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2 **Flood Vulnerability Assessment of Sujawal Taluka, Sindh, Pa-** 3 **kistan: A GIS-Based Multi-Criteria Analysis Approach**

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9 **Abstract**

10 Flood vulnerability assessment is critical for disaster risk reduction in deltaic regions
11 prone to recurrent inundation. This study develops a spatially explicit flood vulnerability
12 map for Sujawal Taluka, Sindh Province, Pakistan, using an integrated approach combin-
13 ing the Analytical Hierarchy Process (AHP), Geographic Information Systems (GIS), and
14 remote sensing. Seven flood-conditioning factors (rainfall, distance to river, elevation,
15 slope, land use/land cover, NDVI, and population density) were systematically weighted
16 using AHP (Consistency Ratio = 0.0177) and integrated through raster-based multi-criteria
17 analysis. Results classified Sujawal into five vulnerability zones: Very Low (97.06 km²,
18 13.7%), Low (148.89 km², 20.9%), Moderate (177.21 km², 24.9%), High (216.44 km², 30.5%),
19 and Very High (71.02 km², 10.0%). Validation against 809,863 historical flood events con-
20 firmed model accuracy, with 40.45% of floods occurring in the High and Very High zones
21 (collectively 40.5% of area). Population exposure analysis revealed 71,544 persons
22 (36.05%) reside in high-risk zones. These findings provide an evidence-based roadmap for
23 prioritizing flood mitigation investments, emergency response planning, and land-use
24 regulation in this vulnerable Indus Delta region.

25 **Keywords:** flood vulnerability; AHP; GIS; remote sensing; Sujawal; Indus Delta; multi-
26 criteria analysis; disaster risk reduction

28 **1. Introduction**

29 The enduring challenge of natural disasters, such as floods, landslides, and cyclones,
30 has shaped human civilization since its inception [1]. Over the past few decades, the fre-
31 quency and intensity of flood events have increased globally, largely driven by climatic
32 variability, escalating anthropogenic pressures, and rapid land-use changes [2] [3]. Flood
33 risk is a complex function where physical drivers (e.g., topography, hydrology, rainfall)
34 interact with socio-economic factors, collectively amplifying both flood exposure and vul-
35 nerability [4] [5]. Among all natural hazards, floods remain the most recurrent and de-
36 structive hydro-meteorological phenomenon, inflicting large-scale damages to human
37 life, agriculture, and critical infrastructure [6] [7]. Globally, floods account for approxi-
38 mately 47% of all recorded weather-related disasters each year [8], making their effective
39 management paramount for human settlements and sustainable development.

41 The impacts of flooding are particularly pronounced in South Asia, where intense
42 monsoon rainfall, low-lying river basins, and inadequate drainage infrastructure exacer-
43 bate flood risks. In Pakistan, floods have become increasingly frequent and severe, espe-
44 cially in the Sindh province, which lies in the lower Indus Basin and is exposed to both
45 riverine and coastal flooding. Historical events, such as the devastating floods of 2010 and
46 2022, have caused unprecedented destruction in Sindh, displacing millions and severely
47 damaging agricultural lands, roads, and housing infrastructure [9] [10]. The 2022 event,
48 in particular, was driven by multiday extreme rainfall on already saturated antecedent
49 conditions, underscoring the growing threat of climate extremes [10].

51 Sujawal Taluka, located in southern Sindh along the Indus River and the Arabian
52 Sea, is identified as one of the most vulnerable regions due to its flat terrain, low elevation,
53 and high population density. The taluka's geomorphology and hydrological setup make
54 it highly susceptible to both riverine overflow and storm surge flooding during monsoon
55 periods. Furthermore, rapid urbanization, the conversion of agricultural land, and the
56 degradation of natural wetlands have collectively reduced natural infiltration capacity
57 and increased runoff potential. Climate change projections indicate that future flood haz-
58 ards in coastal Sindh may intensify significantly under scenarios of increased precipitation
59 variability and sea-level rise.

61 Accurate and spatially explicit mapping of flood-prone zones is, therefore, essential
62 for effective mitigation planning. Traditional flood assessments, which often rely solely
63 on hydrological or statistical models, frequently lack the spatial detail required for local-
64 level planning and fail to integrate the full spectrum of contributing factors. In contrast,
65 the integration of Geographic Information System (GIS) and Remote Sensing (RS) tech-
66 niques with Multi-Criteria Decision Analysis (MCDA) frameworks, such as the Analytical
67 Hierarchy Process (AHP) developed by Saaty [11], has proven to be a robust and effective
68 approach for flood susceptibility mapping [12] [13]. The AHP method allows for the sys-
69 tematic weighting and ranking of multiple flood-inducing parameters based on their rel-
70 ative importance and expert judgment [14] [15].

72 Numerous studies have successfully employed GIS-based AHP models to assess
73 flood vulnerability in diverse environments, including river basins in India, urban catch-
74 ments in Bangladesh, and floodplains in Iraq and Ethiopia [3] [7]. Within Pakistan, similar
75 approaches have been applied in Larkana, Hunza-Nagar, and Karak District, demonstat-
76 ing the adaptability of GIS-AHP methods to various topographic, climatic, and socio-eco-
77 nomic settings [9].

79 The present study aims to apply a GIS-based Multi-Criteria Analysis to identify and
80 delineate flood vulnerability zones in Sujawal Taluka, Sindh, Pakistan. The analysis incor-
81 porates seven flood conditioning parameters: slope, elevation, distance to river, rainfall,
82 land use/land cover (LULC), Normalized Difference Vegetation Index (NDVI), and pop-
83 ulation density. These parameters reflect both the physical dimensions of flood suscepti-
84 bility (hazard) and the socio-economic dimension of exposure. By integrating these pa-
85 rameters into a geospatial decision-support system, this study develops a flood vulnera-
86 bility model for Sujawal Taluka, classifying the region into very low, low, moderate, high,
87 and very high flood risk zones. The findings are intended to provide a critical, evidence-
88 based roadmap for local disaster management authorities and urban planners in priori-
89 tizing areas for infrastructure resilience, emergency response, and sustainable land-use
90 planning in coastal Sindh.

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2. Materials and Methods

The study area is Sujawal Taluka, located in Sujawal District, Sindh Province, Pakistan .

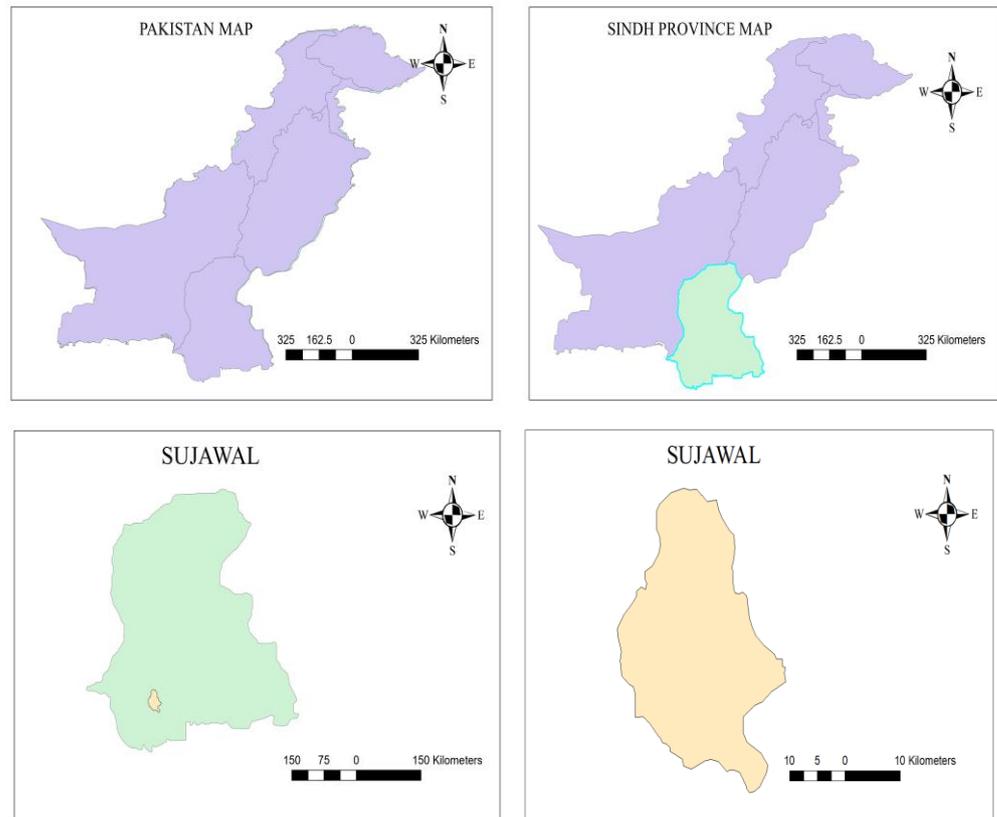


Figure 1. Location map showing Sujawal Taluka in Sindh Province, Pakistan.

The taluka covers approximately 710 km² of low-lying deltaic terrain characterized by extensive river networks and seasonal inundation from monsoon rainfall and riverine flooding. Sujawal Taluka is bounded by coordinates 24°30'N to 24°50'N latitude and 68°0'E to 68°10'E longitude. The region experiences a semi-arid climate with mean annual temperatures ranging from 21°C to 35°C. Monsoon rainfall (June–September) delivers 186–262 mm annually, exhibiting high spatial variability.

The taluka's topography is predominantly flat, with elevations ranging from near sea level (<5 m) to approximately 13 m above mean sea level. The Indus River distributary system traverses the taluka, creating a dense network of natural and artificial channels. Land use is dominated by agriculture (68% of area), with smaller proportions of built-up areas, water bodies, and sparse vegetation. The population of Sujawal Taluka is approximately 198,587 according to the 2017 census, concentrated in rural agricultural settlements and peri-urban centers.

2.1. Data Sources and Acquisition

Seven flood-conditioning criteria were selected based on hydrological relevance, data availability, and consistency with established flood vulnerability frameworks. All datasets were sourced from publicly available global and regional repositories. Spatial data preprocessing was conducted in ArcGIS 10.8, with all layers projected to WGS 1984 UTM Zone 42N and resampled to 30 m spatial resolution.

Table 1. Datasets Used in the Study:

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Table 1. This is a table. Tables should be placed in the main text near to the first time they are cited.

Dataset	Description/Derivation	Spatial Resolution/Scale	Source
Digital Elevation Model (DEM)	Shuttle Radar Topography Mission (SRTM) DEM used as the primary topographic input	30 m	USGS Earth Explorer
Elevation	Extracted directly from the DEM	30 m	USGS (SRTM DEM)
Slope	Derived from DEM using spatial analyst tools	30 m	USGS (SRTM DEM)
Rainfall	Gridded precipitation data used to generate mean annual rainfall surface	Coarse resolution (resampled to 30 m for analysis)	Climate Hazards Center (CHC), University of California, Santa Barbara (chc.ucsb.edu)
Distance to River	Euclidean distance raster generated from river network	30 m	HydroSHEDS (data.hydrosheds.org)
Land Use/Land Cover (LULC)	ESA WorldCover global land cover classification	10 m (resampled to 30 m)	ESA WorldCover (esaworldcover.org)
NDVI	Normalized Difference Vegetation Index calculated from Sentinel-2 imagery	10 m (resampled to 30 m)	Copernicus Sentinel-2
Population Density	Gridded population density data (persons/km ²)	Resampled to 30 m	WorldPop (data.worldpop.org)
Flood History	Historical flood occurrence data used for model validation	~250 m	Global Flood Database (MODIS), Google Earth Engine
Taluka Boundary	Administrative boundary of the study area	Vector	Humanitarian Data Exchange (HDX)

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2.2. Analytical Hierarchy Process (AHP)

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The AHP method systematically quantifies expert judgments through pairwise comparisons [11]. Seven flood-conditioning factors were ranked based on hydrological theory and

127 literature review: Rainfall > Distance to River > Elevation > Slope > LULC > NDVI > Pop-
 128 ulation Density. A 7×7 pairwise comparison matrix was constructed using Saaty's 1–9
 129 scale (Table 2), where 1 indicates equal importance and 9 represents extreme preference.

130 **Table 2.** Pairwise Comparison Matrix (7×7)

Criteria	Rainfall	Distance to River	Elevation	Slope	LULC	NDVI	Population
Rainfall	1	3	5	5	7	7	9
Distance to River	1/3	1	3	3	5	5	7
Elevation	1/5	1/3	1	3	5	5	7
Slope	1/5	1/3	1/3	1	3	5	7
LULC	1/7	1/5	1/5	1/3	1	3	5
NDVI	1/7	1/5	1/5	1/5	1/3	1	3
Population	1/9	1/7	1/7	1/7	1/5	1/3	1

131 The matrix was normalized and the priority vector (normalized weights) computed by
 132 averaging normalized row values. Consistency was verified using the
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$$\text{Consistency Ratio (CR = CI/RI), where CI = } (\lambda_{\text{max}} - n)/(n - 1), \lambda_{\text{max}} \tag{1}$$

134 is the principal eigenvalue, n = 7, and RI = 1.32 (Random Index for n=7). The derived CR =
 135 0.0177 (1.77%), which is well below the 0.10 threshold, confirming the high consistency of
 136 the matrix.
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138 **Table 3.** Normalized Weights of Flood Conditioning Factors:

Rank	Criterion	Weight	Weight (%)
1	Rainfall	0.278	27.8
2	Distance to River	0.200	20.0
3	Elevation	0.167	16.7
4	Slope	0.123	12.3
5	LULC	0.111	11.1
6	NDVI	0.089	8.9
7	Population Density	0.032	3.2

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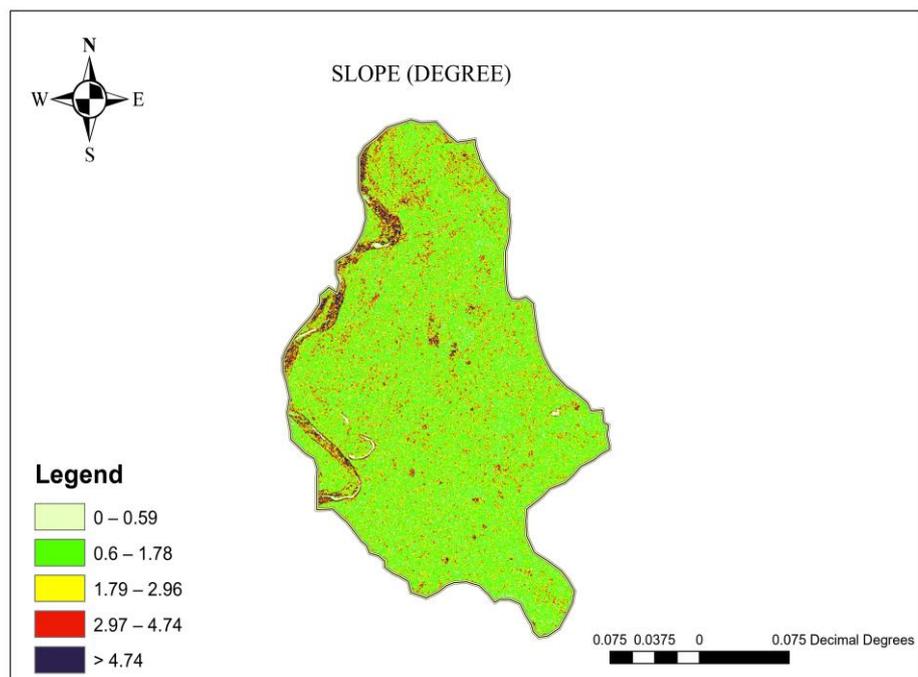
2.3. Reclassification of Flood-Conditioning Factors

Each criterion was reclassified into five ordinal vulnerability classes (1 = Very Low to 5 = Very High) based on statistical distribution and hydrological rationale. Classification schemes are summarized in Table 4. Figures 2–8 illustrate the spatial distribution of reclassified factors.

Table 4. Classification Scheme Summary

Factor	Class 1 (Very Low)	Class 5 (Very High)	Rationale
Slope (°)	0–0.59	>4.74	Flat terrain increases ponding; steep slopes accelerate runoff
Elevation (m)	>13.10	<5.64	Low elevation increases inundation risk
Distance to River (m)	>5,000	0–250	Proximity to channels increases flood exposure
Rainfall (mm)	186–231	258–262	High rainfall intensity drives flood events
Population (persons/km ²)	123–174	241–267	High density increases exposure
LULC	Vegetation	Water/Built-up	Impervious surfaces reduce infiltration
NDVI	-1.00–0.00 (water)	0.00–0.20 (bare)	Sparse vegetation reduces retention

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Figure 2. Classified slope map (degrees) for Sujawal Taluka.

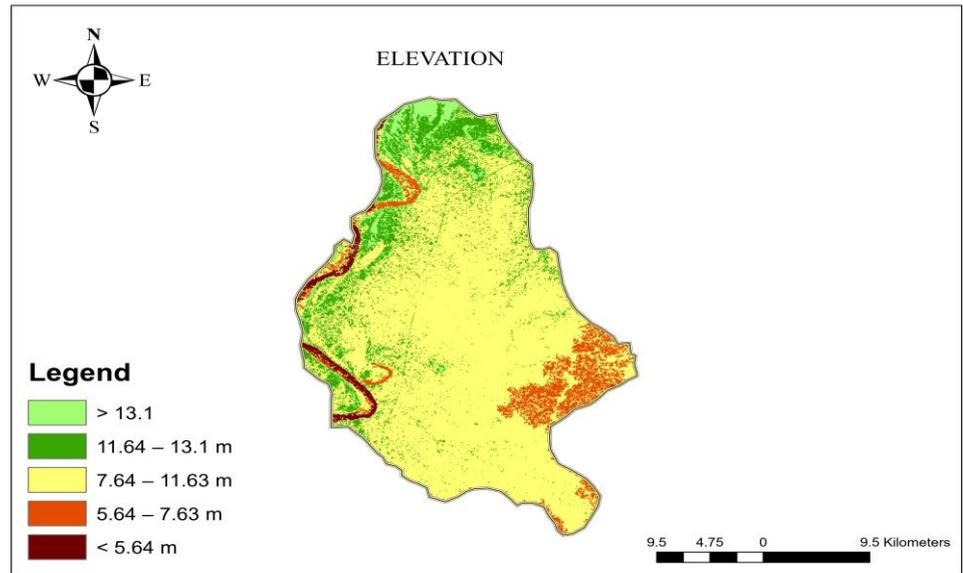


Figure 3. Classified elevation map (meters) for Sujawal Taluka.

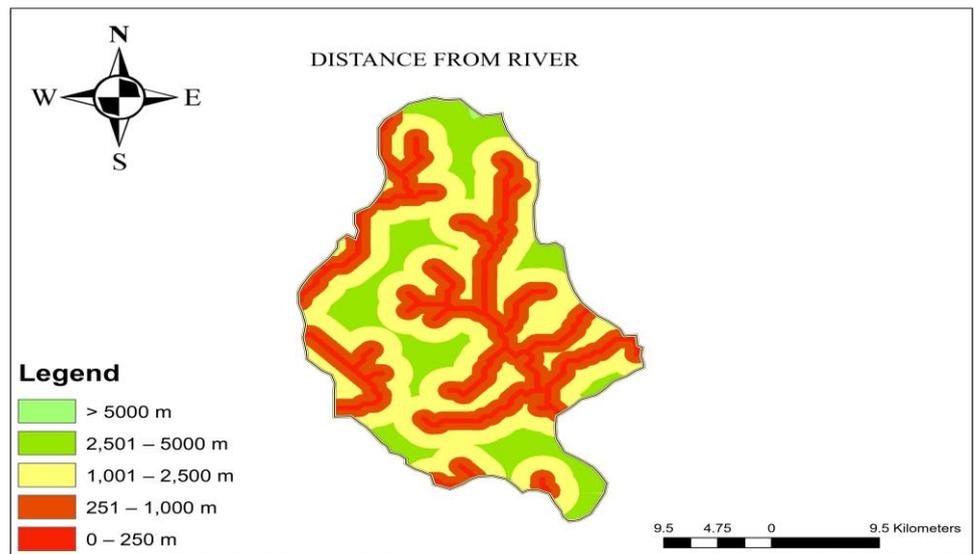


Figure 4. Classified distance to river map for Sujawal Taluka.

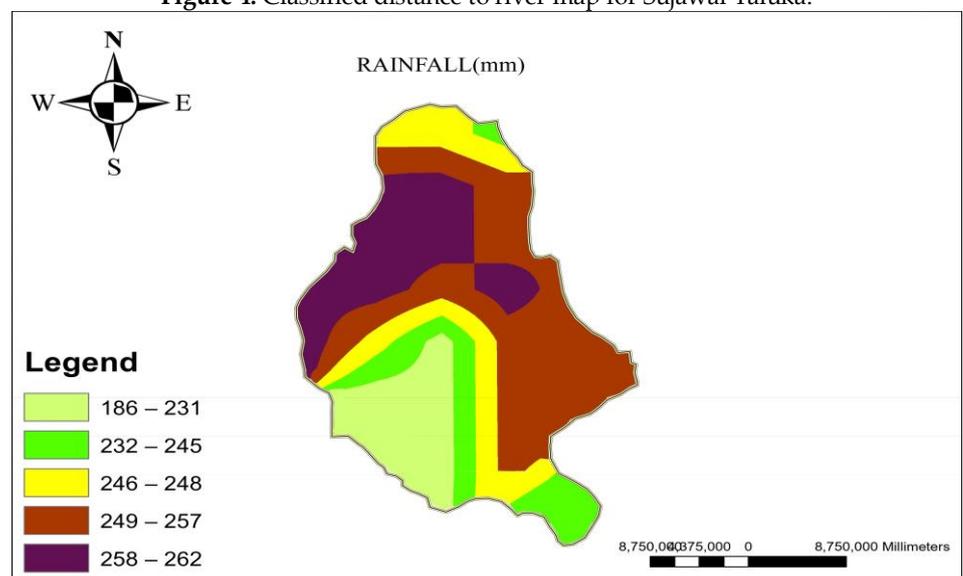


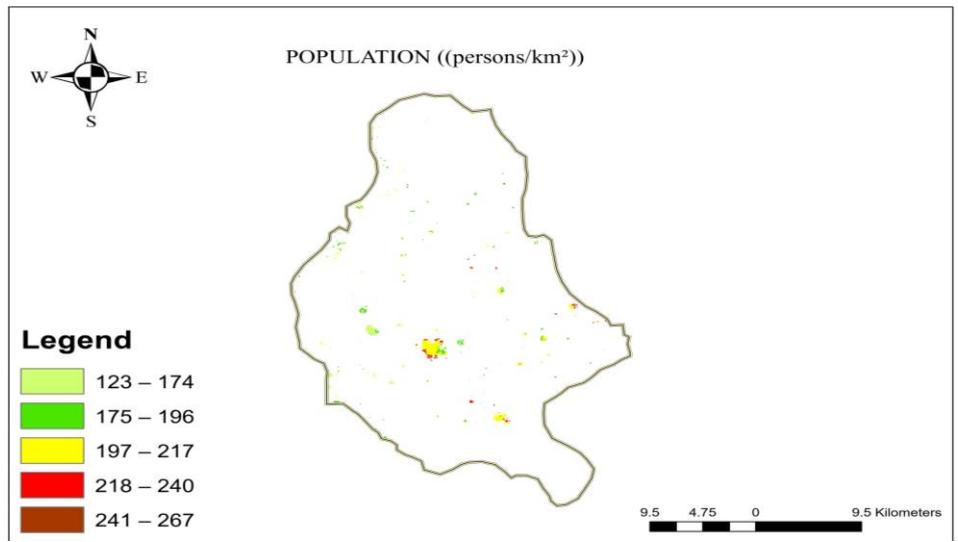
Figure 5. Classified rainfall map (millimeters) for Sujawal Taluka.

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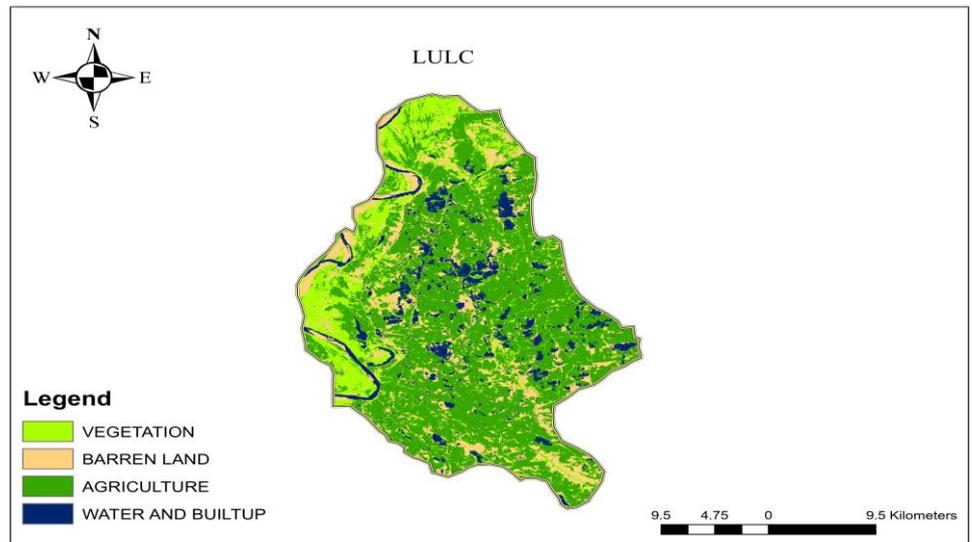


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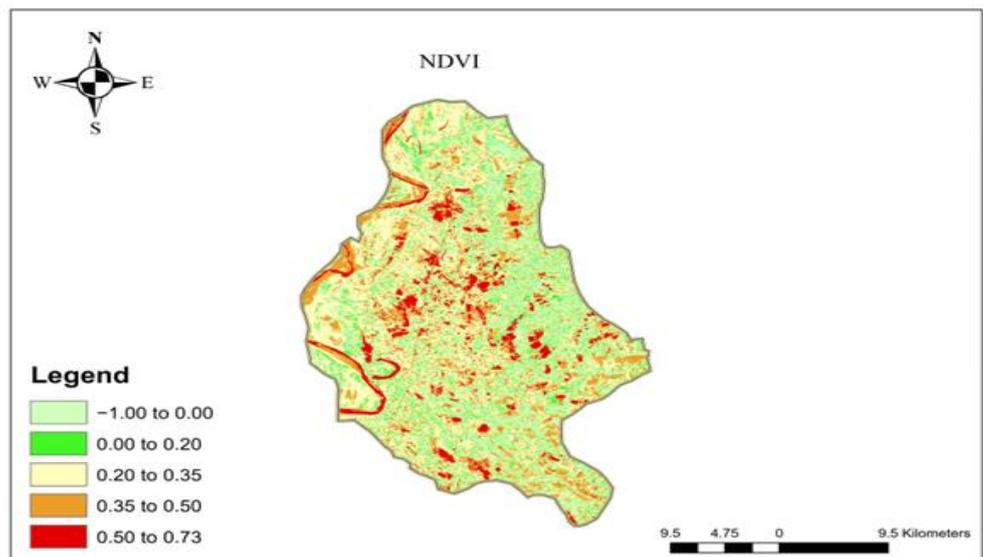
Figure 6. Classified population density map (persons/km²) for Sujawal Taluka.



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Figure 7. Classified land use/land cover (LULC) map for Sujawal Taluka.



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Figure 8. Classified NDVI map for Sujawal Taluka.

2.4. Weighted Linear Combination and Vulnerability Classification

The Flood Vulnerability Index (FVI) was computed using the Weighted Linear Combination (WLC) method in ArcGIS Raster Calculator:

$$\text{FVI} = (\text{Rainfall} \times 0.278) + (\text{Distance to River} \times 0.200) + (\text{Elevation} \times 0.167) + (\text{Slope} \times 0.123) + (\text{LULC} \times 0.111) + (\text{NDVI} \times 0.089) + (\text{Population} \times 0.032) \quad (2)$$

The continuous FVI surface was reclassified into five discrete zones using natural breaks: Very Low (2.00–2.40), Low (2.41–2.80), Moderate (2.81–3.20), High (3.21–3.80), and Very High (3.81–5.00).

2.5. Validation and Population Exposure

Model validation employed a spatial overlay of historical flood events (Global Flood Database, 809,863 MODIS-derived flood pixels) with the vulnerability zones. Population exposure was quantified by rescaling the WorldPop raster (raw sum 24,884) to the correct 2017 census total for the Taluka (198,587) using a multiplication factor of approximately 7.979, and then aggregating the population by vulnerability zone using Zonal Statistics.

3. Results

3.1. Spatial Distribution of Flood-Conditioning Factors

Individual factor maps reveal distinct spatial patterns consistent with Sujawal Taluka's deltaic geomorphology (Figures 2–8):

- Slope: A significant 87% of the taluka exhibits flat to gentle slopes (<1.78°), indicating an inherent susceptibility to sheet flooding and poor drainage.
- Elevation: 61% of the area lies below 7.64 m, with the lowest areas (<5.64 m) concentrated along coastal and near-river zones, which are highly susceptible to inundation.
- Distance to River: 41% of the area falls within 1,000 m of major channels, classifying it as High to Very High vulnerability due to immediate hydrological connectivity.
- Rainfall: The spatial gradient shows that 34% of the area receives >249 mm of mean annual rainfall, indicating High to Very High intensity zones.
- LULC: Agriculture dominates (68%), which is classified as High vulnerability due to reduced infiltration compared to natural forests or wetlands.
- NDVI: 58% of the area exhibits sparse vegetation (NDVI 0.00–0.35), indicating low natural retention capacity for surface water.
- Population: High-density clusters (>218 persons/km²) occupy 23% of the area, concentrating human exposure.

3.2. Flood Vulnerability Zonation

The weighted integration produced a final vulnerability map (Figure 9)

The High and Very High vulnerability zones collectively occupy 287.46 km² (40.5%) of the taluka. These zones are concentrated in the southwestern coastal areas and south-central riverine corridors, exhibiting a convergence of multiple risk factors: lowest elevations, immediate floodplain proximity, highest rainfall, and dense agricultural/built-up land use. Moderate zones (24.9%) form transitional belts, while Low and Very Low

zones (34.6%) occur in northern inland areas with relatively higher elevations and greater distance from rivers.

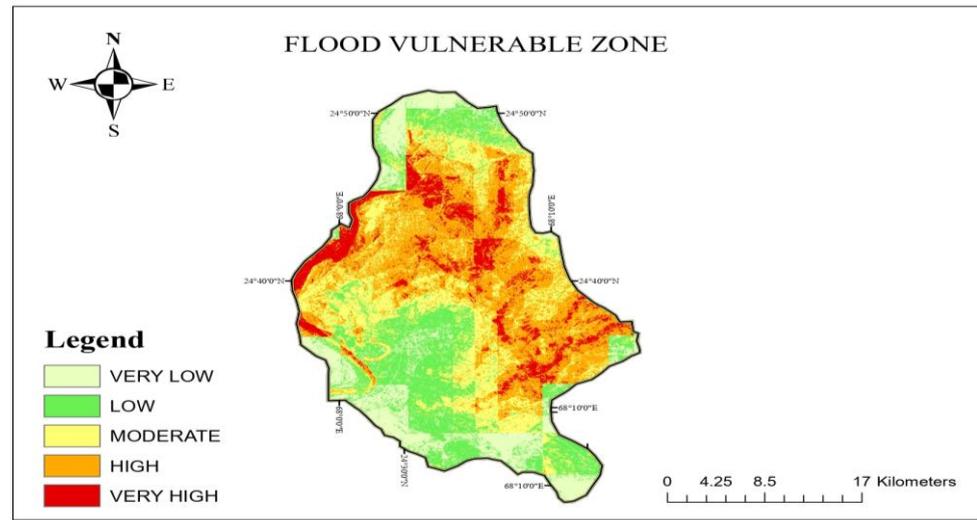


Figure 9. Flood Vulnerable Zone

Table 5. Area Distribution of Flood Vulnerability Zones

Vulnerability Class	Zone	Area (km ²)	Percentage (%)
1	Very Low	97.06	13.7
2	Low	148.89	20.9
3	Moderate	177.21	24.9
4	High	216.44	30.5
5	Very High	71.02	10.0
Total	---	710.62	100

3.3. Model Validation

Historical flood event validation (Figure 10) demonstrates a strong spatial correspondence between the modeled vulnerability and observed floods.

Table 6. Validation Using Historical Flood Events

Vulnerability Class	Zone	Flood Events (Count)	Percentage (%)
1	Very Low	110,609	13.66
2	Low	169,686	20.95
3	Moderate	201,958	24.94
4	High	246,670	30.46
5	Very High	80,940	9.99
Total	---	809,863	100

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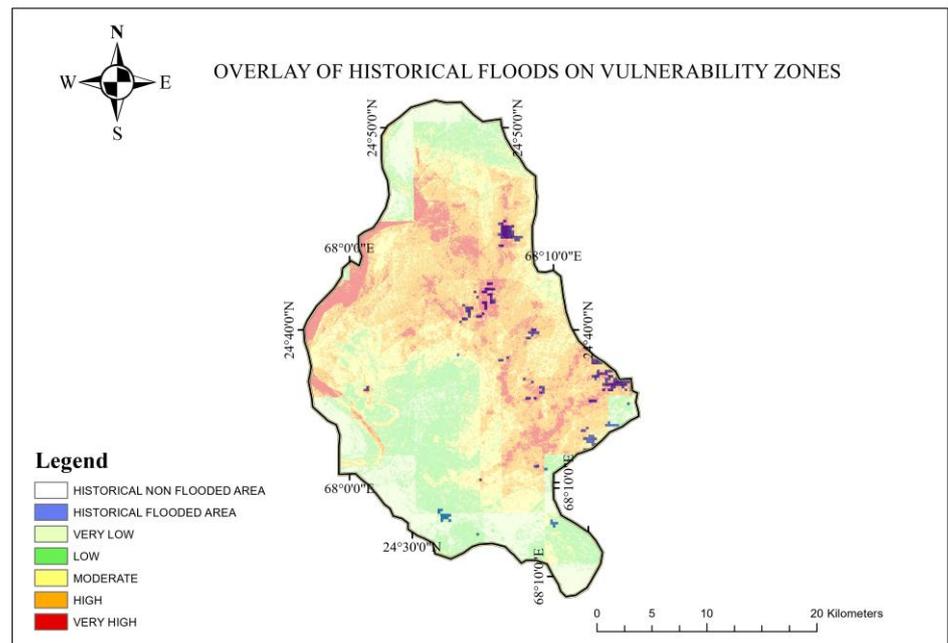


Figure 10. Overlay of historical flood extent on vulnerability zones for validation.

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The model demonstrates a strong spatial correlation, capturing 40.45% of historical flood events within the 40.5% of the area classified as High and Very High risk, confirming the model's predictive capability. The progressive increase in flood frequency across the vulnerability classes (from 13.66% in Very Low to 30.46% in High) confirms the effectiveness of the ordinal ranking. The presence of floods in lower vulnerability zones reflects spatial extent bias, temporal variability (extreme events), and the inherent limitations of a static assessment model.

3.4. Population Exposure

The corrected population distribution across vulnerability zones (Figure 11) quantifies human exposure based on the 2017 Taluka population of 198,587.

Table 7. Corrected Population Exposure by Vulnerability Zone (Based on 2017 Taluka Population of 198,587)

Vulnerability Class	Zone	Population (Persons)	Exposure (%)
1	Very Low	18,389	9.26
2	Low	79,715	40.14
3	Moderate	28,939	14.57
4	High	40,270	20.28
5	Very High	31,274	15.77
Total	---	198,587	100

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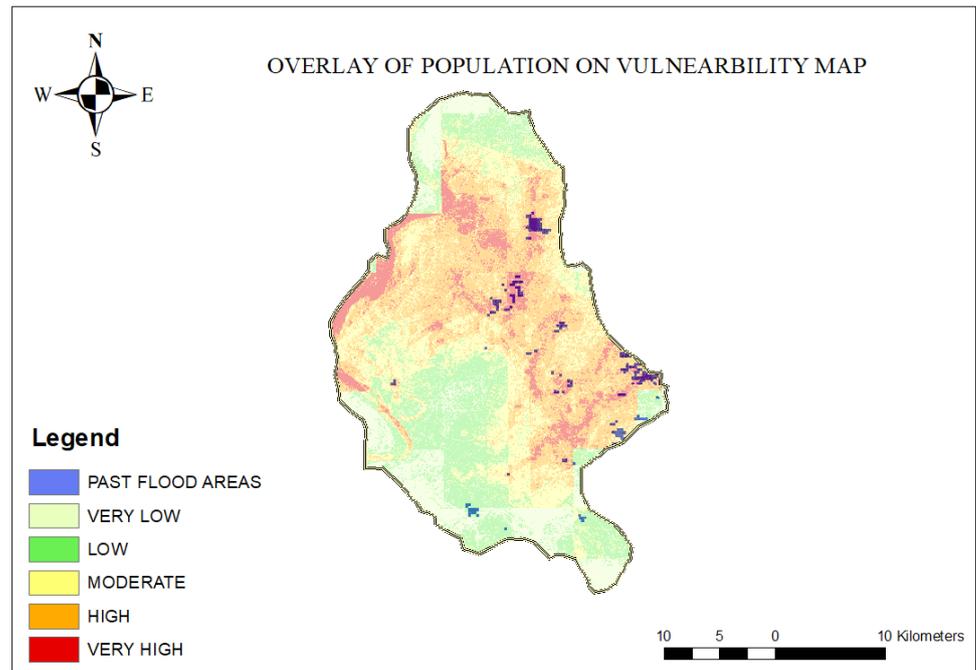


Figure 11. Overlay of population on vulnerability map

A total of 71,544 persons (36.05%) reside in the High and Very High zones, facing an elevated flood risk. The Low zones contain the highest single concentration of population (40.14%), which may reflect historical settlement preferences for relatively safer areas. However, the substantial population in the highest-risk zones necessitates targeted and immediate interventions.

4. Discussion

4.1. Vulnerability Patterns and Regional Context

The spatial concentration of vulnerability in southwestern and south-central Sujawal is a direct reflection of the region's deltaic floodplain characteristics: minimal relief, dense drainage networks, and intensive monsoon precipitation. This pattern is consistent with flood vulnerability studies in adjacent Sindh districts (Larkana, Thatta), where low-elevation deltaic zones consistently exhibit the highest susceptibility [9]. The vulnerability is further exacerbated by the ecological degradation of the Indus Delta—including a 92% area reduction since 1833, sediment starvation, subsidence, and seawater intrusion—which collectively lower ground elevations relative to flood sources.

4.2. AHP Weights and Hydrological Interpretation

The dominance of Rainfall (weight = 0.278) as the most influential factor accurately reflects the monsoon-driven flood regime of the region. The catastrophic 2022 Pakistan floods, for instance, were directly linked to 784% above-average August precipitation in Sindh [10]. Distance to River (0.200) is the second most critical factor, acknowledging the significant hydrological connectivity in this distributary-dominated landscape. The combined 29% weight of topographic factors (Elevation and Slope) underscores the critical role of terrain control on water accumulation in the flat deltaic environment.

The inclusion of Population Density (weight = 0.032) in the AHP model for flood vulnerability is justified by adopting a comprehensive definition of vulnerability as the inter-

257 section of physical susceptibility (hazard) and human exposure. While population den-
258 sity is primarily an exposure indicator, its inclusion ensures that the final FVI map prior-
259 itizes areas where physical flood potential directly overlaps with human presence,
260 providing a more actionable result for disaster management planning.

261 4.3. Model Performance and Limitations

262 The validation results, which show that 40.45% of historical floods occurred in the 40.5%
263 high-risk area, indicate a reasonable and reliable predictive performance for a static sus-
264 ceptibility model. This performance is a strong indicator that the selected criteria and
265 their assigned weights accurately capture the dominant physical and human factors con-
266 tributing to flood risk in the region.

267 However, the model is subject to several limitations that should be addressed in future
268 work: (1) It is a static assessment and does not capture dynamic flood processes such as
269 flow depth or velocity, which are critical for detailed risk assessment. (2) The reliance on
270 coarse rainfall data may inadequately represent the high spatial and temporal variability
271 of convective monsoon precipitation. (3) The model excludes drainage infrastructure
272 condition, which significantly affects actual flood occurrence and is a major policy lever.
273 (4) The model's validation, while strong, could be further enhanced by employing ad-
274 vanced metrics such as the Area Under the Curve (AUC) or Success Rate Curve to pro-
275 vide a more rigorous statistical measure of predictive power.

276 4.4. Policy Implications

277 The vulnerability map developed in this study enables evidence-based spatial prioritiza-
278 tion for flood risk management:

- 279 1. Priority Interventions: Direct a majority of mitigation investments to the High/Very
280 High zones (287.46 km², 71,544 persons exposed).
- 281 2. Land Use Regulation: Implement strict restrictions on new development in Very
282 High zones and incentivize settlement consolidation in safer areas.
- 283 3. Early Warning Systems: Deploy real-time monitoring and early warning systems
284 with last-mile connectivity specifically targeting the most vulnerable communities.
- 285 4. Ecosystem Restoration: Prioritize the rehabilitation of drainage channels blocked by
286 encroachments and the restoration of protective mangrove forests in coastal zones.
- 287 5. Climate Adaptation: Integrate climate projections into all new infrastructure design
288 to address the intensifying monsoon extremes and sea-level rise scenarios.

289 5. Conclusions

290 This study successfully developed a spatially explicit flood vulnerability assessment for
291 Sujawal Taluka using an integrated GIS-AHP framework. Seven flood-conditioning fac-
292 tors were systematically weighted (CR = 0.0177) and integrated to classify the taluka into
293 five vulnerability zones. Key findings include:

294 40.5% of Sujawal Taluka (287.46 km²) is classified as High to Very High vulnerability,
295 concentrated in low-lying southwestern and south-central regions.

Validation confirmed the model's predictive capability, with 40.45% of historical floods occurring in the high-risk zones.

36.05% of the Taluka's population (71,544 persons) is exposed to elevated flood risk.

Rainfall (0.278) and distance to river (0.200) were identified as the dominant flood drivers.

The methodology demonstrates the applicability of AHP-MCDM frameworks for robust flood vulnerability assessment in data-scarce deltaic environments. The vulnerability map provides actionable spatial information for disaster management authorities, enabling evidence-based prioritization of structural flood defenses, early warning systems, land use planning, and ecosystem-based adaptation.

Future research should focus on integrating hydrodynamic modeling to simulate flood depths for specific return periods, incorporating high-resolution topographic and rainfall data, expanding criteria to include drainage infrastructure and socioeconomic vulnerability, and extending the framework to district and regional scales encompassing broader Indus Delta areas (Thatta, Badin districts). As climate change intensifies monsoon extremes and sea-level rise exacerbates delta subsidence, the vulnerability patterns documented here represent a critical baseline requiring proactive adaptation to prevent worsening flood impacts on vulnerable communities in coastal Sindh.

6. Patents

Data Availability Statement: The datasets generated and analyzed during this study are available from the corresponding author upon reasonable request. Global datasets used are publicly available from sources listed in Table 1.

Conflicts of Interest: The author declares no conflicts of interest.

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