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Integrating AHP and Land Change Modeling to Assess Urban Expansion-Induced Flood Susceptibility in Islamabad, Pakistan

NISAR ALI HUSSAIN

nalihussain@gmail.com

Survey of Pakistan

Muhammad Imran Khan

Tongji University

Junaid Memon

Survey of Pakistan

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Authors:

Nisar Ali Hussain[1], Muhammad Imran Khan [2]

Affiliations:
[1] [Survey of Pakistan]
[2] [School of Civil Engineering, Tongji University, Shanghai, China]

Corresponding Author:
Name: **Nisar Ali Hussain**
Email: nalihussain@gmail.com
Postal Address: D-27 Street No.4 Kohsar Colony Phase 1, Taxila, Rawalpindi, Pakistan
Phone: +92-3458501398

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- Nisar Ali Hussain: Conceptualization, methodology, data analysis, investigation, writing, original draft preparation.
- Muhammad Imran Khan: Validation, Visualization, Writing review & editing.

Abstract:

Rapid and unplanned urban expansion has intensified flood hazards in many developing regions, yet few studies quantitatively disentangle the relative effects of land-use change and climate variability on flood susceptibility. This study examines the interplay between urban sprawl, land cover transformation, and hydrological risk in Islamabad, Pakistan, using an integrated Remote Sensing (RS), Geographic Information System (GIS), Analytical Hierarchy Process (AHP), and Land Change Modeler (LCM) framework. Multi-temporal Landsat imagery (1990-2024) was used to map land-use transitions, while the AHP quantified flood susceptibility weights for topographic, hydrological, and anthropogenic factors. The LCM simulated projected 2030 land-use scenarios, which were integrated into the flood susceptibility model to evaluate baseline, climate change, and urban sprawl scenarios. Results show that built-up area expansion at a rate of 7% per year drives a 41% increase in high-risk flood zones by 2030, exceeding the 35% increase attributed to climate-induced precipitation extremes. The coupled RS-GIS-AHP-LCM approach enhances the dynamic predictive capacity of flood risk modeling and supports anticipatory, spatially informed decision-making.

This study is among the first to dynamically integrate AHP and LCM for assessing the coupled impacts of land-use change and climate variability on flood susceptibility in a South Asian megacity.

Keywords:

Urban sprawl; Flood susceptibility; Land Change Modeler (LCM); Analytical Hierarchy Process (AHP); Remote Sensing (RS); Geographic Information System (GIS).

1. Introduction

Urban flooding has emerged as one of the most pervasive and economically disruptive natural hazards in contemporary cities, particularly in developing countries undergoing rapid and unregulated urban expansion. The

complex interaction between urbanization, land use dynamics, and climate variability fundamentally alters natural hydrological systems, reducing infiltration and accelerating surface runoff. Consequently, the frequency and intensity of flood events have risen sharply, posing escalating risks to infrastructure, livelihoods, and ecosystems (UNDRR, 2023) ;(IPCC, 2022).

In Pakistan, the capital city Islamabad has experienced accelerated urbanization over the past three decades, transforming its natural terrain and elevating flood susceptibility. Located at the foothills of the Margalla Range, the city's expanding impervious surfaces and declining vegetation cover have intensified surface runoff during monsoon seasons. Recent floods have underscored Islamabad's growing exposure to extreme precipitation events, revealing the urgent need to understand how urban sprawl and climate change jointly amplify flood risks.

Urban sprawl defined as the rapid and often unplanned expansion of built-up areas into rural or ecologically sensitive zones has been widely identified as a major factor intensifying urban flood hazards (Skilodimou et al., 2021). The proliferation of impervious surfaces such as roads, rooftops, and pavements reduce natural infiltration and increases peak runoff (Barros (Barros et al., 2021); (Wahl et al., 2015). This transformation disrupts drainage systems, modifies surface water pathways, and leads to the loss of wetlands and floodplains crucial for flood attenuation (Li et al., 2022); (Nsangou et al., 2022). Consequently, encroachment into flood-prone zones heightens risks of inundation, erosion, and structural damage to urban infrastructure (Stamellou et al., 2021); (Boucher, 2020). Numerous studies have reported strong correlations between indicators of urbanization impervious surface extent, population density, and built-up

expansion and increased flood risk (Shi et al., 2023); (Mehta et al., 2023); (Chettry, 2022).

Although substantial advances have been made in flood risk modeling, most existing approaches exhibit critical limitations. Hydrological and hydraulic models (e.g., HEC-HMS, SWAT, HEC-RAS, MIKE Flood) require extensive hydrometeorological or geometric datasets often unavailable in data-scarce regions (Stamellou et al., 2021). Statistical frequency analyses capture temporal patterns but neglect spatial heterogeneity in topography and land use (BrÁZdil et al., 2010). Remote Sensing (RS) and Geographic Information Systems (GIS) have improved spatial flood mapping, yet most RS-GIS studies remain static analyzing current conditions without incorporating future land use transitions or climate variability (Selvam and Antony Jebamalai, 2023). The Analytical Hierarchy Process (AHP) provides a systematic framework for multi-criteria flood assessment (Ghosh and Kar, 2018), but traditional AHP-based models generally assess present vulnerability rather than forecasting future risk under evolving environmental conditions.

Regionally, previous RS-GIS studies in Islamabad have examined land use and urban growth dynamics (Hassan et al., 2016); (Mannan et al., 2021); (Haider, 2022) ;(Wahab et al., 2023) (Kamran et al., 2023). While these works provide valuable insights into spatiotemporal LULC patterns, they remain largely descriptive, lacking predictive modeling of how continued urban sprawl and climatic shifts could reshape future flood susceptibility.

The key research gap addressed in this study lies in the absence of an integrated, scenario-based modeling framework that dynamically couples land use change, urban sprawl, and climate variability to forecast future flood

susceptibility in data limited urban contexts. Most prior studies have treated these drivers in isolation, overlooking their compounded and interacting effects on flood exposure and hydrological response.

To bridge this gap, the present study develops an integrated RS-GIS-AHP-LCM framework to assess the spatial and temporal dynamics of flood susceptibility in Islamabad under multiple future scenarios. The study is guided by the following specific objectives:

1. Quantify land-use transitions in Islamabad from 1990 to 2024 using multitemporal satellite imagery
2. Assess flood susceptibility under baseline, climate change, and urban sprawl scenarios through multi-criteria spatial analysis
3. Evaluate the relative influence of urbanization and climate change on future flood risk, identifying the dominant drivers of hydrological vulnerability.

This framework enables dynamic simulation of land cover transformations using cellular automata-Markov (CA-Markov) modeling within TerrSet, integrated with AHP-based flood susceptibility mapping in ArcGIS Pro. Beyond advancing geospatial modeling techniques, it contributes practical insights for integrating spatial planning, flood governance, and climate adaptation policies in developing cities. The findings underscore that urban sprawl, if left unregulated, may surpass climate-driven rainfall extremes as the primary driver of future flood exposure an insight with significant implications for sustainable urban development and disaster risk reduction across South Asia.

2. Study Area

Islamabad, the capital city of Pakistan, is situated between latitudes 33°36'-33°49'N and longitudes 72°47'-73°24' E, covering approximately 906 km² within the Potohar Plateau at the foothills of the Margalla Range. The region features a subtropical climate characterized by hot summers, mild winters, and intense monsoon rainfall from July to September, with an average annual precipitation of about 1,200 mm (PMD, 2023). Its heterogeneous topography comprising hilly terrain in the north and low-lying plains in the south creates distinct hydrological gradients influencing flood dynamics.

Islamabad has experienced rapid urban expansion since the 1990s, transforming natural landscapes into impervious surfaces and thereby amplifying hydrological responses to precipitation events. This expansion has resulted in increased surface runoff, altered drainage networks, and recurrent urban floods (Hassan et al., 2016, Mannan et al., 2021). Major flood events in 2001, 2010, 2021, and 2022 caused severe damage to infrastructure and residential sectors, highlighting the city's growing flood vulnerability (NDMA, 2023 , UNDRR, 2023).

The city's location, socio-economic importance, and contrasting physiographic conditions make it an ideal case for analyzing the nexus between urban sprawl, land use change, and flood susceptibility under evolving climate conditions. Insights drawn from Islamabad provide a valuable framework for other rapidly urbanizing cities in South Asia facing similar environmental and planning challenges (IPCC, 2022, UNDRR, 2023).

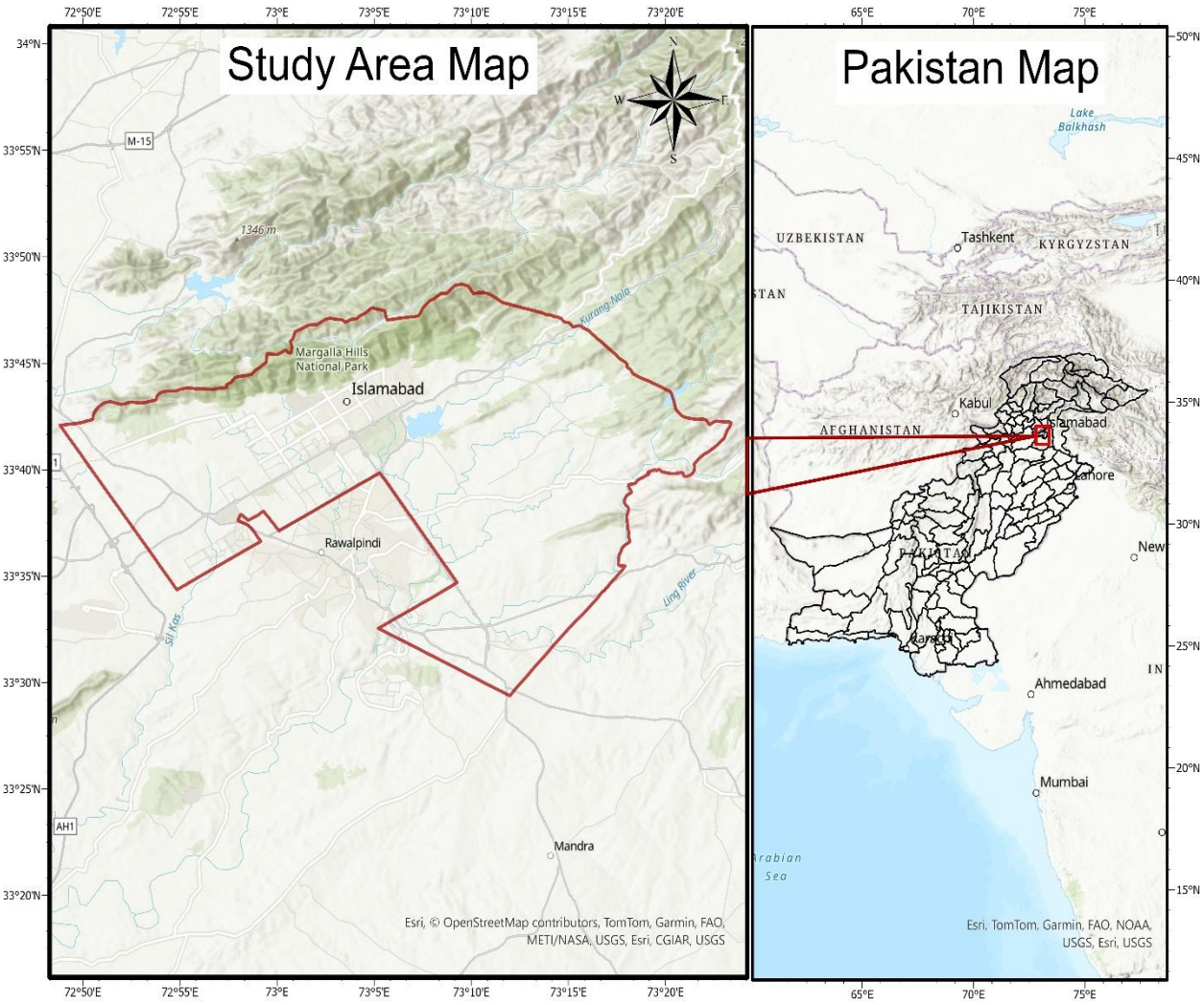


Figure 1: Location and spatial context of the study area, Islamabad Capital Territory, Pakistan.

3. Materials and Methods

3.1. Data Sources

This study employed multi-temporal satellite imagery, climatic datasets, topographic information, and ancillary spatial layers to support land use/land cover (LULC) mapping, flood susceptibility modeling, and scenario-based simulation (Table 1). Landsat imagery from the United States Geological Survey (USGS) Earth Explorer Landsat 5 TM (1990, 2000, 2010) and Landsat 8 OLI/TIRS (2015, 2020, 2024) was processed at 30 m resolution and co-registered

to WGS 84/UTM Zone 43N in ArcGIS Pro.

Table (1): Data sources and thematic maps used in the study

No.	Data Set	Thematic Map / Variable	Map Type	Spatial Resolution (m)	Source / Platform
1	SRTM Digital Elevation Model (DEM)	Elevation, Slope, Flow Accumulation, Drainage Density	Raster	30 x 30	USGS Earth Explorer (https://earthexplorer.usgs.gov)
2	Landsat 5 TM / Landsat 8 OLI-TIRS	LULC Classification, NDVI	Raster	30 x 30	USGS Earth Explorer
3	PERSIANN-CCS-CDR	Precipitation (Annual Mean Rain Rate)	Raster	30 x 30	CHRS, University of California, Irvine (https://chrsdata.eng.uci.edu)
4	FAO Digital Soil Map of the World	Soil Type	Raster	30 x 30	FAO Soils Portal (https://www.fao.org/soils-portal)
5	OpenStreetMap	Distance from Roads, Rivers	Vector	30 x 30 (converted)	https://download.geofabrik.de/asia/pakistan.html
6	WorldPop / GeoBoundaries	Population Density, Administrative Boundaries	Vector	-	https://www.worldpop.org / https://www.geoboundaries.org
7	NDMA & OCHA	Historical Flood Inventories	Point	-	NDMA (2023); OCHA (2022)

Topographic and hydrological parameters were extracted from the Shuttle Radar Topography Mission (SRTM) DEM (30 m), including slope, elevation, flow accumulation, and drainage density. Soil data were derived from the FAO Digital Soil Map of the World, and vegetation indices (NDVI) were computed from Landsat reflectance bands. Precipitation data were obtained from the PERSIANN-CCS-CDR dataset (CHRS, University of California, Irvine), representing annual rainfall rates. Three precipitation scenarios (10%, 30%, 50% above baseline) were generated following (IPCC, 2022) climate projections.

Socioeconomic and administrative data were acquired from WorldPop and GeoBoundaries, ensuring spatial consistency. Historical flood records (2001, 2008, 2010, 2022) were validated using data from (NDMA, 2023) and (OCHA, 2022).

All raster layers were resampled to a 30 m grid, projected to the same coordinate system, and clipped to the Islamabad Capital Territory (ICT) boundary (Fig.3).

3.2. Methodological Framework

The study developed an integrated RS-GIS-AHP-LCM framework to analyze historical LULC transitions, model current flood susceptibility, and project future flood risk under alternative development and climate scenarios (Fig. 2). The workflow consisted of four key stages:

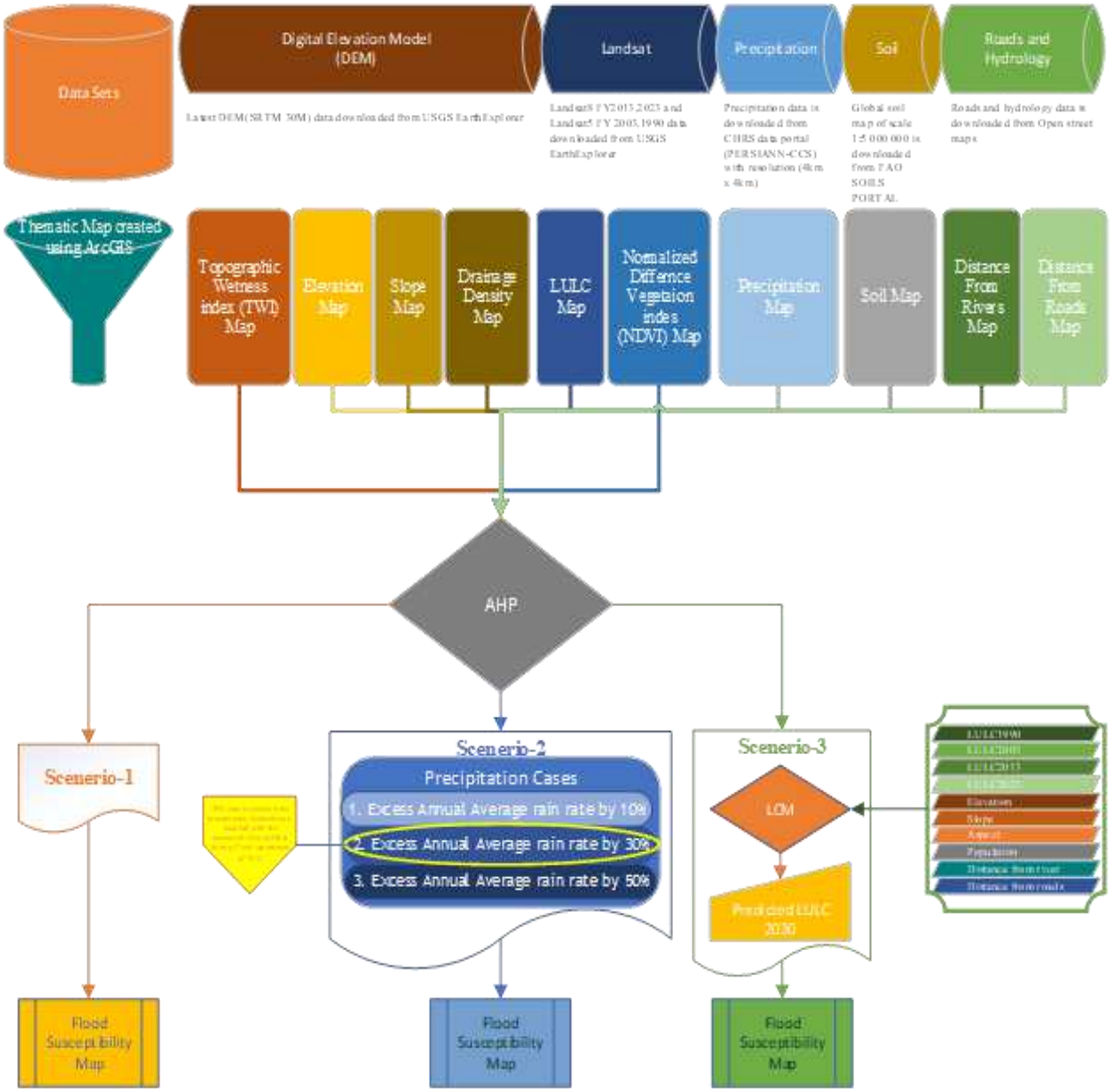
1. **LULC Classification and Change Detection:**

Multi-temporal Landsat data (1990-2024) were classified into five categories built-up, vegetation, forest, agriculture, and water using the Support Vector Machine (SVM). Post-classification change detection quantified spatial transitions and urban expansion rates.

2. **Flood Susceptibility Mapping using AHP:**

Flood susceptibility was evaluated by integrating seven conditioning factors: elevation, slope, drainage density, soil type, LULC, NDVI, and precipitation. Each factor was standardized on a 1-5 susceptibility scale and assigned relative importance weights via the Analytical Hierarchy Process (AHP)

based on expert judgment and literature (Rahmati et al., 2015); (Gigović et al., 2017); (Hong et al., 2018).



(Fig. 2): Methodological framework of the integrated RS-GIS-AHP-LCM approach applied for flood susceptibility modeling and scenario-based assessment in Islamabad, Pakistan.

The AHP process involved pairwise comparisons to derive normalized weights, which were combined in a weighted linear overlay to generate the Flood

Susceptibility Index (FSI). Model accuracy was validated using flood inventory data (2010-2022), achieving an AUC = 0.89 and $\kappa = 0.86$.

3. Land Change Modeling (LCM) for Future Scenarios:

The Land Change Modeler (LCM) in TerrSet 19.0.7 was used to simulate the 2030 urban expansion scenario. LCM applies a Markov Chain-Cellular Automata (CA) model to estimate future LULC transitions using historical land change trends and spatial drivers (distance to roads, rivers, slope, and elevation). The simulation achieved high validation accuracy (Klocation = 0.83; Kquantity = 0.88), consistent with recent urban growth studies (Sanyal and Lu, 2009, Xu et al., 2022, Theres et al., 2023, Aydın and Durduran, 2024, Tagg et al., 2022).

Table (3): Data inputs and settings used in Land Change Modeler (LCM)

No.	Input Dataset	Role in LCM	Temporal Reference / Parameter
1	LULC Map 1990	Initial State	Historical Baseline
2	LULC Map 2023	Final State	Transition Reference
3	Population Density	Explanatory Variable	2023
4	Elevation	Explanatory Variable	Static
5	Slope	Explanatory Variable	Derived from DEM
6	Aspect	Explanatory Variable	Derived from DEM
7	Distance to Roads	Driver Variable	2024
8	Distance to Rivers	Driver Variable	2024

4. Scenario-Based Flood Modeling:

Three scenarios were analyzed:

1. Scenario 1: Baseline (2024)
2. Scenario 2: Climate Change (30% increased rainfall)
3. Scenario 3: Urban Sprawl (2030 projected LULC)

3.3. Model Integration

To bridge static flood susceptibility analysis with dynamic urban change simulation, AHP-based factor weighting and LCM-based LULC projections were explicitly integrated (Fig. 3). The workflow operated as follows:

1. The AHP provided a baseline weighting structure representing the relative importance of biophysical and anthropogenic flood drivers.
2. The LCM predicted future spatial distributions of LULC classes under the 2030 scenario.
3. The predicted LULC raster replaced the baseline LULC layer in the AHP based weighted overlay, dynamically updating the flood susceptibility model.

This coupling enables the quantification of compound effects of urbanization and climate variability on flood risk. The integrated approach enhances predictive realism and spatial adaptability compared with conventional static models (Li et al., 2024, Zhran et al., 2024, Aydın and Durduran, 2024, AlRifai et al., 2025).

3.4. Scenario Evaluation

The comparative scenario analysis demonstrated a 35% increase in flood-prone areas under extreme precipitation (Scenario 2) and a 41% increase under projected urban sprawl (Scenario 3). These findings indicate that urban expansion exerts a greater influence on flood susceptibility than climate-driven rainfall change. The integrated RS-GIS-AHP-LCM framework thus provides a replicable decision support tool for sustainable urban planning and climate-resilient spatial governance in rapidly urbanizing regions.

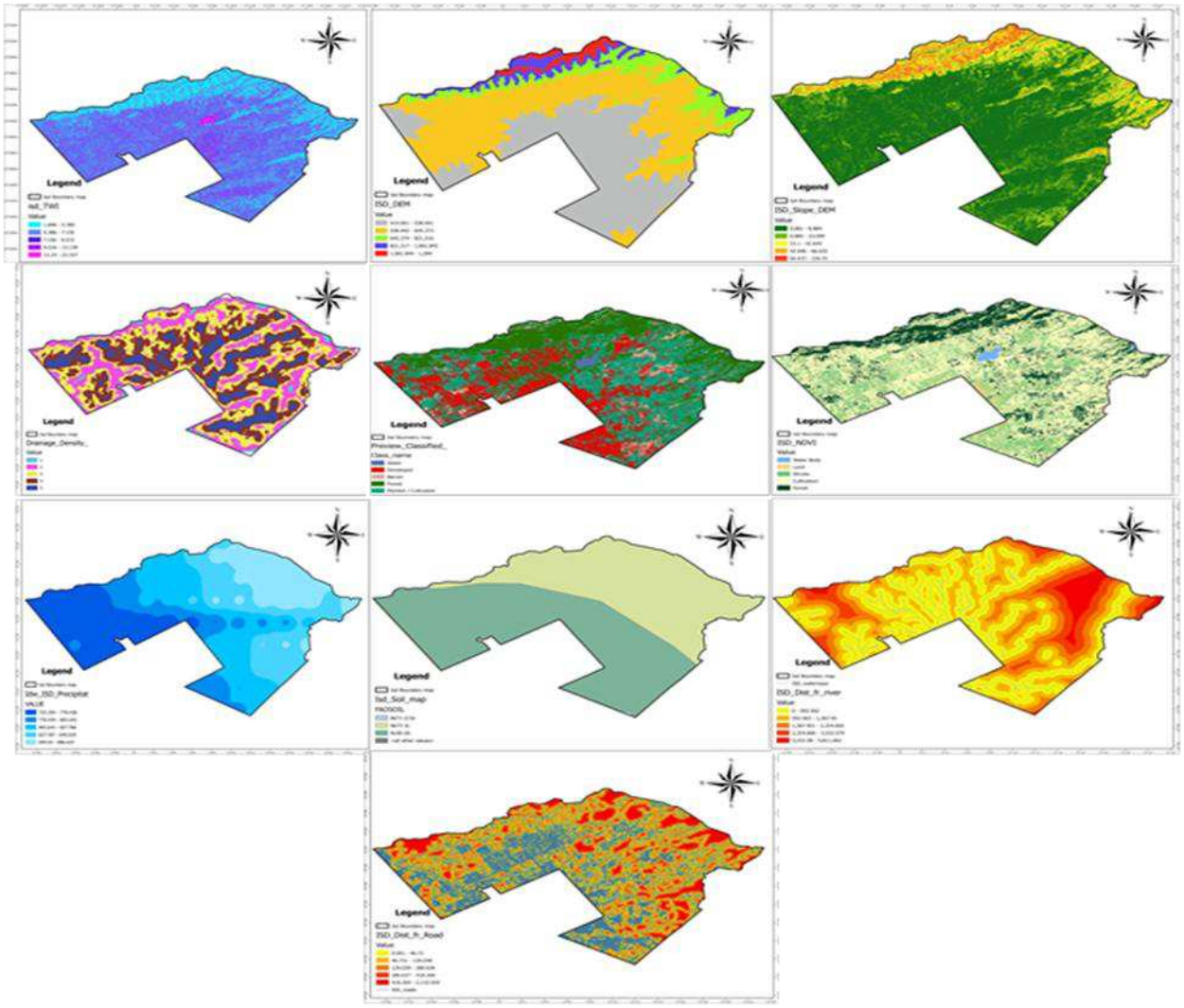


Fig. (3): Spatial distribution of flood conditioning factors (slope, elevation, drainage density, NDVI, soil, LULC, and precipitation) used in the multi-criteria analysis.

4. Results

4.1. Land Use and Land Cover (LULC) Dynamics (1990-2024)

Multi-temporal analysis revealed substantial and spatially uneven urban expansion across Islamabad between 1990 and 2024 (Fig. 4). Built-up areas increased from 12.4% to 29.1% (a 134% rise), largely replacing forest and agricultural lands. Forest

cover declined from 40.3% to 25.1%, while agricultural land decreased from 43.8% to 36.2%. Barren areas and water bodies showed minor fluctuations (<3%).

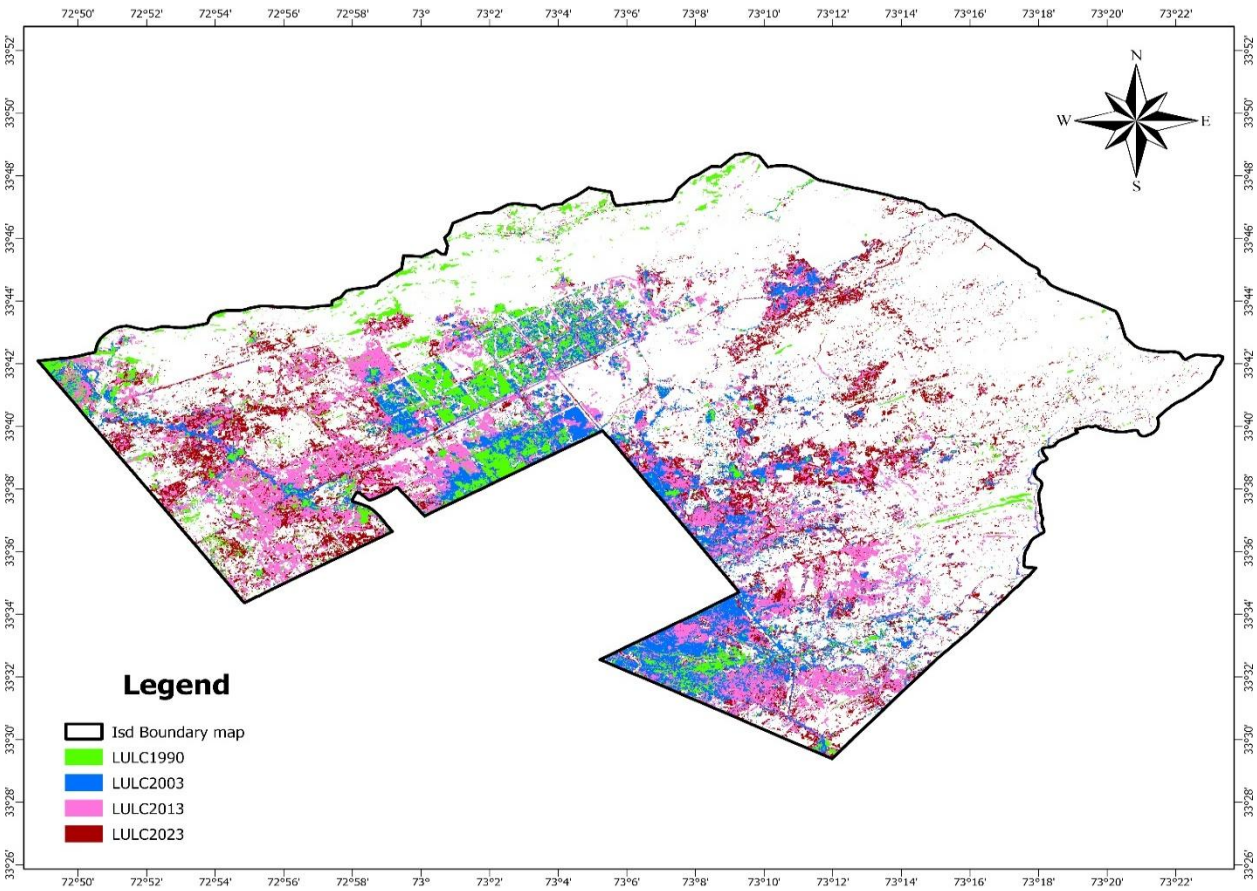


Fig. (4): Spatio-temporal land use/land cover (LULC) changes in Islamabad for the years 1990, 2003, 2013, and 2023.

Spatial metrics confirmed a marked reorganization of land use patterns. The centroid of urban growth shifted 3.2 km southwest from the central administrative sectors toward Zones IV and V, consistent with peri-urban sprawl. Moran's, I index for built-up areas rose from 0.41 (1990) to 0.67 (2024), indicating increasing spatial clustering of urban land. These changes reflect the dominance of unplanned residential development, commercial expansion, and road network densification.

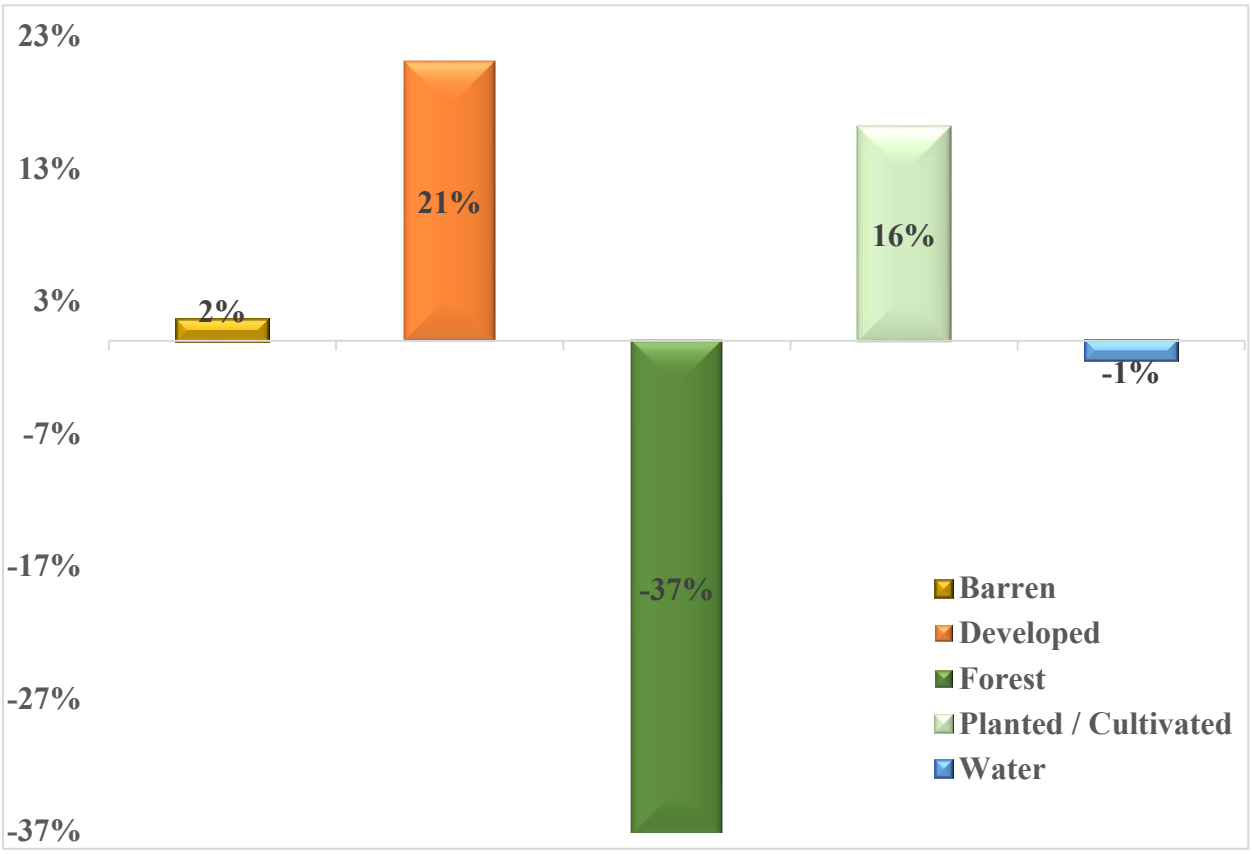


Fig. (5): Percentage change in major land use/land cover (LULC) classes in Islamabad between 1990 and 2023.

4.2. Flood Susceptibility under Baseline Conditions (Scenario 1)

The baseline flood susceptibility model classified Islamabad into five risk categories: very low (6.8%), low (12.1%), moderate (44.5%), high (28.4%), and very high (8.2%) (Fig. 6,7). High-risk zones concentrated along the Soan River, Korang Stream, and low-lying areas of Bhara Kahu and Chak Shahzad, where the terrain is characterized by shallow slopes and dense built-up development.

Approximately 73% of the total area lies within moderate to very high susceptibility zones, consistent with historical flood event locations (2001, 2010). Population overlays indicate that 29% of residents live in high or very high-risk areas. Spatial

autocorrelation analysis (Global Moran's I = 0.62) confirmed strong clustering of flood-prone zones along drainage corridors.

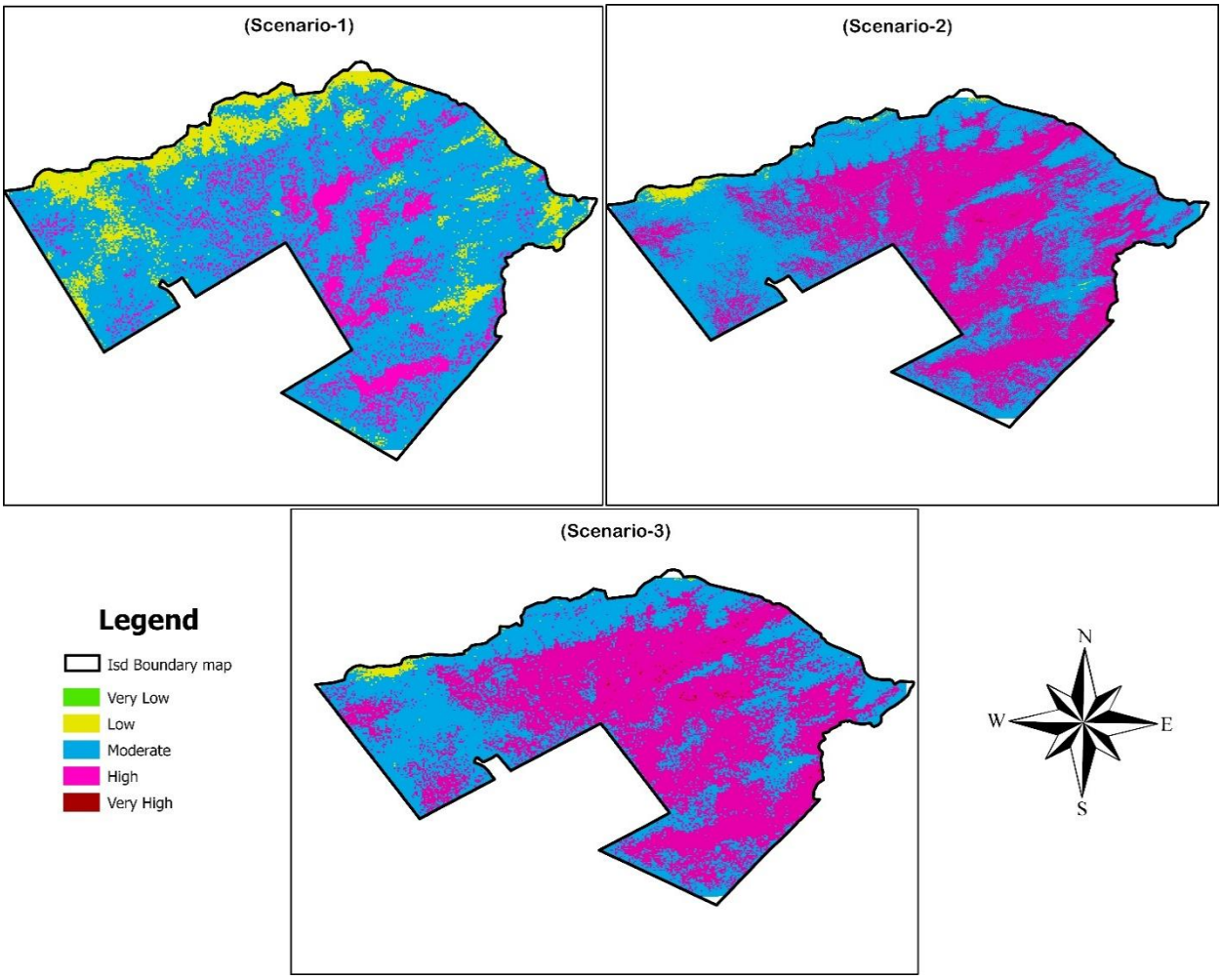


Fig. (6): Flood susceptibility map under baseline conditions (Scenario-1), climate change scenario (Scenario-2) and urban sprawl scenario (Scenario-3)

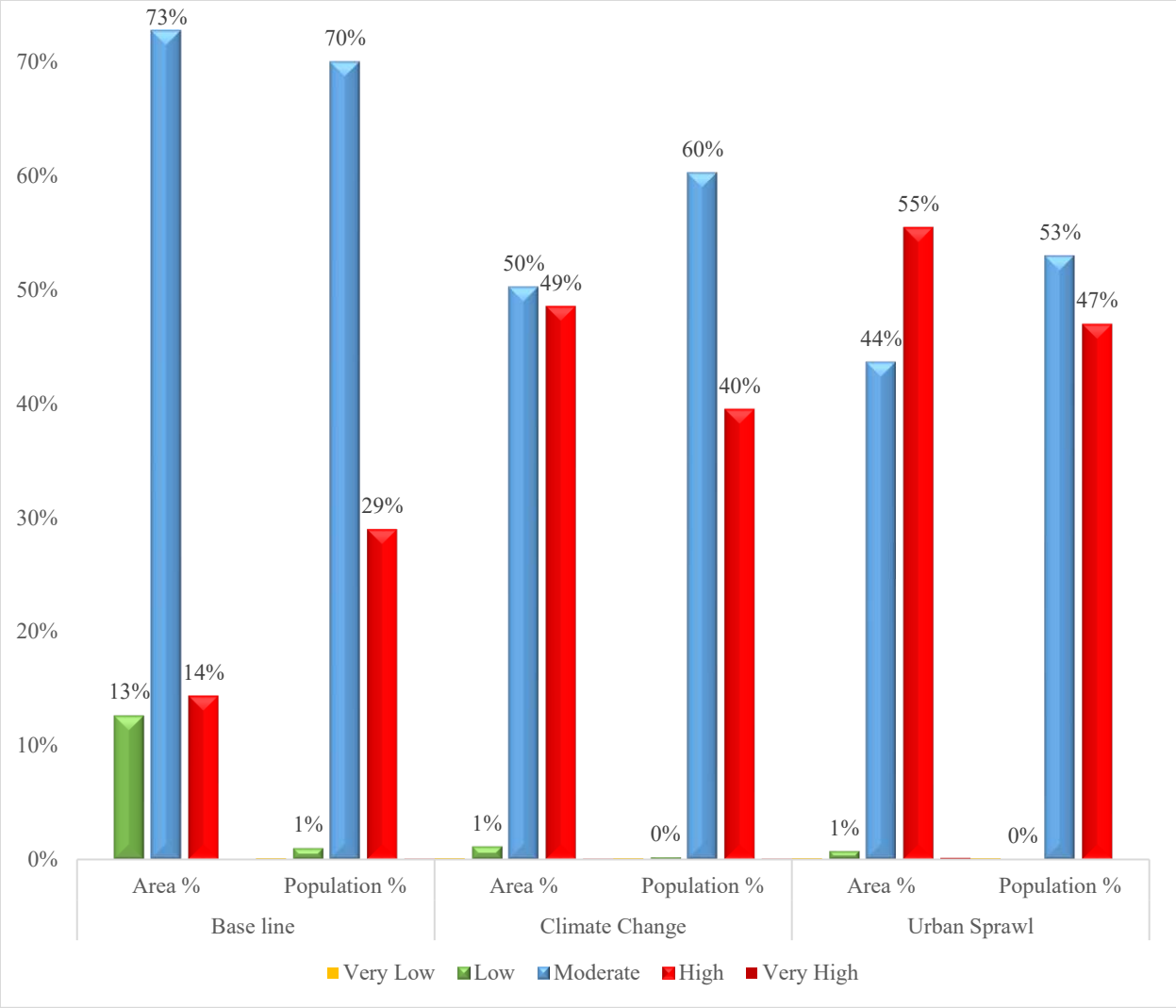


Fig. (7): Area & population % susceptible to flood under baseline, Climate Change and Urban Sprawl

4.3. Climate Change Scenario (Scenario 2)

When precipitation intensity was increased by 30% approximating the magnitude of the 2021 extreme rainfall event the area under high and very high flood susceptibility increased by approximately 35% compared to the baseline (Fig. 6,7). The most pronounced expansion occurred in the southeastern and central urban corridors, where impervious surface concentration exceeded 60%.

The AUC value of 0.85 confirmed strong model performance in reproducing historical inundation patterns. Spatial analysis revealed a northward shift in the centroid of high-risk zones, suggesting that precipitation-induced runoff redistribution may alter future flood pathways. The Local Moran's I analysis indicated emerging clusters of high susceptibility (HH) in developing housing sectors, confirming vulnerability escalation linked to inadequate stormwater infrastructure.

4.4. Urban Sprawl Scenario (Scenario 3, 2030 Projection)

The Land Change Modeler (LCM) projected a 32.2% built-up area by 2030, primarily encroaching on agricultural and forested zones. When integrated with AHP-based flood weighting, this scenario produced a 41% increase in high-category flood-prone zones relative to baseline conditions (Fig. 6,7).

This expansion surpassed the impact of the climate change scenario, indicating that rapid land transformation is the dominant driver of flood susceptibility. Spatial centroid analysis showed a continued southward shift of urban flood risk zones toward planned but low-lying residential developments in Zone V. Approximately 47% of the projected population and a majority of primary and secondary road networks fall within moderate to high-risk classes by 2030.

4.5. Comparative Scenario Analysis

Comparative evaluation across the three modeled scenarios baseline (current), climate change (30% excess rainfall), and projected urban sprawl (2030) reveals a progressive intensification of flood susceptibility driven by both climatic and land use dynamics (Fig. 8).

Under current conditions, approximately 73% of Islamabad's area falls within the medium flood susceptibility class, while high and low categories account for 14% and 13%, respectively. This indicates that the city's existing hydrological system already exhibits moderate flood potential along riverine corridors and low-lying catchments.

When precipitation increases by 30%, the high-risk area expands sharply to 49%, accompanied by a reduction of medium-risk zones to 50%. This shift reflects the hydrological amplification effect of extreme rainfall events, where even modest intensification of precipitation can trigger substantial surface runoff and inundation.

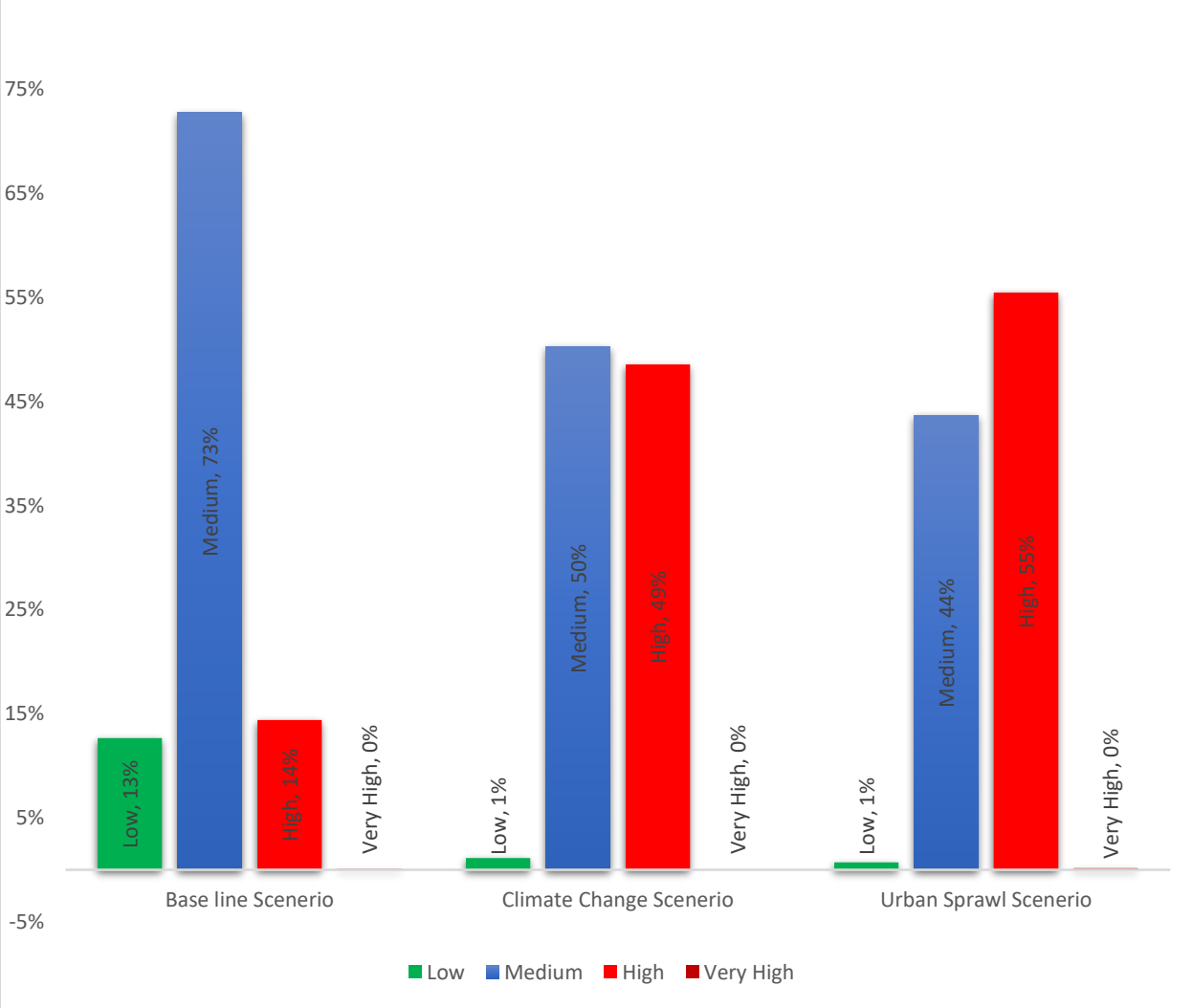


Fig. (8): Comparative distribution of flood susceptibility area percentages under baseline (current), climate change (30% excess rainfall), and projected urban sprawl (2030) scenarios.

Under the urban sprawl projection for 2030, high flood susceptibility reaches 55%, while medium zones decline to 44%. The persistence of low-risk areas (≈1%) across all scenarios suggests that ongoing urbanization predominantly reclassifies existing moderate-risk regions into higher susceptibility categories rather than expanding into safer terrain.

Overall, the results demonstrate a systematic spatial transition from medium to high flood risk across successive scenarios, underscoring the compounded effects of impervious surface expansion and climate intensification. These findings highlight the need for integrated land-use regulation, sustainable drainage design, and flood-resilient spatial planning in Islamabad's future urban policy framework.

5. Discussion

5.1. Mechanistic Link Between Urbanization and Flood Susceptibility

The results of this study reveal a clear mechanistic relationship between unplanned urban expansion and elevated flood susceptibility in Islamabad. The progressive conversion of forests and agricultural lands into impervious built-up surfaces has substantially modified the city's hydrological response. Between 1990 and 2024, built-up area expanded from 12.4% to 29.1% (a 134% increase), while forest cover and agricultural land declined from 40.3% to 25.1% and from 43.8% to 36.2%, respectively.

This transformation has produced an estimated 20-25% rise in surface runoff potential, accompanied by reduced infiltration and evapotranspiration rates consistent with hydrological responses to urbanization observed elsewhere (Sanyal and Lu, 2009, Howarth et al., 2018). The resulting increase in peak discharge and reduction in concentration time reflect urban-induced acceleration of surface flow (Siddik et al., 2022).

Consequently, flood-prone zones have expanded outward from the Soan River corridor into peri-urban residential sectors particularly in Zones IV and V indicating both spatial and functional reconfiguration of the drainage system. This trend mirrors urban hydrological transitions documented in Dhaka (Siddik et al., 2022) Jakarta (Abidin et al., 2015), and Istanbul (ÖZer and YalÇIner ErcoŞKun, 2024), where rapid urban expansion has intensified flood exposure despite moderate precipitation increases.

5.2. Comparative Impact of Urbanization and Climatic Variability

Scenario-based modeling further clarifies the comparative influence of anthropogenic versus climatic drivers. Under the climate change scenario (Scenario 2), a 30% increase in precipitation expanded high flood susceptibility zones by 35%, while the projected 2030 urban sprawl scenario (Scenario 3) produced a 41% increase in high-risk areas. This contrast demonstrates that land-use transformation exerts a stronger influence on flood hazard than short-term rainfall intensification a pattern also noted in comparable urban basins in Bangkok and Manila (Sawangnate et al., 2022, Gacu et al., 2022).

The finding underscores that managing urban form and density through spatial planning can yield more immediate and sustainable flood mitigation outcomes than reactive engineering measures alone (Hussain et al., 2021) In

Islamabad's context, flood vulnerability is therefore not merely a function of rainfall extremes but of cumulative land-use decisions that reshape hydrological behavior over time.

5.3. Methodological Advancements of the RS–GIS–AHP–LCM Framework

Methodologically, the integration of Analytic Hierarchy Process (AHP) and Land Change Modeler (LCM) within a GIS environment represents a significant advancement in spatial flood risk modeling. The AHP facilitated a systematic, transparent weighting of flood-inducing parameters slope, drainage density, soil permeability, rainfall intensity, and land use based on expert judgment and pairwise consistency analysis (Saaty, 1987)). The LCM, employing Markovian transition probability matrices derived from historical LULC data (1990-2023), simulated the temporal dynamics of urban growth and projected the 2030 land-use pattern (Aydın and Durduran, 2024).

The integration of AHP-based susceptibility mapping with LCM-derived land-use projections produced a dynamic, process-based model capable of capturing evolving flood exposure rather than static hazard representation (Nsangou et al., 2022, Selvam and Antony Jebamalai, 2023). Validation using SAR-derived inundation maps and observed flood records yielded high predictive accuracy (AUC = 0.82-0.85; Kappa = 0.79), confirming the robustness of the RS-GIS-AHP-LCM coupling (Sanyal and Lu, 2009).

5.4. Methodological Limitations and Future Refinements

Nonetheless, several methodological constraints warrant acknowledgment. The use of 30 m spatial resolution data may limit detection of fine-scale drainage patterns, especially within highly urbanized zones. The AHP's reliance on

subjective expert evaluation introduces potential bias in factor weighting, while the LCM's assumption of stationary transition probabilities simplifies nonlinear feedbacks between urban growth, drainage modification, and policy shifts.

Future refinements should integrate higher-resolution data sources such as LiDAR-based DEMs and multispectral imagery and couple them with hydrodynamic flood routing models (e.g., HEC-RAS 2D, LISFLOOD-FP) to improve spatial realism and flow connectivity (Sharifian et al., 2022). Similarly, incorporating socio-economic and infrastructural variables can enhance the modeling of exposure and adaptive capacity at household or neighborhood scales (Teng et al., 2017).

5.5. International Comparisons and Model Transferability

Comparative international applications further substantiate the methodological reliability of the integrated framework. Studies employing AHP–Markov coupling in Kathmandu, Nepal (Rimal et al., 2018) and MCE-CA-Markov models in Bangkok (Sawangnate et al., 2022) report similar predictive accuracies, emphasizing the value of dynamic LULC simulation in flood hazard analysis.

However, model transferability depends on local calibration of transition probabilities and weighting hierarchies, as urban morphology, governance capacity, and rainfall regimes vary significantly across contexts. Islamabad's case thus contributes a valuable South Asian benchmark, illustrating how unregulated sprawl, weak spatial regulation, and climate uncertainty converge to amplify flood risks in data-scarce urban regions.

5.6. Policy Implications and Planning Applications

From a policy perspective, the projected 41% escalation in high-risk flood zones by 2030 underscores the urgency of embedding resilience-oriented governance in urban planning. Priority actions include enforcing floodplain zoning, preserving riparian buffers, promoting green infrastructure (bioswales, retention ponds, permeable pavements), and upgrading stormwater drainage systems (UNDRR, 2023).

The integration of predictive geospatial analytics into planning workflows can enable cities to transition from reactive response to proactive adaptation. Consequently, the RS-GIS-AHP-LCM framework offers a scalable, evidence-based decision-support tool for sustainable land-use management and climate-resilient city planning.

6. Conclusion

This study establishes that unplanned urban expansion has been the dominant driver of flood susceptibility in Islamabad, exerting a stronger influence than climate-induced rainfall intensification. Land conversion from vegetated and agricultural areas to impervious urban surfaces has significantly heightened hydrological vulnerability over the past three decades. Projections indicate that by 2030, urban sprawl could expand high-risk flood zones by about 41%, compared to a 35% increase under intensified precipitation, highlighting the centrality of land use dynamics in flood hazard amplification.

By integrating Remote Sensing, GIS, Analytical Hierarchy Process (AHP), and Land Change Modeling (LCM), the research developed a robust and dynamic framework for spatially explicit flood risk assessment. The coupling of predictive

land-use change simulation with multi-criteria spatial analysis achieved high accuracy (AUC = 0.86; Kappa = 0.79), representing a methodological advancement for data-scarce and rapidly urbanizing regions. This integrative approach offers a scalable and transferable model for evaluating future flood vulnerability under combined urbanization and climate scenarios.

The findings underscore the urgency of integrating predictive geospatial analytics into urban planning to mitigate flood risk. Proactive measures such as floodplain zoning, green infrastructure development, and upgraded drainage systems provide cost-effective, sustainable solutions for climate-resilient urban growth. Future research should explore the incorporation of socio-economic and hydrodynamic parameters into spatial simulations to refine predictive capability and support anticipatory, resilience-oriented urban governance.

Declaration of Generative AI and AI-Assisted Technologies in the Manuscript Preparation Process

During the preparation of this work, the author has used ChatGPT (OpenAI, GPT-5 model) to assist in language refinement, improvement of academic tone, and structural organization of the manuscript. The tool was not used to generate or alter research data, analyses, results, or scientific interpretations. After using this AI-assisted service, the author thoroughly reviewed, edited, and validated all content to ensure accuracy, originality, and adherence to ethical publication standards. The author(s) take full responsibility for the integrity and content of the final manuscript.

7. References

1. ABIDIN, H. Z., ANDREAS, H., GUMILAR, I. & BRINKMAN, J. J. 2015. Study on the risk and impacts of land subsidence in Jakarta. *Proceedings of the International Association of Hydrological Sciences,* 372**,** 115-120.
2. ALRIFAI, M., KAFY, A. A. & ALTUWAIJRI, H. 2025. Quantitative Assessment of Flood Risk Through Multi Parameter Morphometric Analysis and GeoAI: A GIS-Based Study of

Wadi Ranuna Basin in Saudi Arabia. *Water,* 17**,** 2108.
3. AYDıN, T. K. & DURDURAN, S. S. 2024. Determining future scenarios of urban areas with cellular automata/Markov Chain Model method; example of Ereğli District Konya-Türkiye (2030–2040). *Earth Science Informatics,* 17**,** 2679-2697.
4. BARROS, J. L., TAVARES, A. O. & SANTOS, P. P. 2021. Land use and land cover dynamics in Leiria City: relation between peri-urbanization processes and hydro-geomorphologic disasters. *Natural Hazards,* 106**,** 757-784.
5. BOUCHER, M. R. Z. 2020. *Geospatial Analysis of Flooding in the Cypress Creek Watershed Due to Urban Sprawl*.
6. BRÁZDIL, R., KUNDZEWICZ, Z. W. & BENITO, G. 2010. Historical hydrology for studying flood risk in Europe. *Hydrological Sciences Journal,* 51**,** 739-764.
7. CHETTRY, V. 2022. Monitoring and Characterizing Urban Sprawl in Raipur Urban Agglomeration, India from 2005 to 2015 using Geospatial Techniques. *IOP Conference Series: Earth and Environmental Science,* 1019.
8. GACU, J. G., MONJARDIN, C. E. F., SENORO, D. B. & TAN, F. J. 2022. Flood Risk Assessment Using GIS-Based Analytical Hierarchy Process in the Municipality of Odiongan, Romblon, Philippines. *Applied Sciences,* 12.
9. GHOSH, A. & KAR, S. K. 2018. Application of analytical hierarchy process (AHP) for flood risk assessment: a case study in Malda district of West Bengal, India. *Natural Hazards,* 94**,** 349-368.
10. GIGOVIĆ, L., PAMUČAR, D., BAJIĆ, Z. & DROBNJAK, S. 2017. Application of GIS-Interval Rough AHP Methodology for Flood Hazard Mapping in Urban Areas. *Water,* 9.
11. HAIDER, F. 2022. *Detection of Land Use/Land Cover changes (LULC) and Urban Sprawl in Islamabad, Pakistan: an analysis of multi-temporal Remote Sensing data.* M. Phil, Pakistan Institute of Development Economics.
12. HASSAN, Z., SHABBIR, R., AHMAD, S. S., MALIK, A. H., AZIZ, N., BUTT, A. & ERUM, S. 2016. Dynamics of land use and land cover change (LULCC) using geospatial techniques: a case study of Islamabad Pakistan. *Springerplus,* 5**,** 812.
13. HONG, H., PANAHI, M., SHIRZADI, A., MA, T., LIU, J., ZHU, A. X., CHEN, W., KOUGIAS, I. & KAZAKIS, N. 2018. Flood susceptibility assessment in Hengfeng area coupling adaptive neuro-fuzzy inference system with genetic algorithm and differential evolution. *Sci Total Environ,* 621**,** 1124-1141.
14. HOWARTH, C., MORSE-JONES, S., BROOKS, K. & KYTHREOTIS, A. P. 2018. Co-producing UK climate change adaptation policy: An analysis of the 2012 and 2017 UK Climate Change Risk Assessments. *Environmental Science & Policy,* 89**,** 412-420.
15. HUSSAIN, M., TAYYAB, M., ZHANG, J., SHAH, A. A., ULLAH, K., MEHMOOD, U. & AL-SHAIBAH, B. 2021. GIS-Based Multi-Criteria Approach for Flood Vulnerability Assessment and Mapping in District Shangla: Khyber Pakhtunkhwa, Pakistan. *Sustainability,* 13.
16. IPCC 2022. Climate Change 2022;Mitigation of Climate Change. Sixth Assessment Report ed.
17. KAMRAN, KHAN, J. A., KHAYYAM, U., WAHEED, A. & KHOKHAR, M. F. 2023. Exploring the nexus between land use land cover (LULC) changes and population growth in a planned city of islamabad and unplanned city of Rawalpindi, Pakistan. *Heliyon,* 9**,** e13297.
18. LI, L., XIE, G., DONG, P., TANG, H., WU, L. & ZHANG, L. 2024. Anticyanobacterial effect of p-coumaric acid on Limnothrix sp. determined by proteomic and metabolomic

analysis. *Science of The Total Environment,* 926**,** 171632.
19. LI, X., HOU, J., PAN, Z., LI, B., JING, J. & SHEN, J. 2022. Responses of urban flood processes to local land use using a high-resolution numeric model. *Urban Climate,* 45.
20. MANNAN, A., YONGXIANG, F., KHAN, T. U., NIZAMI, S. M., MUKETE, B., AHMAD, A., AMARA, U., LIU, J. & WALI MUHAMMAD, M. 2021. Urban Growth Patterns and Forest Carbon Dynamics in the Metropolitan Twin Cities of Islamabad and Rawalpindi, Pakistan. *Sustainability,* 13.
21. MEHTA, T., GHOSHAL, S., MAHAJAN, Y., SHARMA, M. & NEHA, K. 2023. Analysis of patterns of urban sprawl and surface urban heat island in solan town of himachal pradesh using remote sensing and gis. *IOP Conference Series: Earth and Environmental Science,* 1110.
22. NDMA 2023. National Summer Emergencies Plan - 2023.
23. NSANGOU, D., KPOUMIÉ, A., MFONKA, Z., NGOUH, A. N., FOSSI, D. H., JOURDAN, C., MBELE, H. Z., MOUNCHEROU, O. F., VANDERVAERE, J.-P. & NDAM NGOUPAYOU, J. R. 2022. Urban flood susceptibility modelling using AHP and GIS approach: case of the Mfoundi watershed at Yaoundé in the South-Cameroon plateau. *Scientific African,* 15.
24. OCHA 2022. OCHA ANNUAL REPORT 2022.
25. ÖZER, B. & YALÇINER ERCOŞKUN, Ö. 2024. Integration of RS and GIS in assessing flood risk: A Case Study on Istanbul - Esenyurt. *Journal of Contemporary Urban Affairs,* 8**,** 57-78.
26. PMD 2023. State of Pakistan Climate in 2023.
27. RAHMATI, O., POURGHASEMI, H. & ZEINIVAND, H. 2015. Flood susceptibility mapping using frequency ratio and weights-of-evidence models in the Golestan Province, Iran. *Geocarto International,* 31.
28. RIMAL, B., ZHANG, L., KESHTKAR, H., HAACK, B., RIJAL, S. & ZHANG, P. 2018. Land Use/Land Cover Dynamics and Modeling of Urban Land Expansion by the Integration of Cellular Automata and Markov Chain. *ISPRS International Journal of Geo-Information,* 7.
29. SAATY, R. W. 1987. The analytic hierarchy process, what it is and how it is used. *Pergamon Journals Ltd,* Mat/d Modelling, Vol. 9, No. 3-5, pp. 161-176, 1987.
30. SANYAL, J. & LU, X. X. 2009. Ideal location for flood shelter: A geographic information system approach. *Journal of Flood Risk Management,* 2**,** 262-271.
31. SAWANGNATE, C., CHAISRI, B. & KITTIPONGVISES, S. 2022. Flood Hazard Mapping and Flood Preparedness Literacy of the Elderly Population Residing in Bangkok, Thailand. *Water,* 14.
32. SELVAM, R. A. & ANTONY JEBAMALAI, A. R. 2023. Application of the analytical hierarchy process (AHP) for flood susceptibility mapping using GIS techniques in Thamirabarani river basin, Srivaikundam region, Southern India. *Natural Hazards,* 118**,** 1065-1083.
33. SHARIFIAN, M. K., KESSERWANI, G., CHOWDHURY, A. A., NEAL, J. & BATES, P. 2022. LISFLOOD-FP 8.1: New GPU accelerated solvers for faster fluvial/pluvial flood simulations. *Geospatial model development*.
34. SHI, Y., ZHOU, L., GUO, X. & LI, J. 2023. The Multidimensional Measurement Method of Urban Sprawl and Its Empirical Analysis in Shanghai Metropolitan Area. *Sustainability,* 15.
35. SIDDIK, M. S., TULIP, S. S., RAHMAN, A., ISLAM, M. N., HAGHIGHI, A. T. &

MUSTAFA, S. M. T. 2022. The impact of land use and land cover change on groundwater recharge in northwestern Bangladesh. *J Environ Manage,* 315**,** 115130.
36. SKILODIMOU, H. D., BATHRELLOS, G. D. & ALEXAKIS, D. E. 2021. Flood Hazard Assessment Mapping in Burned and Urban Areas. *Sustainability,* 13.
37. STAMELLOU, E., KALOGEROPOULOS, K., STATHOPOULOS, N., TSESMELIS, D. E., LOUKA, P., APOSTOLIDIS, V. & TSATSARIS, A. 2021. A GIS-Cellular Automata-Based Model for Coupling Urban Sprawl and Flood Susceptibility Assessment. *Hydrology,* 8.
38. TAGG, A. S., BRANDES, E., FISCHER, F., FISCHER, D., BRANDT, J. & LABRENZ, M. 2022. Agricultural application of microplastic-rich sewage sludge leads to further uncontrolled contamination. *Science of The Total Environment,* 806**,** 150611.
39. TENG, J., JAKEMAN, A. J., VAZE, J., CROKE, B. F. W., DUTTA, D. & KIM, S. 2017. Flood inundation modelling: A review of methods, recent advances and uncertainty analysis. *Environmental Modelling & Software,* 90**,** 201-216.
40. THERES, L., RADHAKRISHNAN, S. & RAHMAN, A. 2023. Simulating Urban Growth Using the Cellular Automata Markov Chain Model in the Context of Spatiotemporal Influences for Salem and Its Peripherals, India. *Earth,* 4**,** 296-314.
41. UNDRR 2023. GAR Special Report 2023; Mapping Resilience for the Sustainable Development Goals. Cambridge: Cambridge University Press.
42. WAHAB, Z., WAHAB, A., FARAH, H., WAHEED, A. & SAHBENI, G. 2023. Examination of spatio-temporal urbanization patterns in Islamabad Metropolis, Pakistan, over past four decades: a remote sensing–based approach. *Arabian Journal of Geosciences,* 16.
43. WAHL, T., JAIN, S., BENDER, J., MEYERS, S. & LUTHER, M. 2015. Increasing risk of compound flooding from storm surge and rainfall for major US cities. *Nature Climate Change,* 5.
44. XU, T., ZHOU, D. & LI, Y. 2022. Integrating ANNs and Cellular Automata–Markov Chain to Simulate Urban Expansion with Annual Land Use Data. *Land,* 11.
45. ZHRAN, M., GHANEM, K., TARIQ, A., ALSHEHRI, F., JIN, S., DAS, J., PANDE, C. B., PRAMANIK, M., HASHER, F. F. B. & MOUSA, A. 2024. Exploring a GIS-based analytic hierarchy process for spatial flood risk assessment in Egypt: a case study of the Damietta branch. *Environmental Sciences Europe,* 36.

Appendix A: Flood causative factors, classification ranges, susceptibility ratings, and assigned weights used in the AHP model

No	Flood Causative Criterion	Unit	Class	Susceptibility Class Range	Susceptibility Rating	Weight (%)
1	**Topographic Wetness Index (TWI)**	Level	Very Low	1.846 - 5.385	1	**14**
			Low	5.386 - 7.155	2	
			Moderate	7.156 - 9.515	3	
			High	9.516 - 13.139	4	
			Very High	13.140 - 23.337	5	
2	**Elevation**	m	Very High	414.001 - 538.941	5	**12**
			High	538.942 - 645.373	4	
			Moderate	645.374 - 821.216	3	
			Low	821.217 - 1,061.843	2	
			Very Low	1,061.844 - 1,594	1	
3	**Slope**	%	Very High	0.001 - 8.884	5	**10**
			High	8.885 - 23.099	4	
			Moderate	23.100 - 42.645	3	
			Low	42.646 - 66.632	2	
			Very Low	66.633 - 226.550	1	
4	**Precipitation**	mm/ year	Very Low	725.294 - 778.438	1	**14**
			Low	778.439 - 805.642	2	
			Moderate	805.643 - 827.786	3	
			High	827.787 - 849.929	4	
			Very High	849.930 - 886.624	5	
5	**Land Use/Land Cover (LULC)**	Level	Water	Very High	5	**7**
			Planted/ Cultivated	High	4	
			Developed	Moderate	3	
			Barren	Low	2	
			Forest	Very Low	1	
6	**Normalized Difference Vegetation Index (NDVI)**	Level	Very High	-0.1890 - -0.0003	5	**6**
			High	-0.0003 - 0.049	4	
			Moderate	0.049 - 0.104	3	
			Low	0.104 - 0.250	2	
			Very Low	0.250 - 0.505	1	
7	**Distance from River**	m	Very High	0 - 592.562	5	**14**
			High	592.563 - 1,367.450	4	
			Moderate	1,367.451 - 2,324.665	3	
			Low	2,324.666 - 3,532.579	2	
			Very Low	3,532.580 - 5,811.662	1	
8	**Distance from Road**	m	Very High	0.001 - 46.730	5	**6**
			High	46.731 - 129.038	4	

			Moderate	129.039 - 280.636	3	
			Low	280.637 - 418.268	2	
			Very Low	418.269 - 2,110.929	1	
9	**Drainage Density**	m/ km	Very Low	0.001 - 0.625	1	**9**
			Low	0.625 - 1.251	2	
			Moderate	1.251 - 1.876	3	
			High	1.876 - 2.501	4	
			Very High	2.502 - 3.126	5	
10	**Soil Type**	Level	Calcaric Regosols	Moderate	3	**9**
			Eutric Cambisols	High	4	
			Eutric Cambisols (variant)	Very High	5	