with known flood-prone zones. The AHP framework has been widely used for flood risk assessment in regions where detailed hydrological data are unavailable, making it an appropriate tool here. Nonetheless, we recognize that future research should integrate hydrodynamic models for quantitative validation and enhanced predictive accuracy. The ongoing validation of flood risk assessments is qualitative because high-risk zones are compared with areas of known flood hazard, citing past study results as well as recommendations of municipal agencies. The authors see a clear need for quantitative validation. In subsequent studies, further actualization will involve overlaying analyses using historical records of flood events with

attempts to cross-validate predictive maps with data regarding the actual flood extent, and possibly undertaking field surveys or comparisons with hydrodynamic models to enhance the predictive capability.

7. Conclusions

The findings from this study highlight the significant challenges urban areas like Karachi face due to rapid urbanization, primarily characterized by the increase in impervious surfaces and inadequate water management strategies. This research used remote sensing and Geographic Information Systems to assess flood risk factors specific to Karachi, developing a comprehensive flood risk assessment framework based on key flood-conditioning parameters. This study provides a detailed evaluation of various environmental attributes, including elevation, rainfall distribution, slope, distance from roads and rivers, and land use/land cover, ultimately identifying vulnerable areas predisposed to urban flooding.

The findings of this study can directly support implementation of the SC framework in Karachi. The flood risk assessment maps highlight critical high-risk areas, such as DHA, Korangi, and Gulistan-e-Jauhar, where interventions such as permeable pavements, green roofs, and constructed wetlands can be strategically prioritized to improve water infiltration and minimize surface runoff. The analysis of elevation and slope further supports the strategic placement of retention ponds and bioswales in low-lying flood-prone regions to mitigate water accumulation. Additionally, the integration of land use and land cover data emphasizes the role of urban vegetation's role in flood mitigation and highlights the need to expand green infrastructure in impermeable urban zones. The spatial distribution of drainage density provides essential information for optimizing stormwater management and reinforcing natural waterways and hydrological processes. These findings collectively contribute to a data-driven SC implementation strategy, ensuring that interventions are adapted to Karachi's urban hydrology, improving flood resilience while promoting sustainable urban development.

The proposed SC framework provides a method for integrating NBS into urban planning, addressing immediate flood risks while contributing to broader urban sustainability goals. By emphasizing the essential role of green infrastructure such as rain gardens, green roofs, and urban parks, the framework aims to enhance stormwater management capabilities, promote biodiversity, and improve the overall quality of the urban living environment. These interventions not only mitigate flood risks but also promote urban resilience by improving air and water quality as well as community wellbeing, particularly in densely populated cities like Karachi that confront significant environmental challenges.

Moreover, the successful implementation of the SC model in Karachi highlights that we need to employ innovative strategies that enhance urban resilience and sustainability. By ensuring equitable access to green spaces and facilitating community engagement, the SC approach aims to create a more inclusive urban landscape.

In conclusion, conceptualizing Karachi as an SC presents an opportunity not only to address immediate environmental challenges but also to rethink urban design in relation to broader sustainability goals. By navigating the complexities of urbanization, climate change, and ecological preservation, this study hopes to articulate a viable SC framework for Karachi, providing a model that can be reproduced in a similar context, for instance, other rapidly urbanizing cities across the Global South. The results of this article not only offer actionable insights for policymakers and urban planners but also stress the urgent need for a transformative shift in urban management approaches to incorporate effective water management and climate adaptation methodologies.

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Abbreviations

The following abbreviations are used in this manuscript:

GIS	Geographic Information Systems
AHP	Analytical Hierarchy Process
SC	sponge city
NBS	Nature-Based Solutions
MCDA	Multi-Criteria Decision Analysis
LULC	land use/land cover
DEM	Digital Elevation Model
SRTM	Shuttle Radar Topography Mission
CR	Consistency Ratio
CI	Consistency Index
DHA	Defense Housing Authority

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