Geospatial Analysis for Flood Hazard Zonation in District Muzaffargarh (Pakistan)

Awais Munir[1], Muhammad Asad Ghufran[2], Asma Majeed[3], Iftikhar Ahmed[4], Farheen Nazli[5], Hafiza Momina Rafiq[6], Afshan Hafeez[7], Usama Hafeez[8] and Waqas Munir[9]

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Abstract

Flash floods pose a significant hazard to communities worldwide, underscoring the need for effective risk assessment strategies to mitigate their impact. This study applies a Flood Risk (FR) model to evaluate flash flood vulnerability in the Muzaffargarh District of Punjab, Pakistan. Six key conditioning factors—elevation, slope, aspect, curvature, land use/land cover, and rainfall—were integrated within a geospatial framework to identify and map flood-prone areas. The analysis categorised the region into five vulnerability zones: very high (36%), high (24%), moderate (16%), low (12%) and very low (11%). Notably, the high-to-very high-vulnerability zones are predominantly concentrated in the eastern, western, and southern portions of the district. The model's accuracy was validated through historical flood records and spatial overlay techniques, confirming its reliability. This geospatial approach offers a cost-effective and scalable solution for rapid flood risk assessment in data-scarce regions. The findings serve as a vital tool for integrating disaster risk reduction into regional planning and climate adaptation strategies.

Keywords: Geospatial Analysis, Flood Hazards, Flood Susceptibility.

Introduction

A catastrophic flood can occur as a result of rapid water accumulation in a specific area, often regarded as one of the most devastating forms of natural disasters (Sikha et al., 2014). The type and intensity of flooding depend on the hydrological, geological, and climatic conditions of a

[1]*PhD Scholar, Department of Environmental Science, International Islamic University Islamabad, Pakistan Lecturer, Institute of Agro-Industry and Environment, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Pakistan. Corresponding Author Email: awais.munir@iub.edu.pk*

[2]*Professor, Department of Environmental Science, International Islamic University Islamabad, Pakistan. Email: asad.ghufran@iiu.edu.pk*

[3]*Assistant Professor, Institute of Agro-Industry and Environment, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Pakistan. Email: asma.majeed@iub.edu.pk*

[4]*Assistant Professor, Department of Agricultural Engineering, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, Pakistan. Email: iftikhar.ahmed@kfueit.edu.pk*

[5]*Lecturer, Institute of Agro-Industry and Environment, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Pakistan. Email: farheenmaqshoof@gmail.com*

[6]*Student at Institute of Agro-Industry and Environment, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Pakistan. Email: hafizamominarafiq@gmail.com*

[7]*MS Scholar at Institute of Agro-Industry and Environment, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Pakistan. Email: afshisheikh98@gmail.com*

[8]*MS Scholar at Soil Microbiology and Biochemistry Lab, Institute of Soil and Environmental Science, Pir Meher Ali Shah Arid Agriculture University, Rawalpindi, Pakistan Email: usamahafeez177@gmail.com*

[9] *Lecturer, Department of Architecture, The Islamia University of Bahawalpur, Pakistan. waqas.munir@iub.edu.pk*

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region, leading to various forms, such as seasonal floods, urban floods, flash floods, and coastal floods (Qurratulain & Munazza, 2014). The consequences of floods are far-reaching, including the destruction of homes, infrastructure, and agricultural land, as well as direct loss of life and indirect effects such as displacement, temporary housing, and disruption of social systems (Jonkman et al., 2008). Due to the significant environmental, social and economic implications, practical and integrated flood management is critically important (Markantonis et al., 2013). Although floods can occur anywhere, they are more common in monsoon-affected Asian countries, including Pakistan, India, Bangladesh, China, and Thailand. South Asia is the region most at risk from the effects of climate change, particularly in terms of flooding. Consequently, floods remain the leading cause of water-related disasters in Bangladesh (Ahmed, 2006). In Pakistan, the vast river basins, such as the Indus River, are particularly vulnerable to flooding that happens between July and October, when the summer monsoon rains and snowmelt coincide. Extreme runoff floods naturally occurring floodplains as a consequence of the monsoon rains and snowmelt combining to raise the water flow within these river basins (Moharana et al., 2014). To better manage future flood disasters, Dewan et al. (2007) have called for land-use planning techniques that incorporate comprehensive flood hazard management, utilising Synthetic Aperture Radar (SAR) data and geographical information systems (GIS). This is especially important in the Greater Dhaka area. Flooding has become more likely due to rivers' diminished natural flood management capabilities caused by human activities such as building on river floodplains and overstepping natural river pathways, as well as the increasing population and rapid urban and rural development (Ahmadisharaf et al., 2016). When the Indus River reaches its upper basin in Khyber Pakhtunkhwa and Punjab, the water levels rise above the riverbanks and then fall back into the riverbed. However, embankments are built along the river's banks in Sindh, a lower region of the Indus Basin, to control floodwaters because the river flows at a higher height there. Inundation of settlements and agricultural land is a direct result of embankment breaches, which worsens the flood scenario (Siyal et al., 2018). Flooding in Pakistan was caused by monsoon rainfall and affected 33 million people in over 75 per cent of the country's districts. Along with over 161,000 people seeking shelter in camps, the World Health Organisation (WHO) recorded over 1,000 fatalities and 1,500 injuries (Feng & Wang, 2021).

Sustainable development cannot be achieved without effective flood hazard management to mitigate potential damage (Kumar et al., 2010). Although numerous hydrological methods have been used to identify flood-prone areas within watersheds, these techniques often encounter limitations related to high costs and practical constraints. As a result, many watershed studies have increasingly turned to environmental assessment tools, particularly Geographic Information Systems (GIS). In addition, the past decade has witnessed the emergence of various methodologies for natural hazard mapping that incorporate statistical techniques alongside GIS technology to improve flood risk analysis (Devkota et al., 2013). As one of the most extensive threats on a global scale, flood control is a top priority for everyone involved. All phases of flood management, from preparation to response and cleanup, can benefit significantly from the use of GIS and Remote Sensing (RS) technologies. Effective flood management requires the participation of experts from all fields. It is also possible to infer that RS methods provide quicker and less expensive ways to obtain geographical data regarding the flood event, even in places that are physically inaccessible (Dano et al., 2011). In underdeveloped nations, where RS and GIS have seen comparatively little use, there has been a notable increase in scientists' awareness of the potential benefits of these methods in flood management. As a result of the flood's inundation of many farmed areas, the planting of upcoming Rabi crops was also impeded (Opolot, 2013; Wang & Xie, 2018). Many

people in the Muzaffargarh district make their living from raising cattle. This district is second in size in Punjab in terms of livestock farming. Losses in cattle, buffalo, goats, sheep, donkeys, camels and oxen were high due to the 2010 flood, which devastated the livestock population. Over half of the livestock population was believed to have been negatively impacted by the flood. In flood-affected areas, school buildings accounted for 74.7% of the total damage, with 25.3% suffering partial damage. Four hundred seven feeder schools in the district were constructed by the National Commission for Human Development (NCHD), but 229 of them were damaged.
Furthermore, flooding swept into several private schools (Khan & Niazi, 2016). Due to the lack of medical facilities and stagnant water, several diseases emerged after the disaster. The objective of this research was to evaluate the extent of damage caused by floods, to develop a flood hazard and risk zonation map to support future disaster preparedness and planning, and to propose community-based adaptation and resilience strategies to minimise flood risks in the most affected areas of District Muzaffargarh.

Methodology

Study Area

Nawab Muzaffar Khan, the governor of Multan, established Muzaffargarh in 1794. The name "Muzaffargarh" translates to "Fort of Muzaffar," as the old town is located within the fortifications constructed by Nawab Muzaffar Khan (Government of Punjab, 2020). Before its establishment, the area was recognised by a store named "Musan Hatti" on the route connecting Multan and Dera Ghazi Khan (Punjab Portal, 2020). Muzaffargarh was declared a district in 1861 (Pakistan Bureau of Statistics, 1998). Located almost in the centre of Pakistan in southern Punjab, Muzaffargarh lies near the city of Multan. The region is renowned for its flat, alluvial plains, which are highly suitable for agriculture, particularly for citrus and mango orchards (Khan et al., 2017). Numerous canals traverse the Muzaffargarh District, channelling water to the surrounding farmland and contributing to its fertile soil. However, land along the Chenab River is prone to flooding during the monsoon season (Ahmed & Raza, 2015). The climate is arid, characterised by scorching summers and mild winters, with some of the most extreme weather in Pakistan. The highest recorded temperature in Muzaffargarh is approximately 54 °C (129 °F), making it one of the hottest places in the country (PMD, 2021).

Figure 1: National Boundary of Pakistan

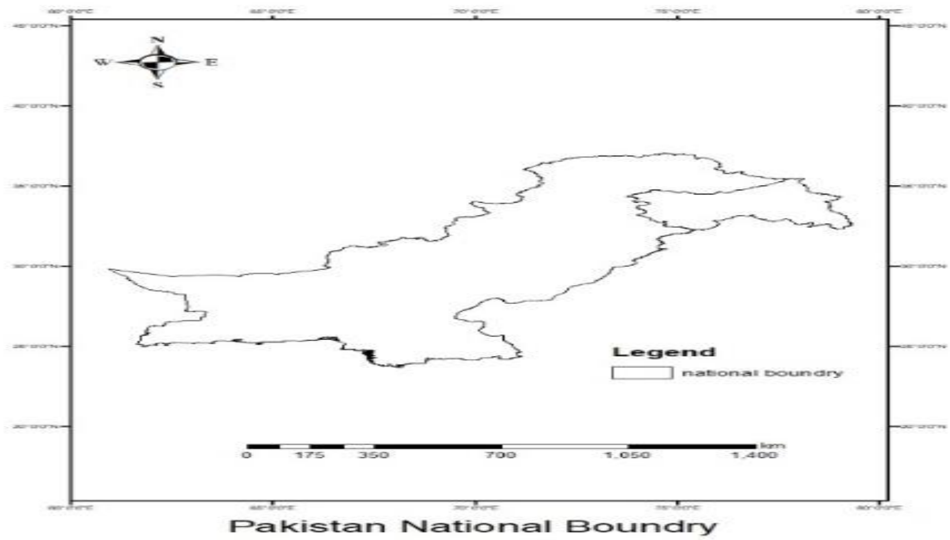
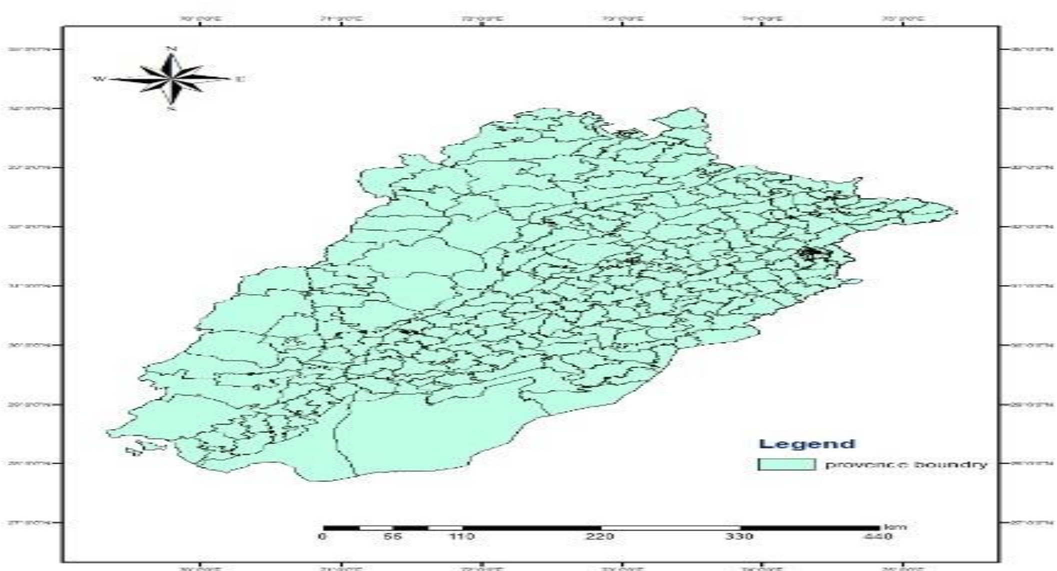


Figure 2: Boundary of Punjab Province



Preparation of Spatial Database

Developing a spatial database involves gathering relevant flood components, which is an essential step in the flood susceptibility study process. Most of the time, multiple factors combine to generate flooding. Nevertheless, different parameters have different roles in flood susceptibility assessment (Rahmati et al., 2016).

Figure 3: District Muzaffargarh Boundary

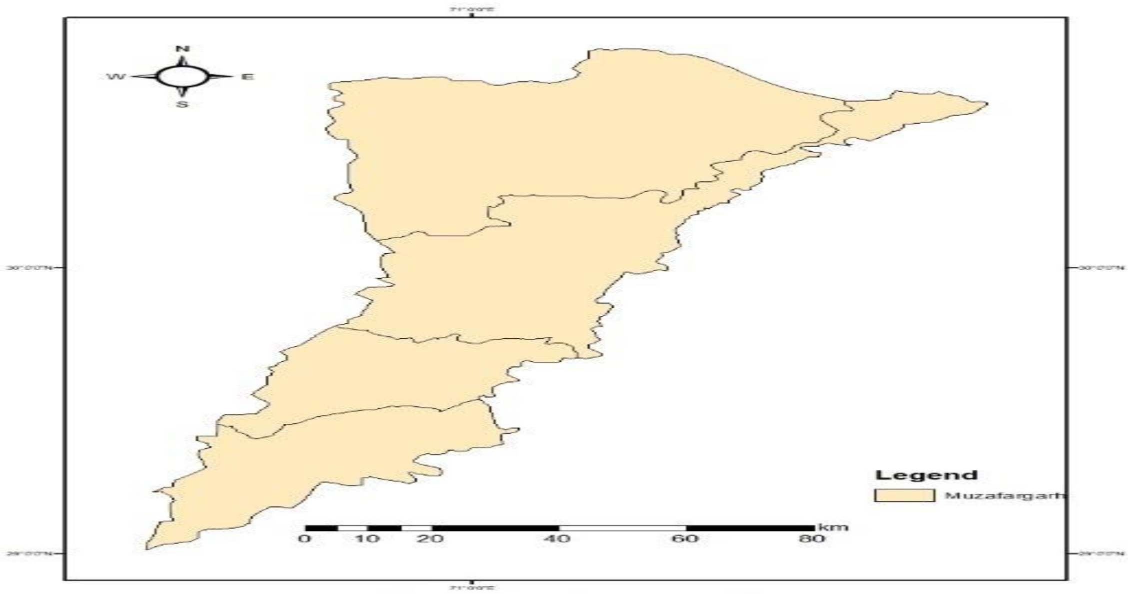


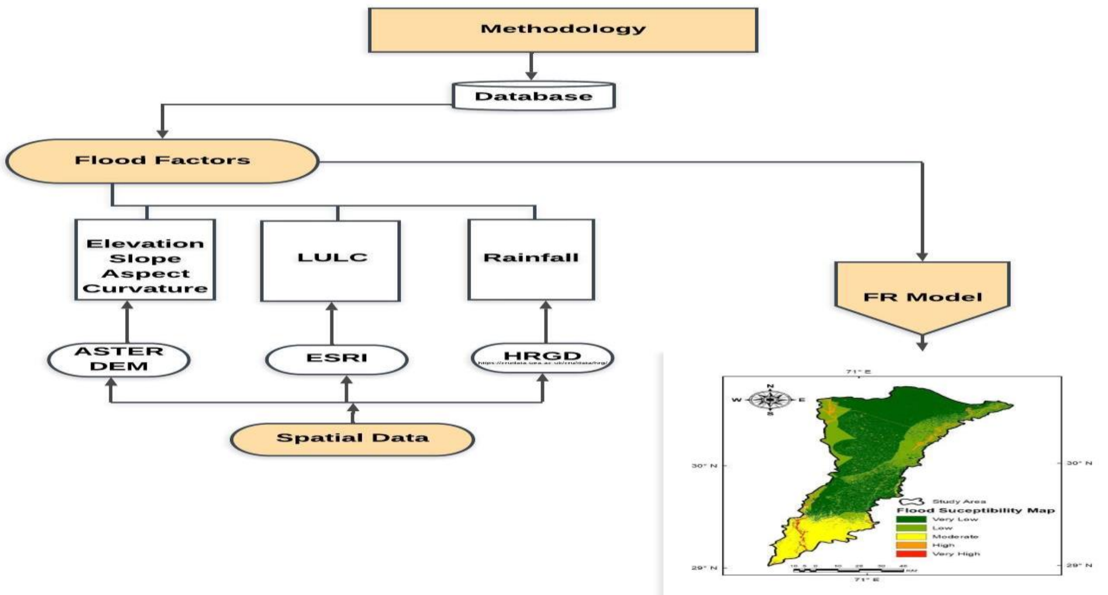
Table 1: Flood Prediction Parameters with Cell Sizes

Parameter	Sub-Classification	Resolution (Point Coordinates)
Floods Record Area	Flood Extent	30m
Flood Prediction	Elevation	30m
	Slope	30m
	Aspect	30m
	Curvature	30m
	Rainfall	30m
	LULC	30m

Flood Susceptibility Mapping

This study evaluated flood susceptibility using an integrated method that combined geographic approaches and the bivariate statistical method known as the Frequency Ratio (FR). The correlation between the occurrence of floods and the factors that trigger them was calculated using FR, which is widely applied in flood hazard modeling due to its simplicity and efficiency (Lee & Pradhan, 2007; Tehrany et al., 2013). The association between various flood causative elements, their sub-classes and the frequency of floods in the PRB is displayed in Table 1. The study examined six flood-triggering factors: Elevation, Slope, Aspect, Curvature, Rainfall and Land Use/Land Cover, which are considered significant in flood modeling (Kazakis et al., 2015; Samanta et al., 2018). A clear positive correlation exists between flood probability and the FR, supporting the utility of the FR model for spatial flood risk analysis (Rahmati et al., 2016).

Figure 4: Methodology-Bivariate Statistical Analysis



Frequency Ratio Model

Flood Risk (FR) is a statistical analytic technique that is bivariate in nature. It is based on the geographical distribution (probability), flood location as a dependent factor and flood triggering and causative elements slope, elevation (Munir et al., 2022). Each independent flood triggering factor's bivariate probability was calculated based on how closely it related to the incidence of floods (The link between flood incidence and flood triggering factors is stronger when the bivariate probability is higher (greater than 1) and weaker when the likelihood is lower less than 1 (Samanta et al., 2018). For each subclass of flood triggering factors, the FR values were determined using following equation in accordance with their associations with flood inventory.

$$\text{FR} = \frac{\text{Flood Points in Factor Class} \div \text{Total Flood Points}}{\text{Factor Class Area} \div \text{Total Area}}$$

Next, using equation the FR was normalized as relative frequency (RF) in a probability range of values [0, 1] (Munir et al., 2022).

$$\text{LRF} = \frac{\text{Factor Class FR}}{\sum \text{Factor Classes FR}}$$

Results

The results of the flood susceptibility assessment using the Frequency Ratio (FR) model highlight the significance of six key parameters: elevation, slope, aspect, curvature, land use/land cover (LULC) and rainfall. Each parameter was divided into classes and analyzed based on the percentage of flood pixels within each class and the corresponding FR values.

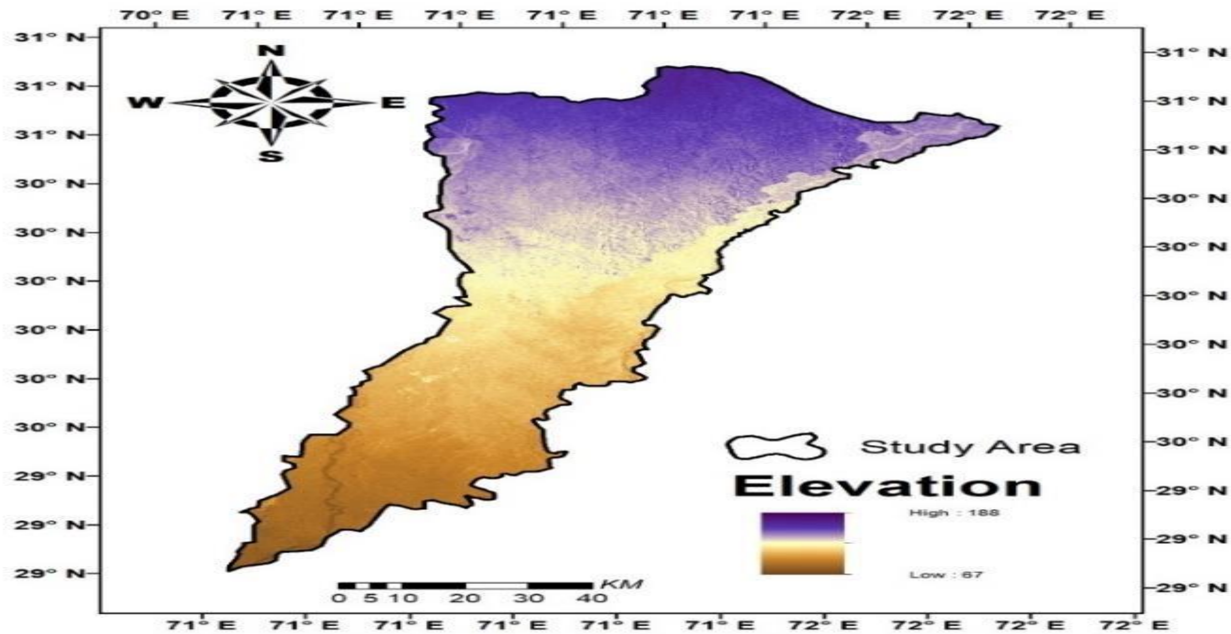
Table 2: Parameters Used for Flood Assessment Through FR Model

Parameter	Class	Class Pixels	% Class Pixels	Flood Pixels	% Flood Pixels	FR
Elevation	< 104	1396627	16	605726.973	39	0.434
	104 – 114	1801124	21	228370.529	15	0.127
	114 – 123	1479516	17	233969.305	14	0.151
	123 – 131	1921816	23	286906.13	18	0.151
	131 – 181	1982487	23	211040.085	13	0.11
Total		8621871		1668984.711		0.879
Slope	< 1.2	3866511	45	781265.9222	50	0.202
	1.2 – 2.6	2960647	34	704207.3473	42	0.178
	2.6 – 4.2	1327081	15	193100.1799	12	0.151
	4.2 – 7.01	444539	5	82397.76211	5	0.187
	7.01 – 51.1	66561	1	22641.33602	1	0.325
Total		8605248		1668607.651		1.098
Aspect	< -63.98	1800478	21	351636.5461	22	0.195
	60.98 – 140.26	1828733	22	344051.4788	22	0.185
	140.26 –212.31	1583638	19	288361.2867	18	0.177
	212.31 –282.96	1660979	20	296476.3205	19	0.178
	282.96 –359.92	1624301	19	288746.9405	18	0.176
Total		8608249		1668607.651		0.918
Curvature	< -0.58	386027	4	72117.00919	5	0.201
	-0.58 – -0.25	1894533	22	333471.2867	21	0.176
	-0.25 – -0.07	4023584	47	753874.3177	48	0.187
	-0.07 – 0.40	1893442	22	345770.3115	22	0.182
	0.40 – 15.44	362465	4	63451.78715	4	0.175
Total		8621971		1668984.711		0.923
LULC	Water	2350649	4	235078.1846	15	0.091
	Forest	943672	1	12858.02199	1	0.014
	Vegetation	4653022	66	891165.1791	57	0.019
	Built-up	1054258	15	227251.5625	14	0.022
	Dry Land	1002677	14	203276.0862	13	0.02
Total		7608078		1668878.882		0.165
Rainfall	< 331	304833	4	96715.2212	6	0.317
	331 – 344	801174	9	299368.9477	19	0.374
	344 – 356	2944132	33	549543.7135	33	0.295
	356 – 366	3741377	45	394375.9651	23	0.195
	366 – 389	731657	9	258896.4091	17	0.356
Total		8621812		1668896.44		1.356

Flood Risk Assessment by Elevation

Elevation proved to be a significant determinant of flood risk in table 2. The lowest elevation class (<104 m) covered 16% of the study area but accounted for 39% of the flood pixels, resulting in the highest FR value of 0.434. This suggests that areas at lower elevation are more vulnerable to flooding. Conversely, the highest elevation class (131–181 m), although covering 23% of the area, contributed only 13% of the flood pixels, showing a low FR value of 0.11.

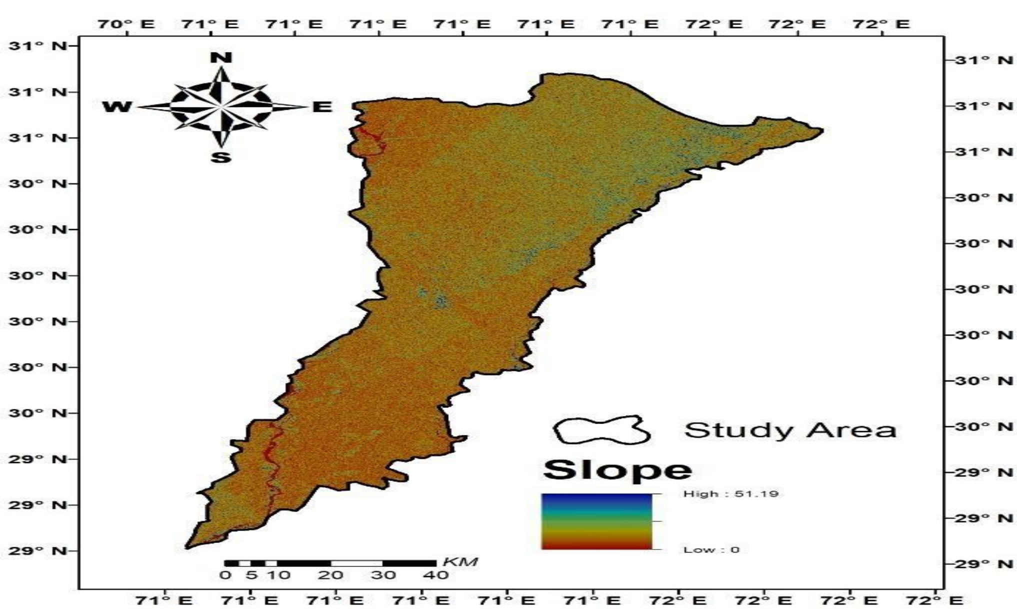
Figure 5: Elevation of District Muzaffargarh



Flood Risk Assessment by Slope

Slope analysis revealed that flatter areas are more susceptible to flooding depicts in table 2. The class with a slope of less than 1.2° covered 45% of the land and had 50% of the flood pixels, giving an FR value of 0.202—the highest among all slope categories. In contrast, steeper slopes (7.01–51.1°) made up only 1% of the area and flood pixels, with a moderate FR of 0.325, suggesting localized but significant flood potential in very steep zones.

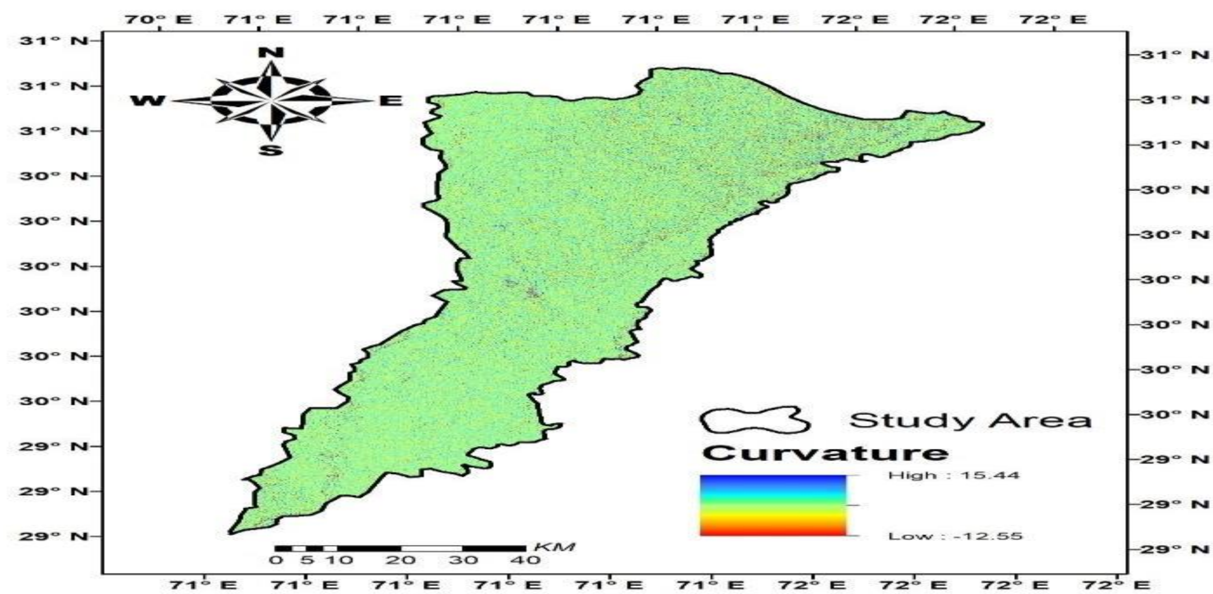
Figure 6: Slope of District Muzaffargarh



Flood Risk Assessment by Curvature

Curvature also played a moderate role in flood susceptibility showed in in table 2. The slightly concave class (-0.25 to -0.07) and flat terrain classes showed higher flood pixel percentages (48% and 22%, respectively), corresponding to moderate FR values of 0.187 and 0.182. The most concave curvature (< -0.58) showed an FR value of 0.201, indicating increased flood risk in such areas due to water accumulation.

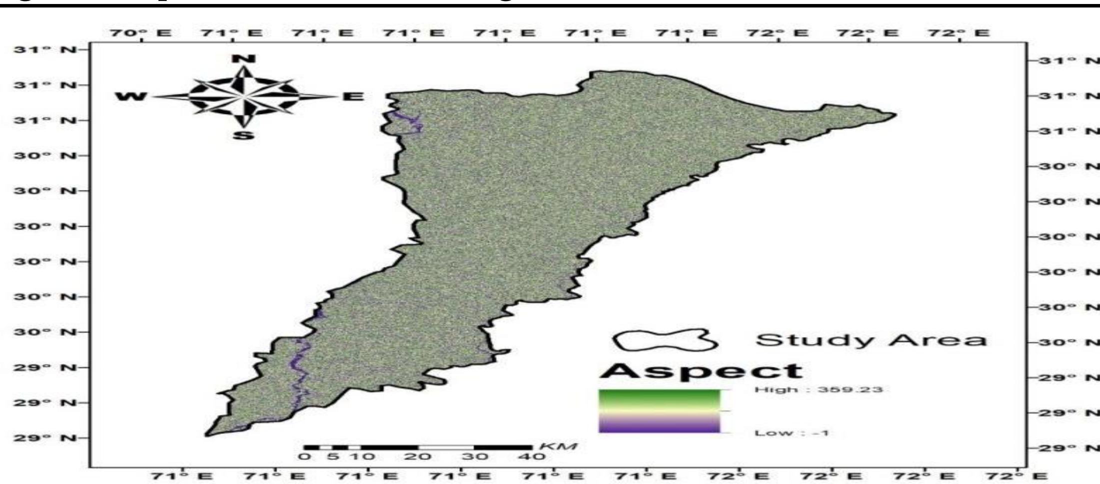
Figure 7: Curvature of District Muzaffargarh



Flood Risk Assessment by Aspect

Aspect, which affects solar radiation and evapotranspiration, showed relatively uniform flood susceptibility across different directional classes. The highest FR value of 0.195 was observed in the < -63.98° class, followed closely by the 60.98–140.26° class (FR = 0.185). This indicates that specific aspect orientations may slightly influence flood risk, likely due to differential moisture retention and vegetation cover.

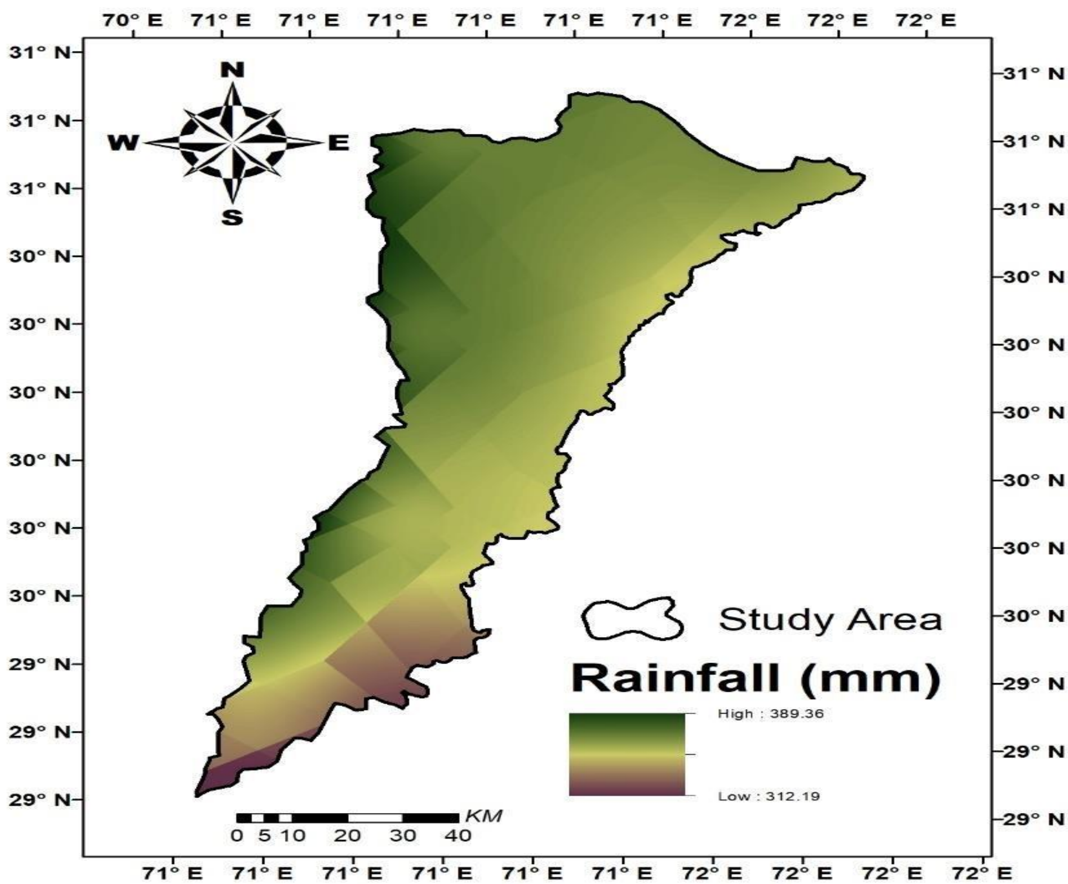
Figure 8: Aspect of District Muzaffargarh



Flood Risk Assessment by Rainfall

Rainfall was the most dominant parameter influencing flood susceptibility. Areas receiving rainfall between 331–344 mm and 366–389 mm had high FR values of 0.374 and 0.356, respectively in table 2. These rainfall classes collectively contributed 36% of the flood pixels, despite covering only 18% of the area. The lowest rainfall class (<331 mm) also showed a significant FR value of 0.317. Overall, the total FR for rainfall was 1.356—the highest among all parameters—indicating that rainfall is the most critical flood-triggering factor in the region.

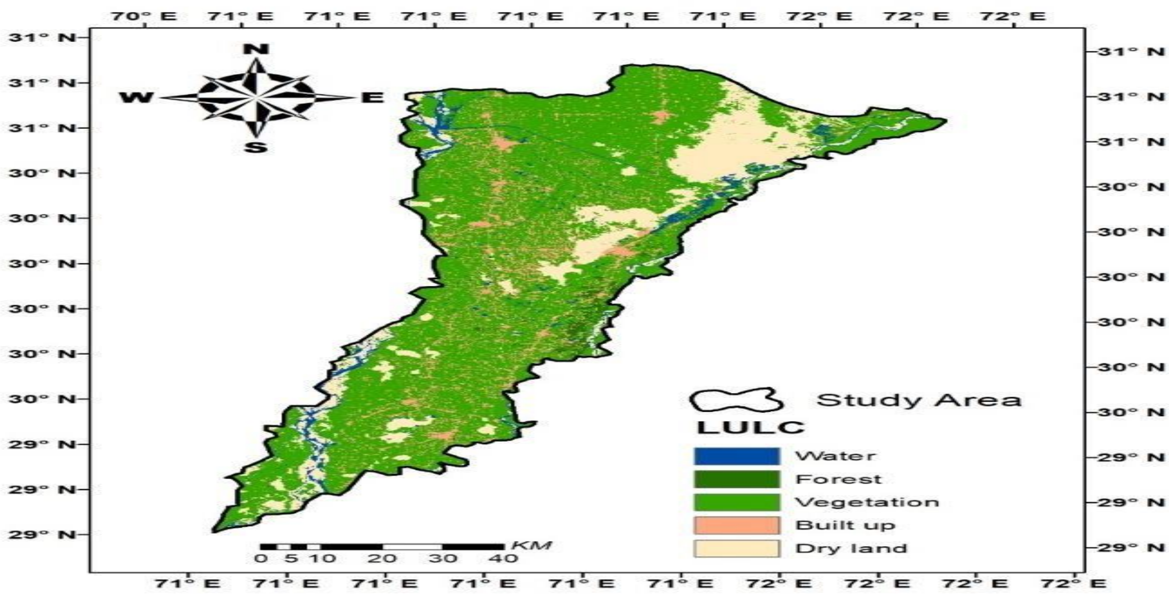
Figure 9: Rainfall of District Muzaffargarh



Flood Risk Assessment by Land Covers Land Use

Land Use and Land Cover was a critical factor influencing flood behavior displayed in table 2. Water bodies, although covering only 4% of the area, contributed 15% of the flood pixels, with an FR value of 0.091—the highest in this category. Built-up and dry land classes also exhibited higher flood pixel percentages (14% and 13%) with low FR values (0.022 and 0.020), reflecting high runoff potential and reduced permeability. In contrast, forest and vegetation areas showed minimal flood association, with FR values of 0.014 and 0.019, indicating their role in mitigating flood risks through better infiltration and water retention.

Figure 10: LULC of District Muzaffargarh



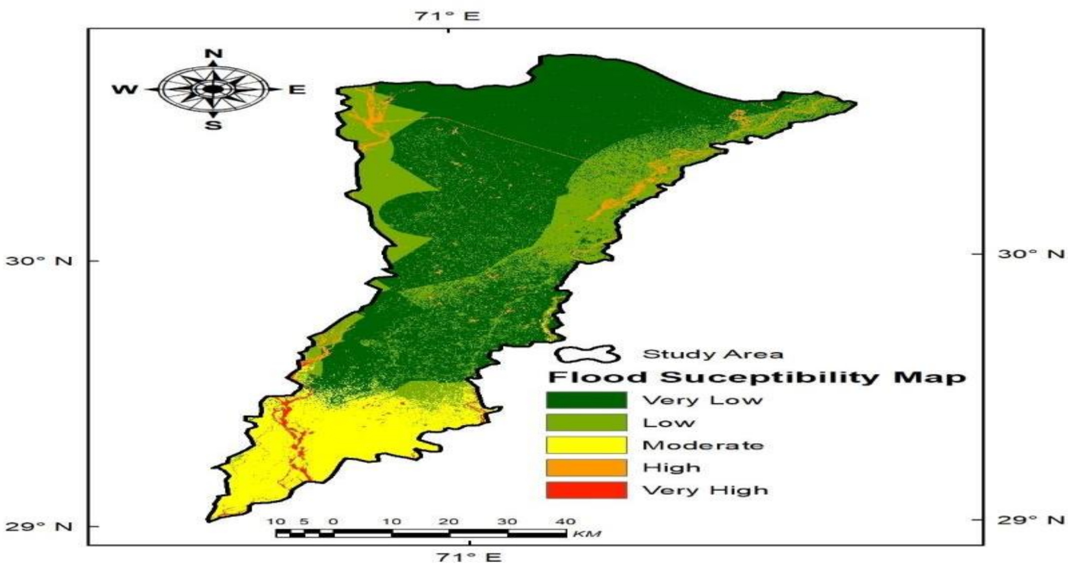
Ranges of Floods in District Muzaffargarh

According to Table 3, each subclass rating for every conditioning parameter was produced using the FR values. The research area FR value ranged from 0.094 to 0.37. A greater FR score suggested a higher likelihood of flood events. Five (5) distinct flood susceptibility zones were created from the developed database: very low (less than 755). These findings confirm that flood susceptibility in Muzaffargarh is spatially influenced by a complex interplay of topographic, climatic and land cover variables, with rainfall, elevation and LULC emerging as the most significant contributors.

Table 3: Ranges of Floods in District Muzaffargarh

Sr. No	Flood Vulnerable Classes	FR Range	% of Area
1.	Very Low	775.0	11%
2.	Low	890.9	12%
3.	Moderate	1177.0	16%
4.	High	1725.0	24%
5.	Very High	2611.6	36%

Figure 11: Flood Susceptibility Map of District Muzaffargarh



Flood Susceptibility Zonation

Susceptibilities range from low (775–890), moderate (890–1177), high (1177–1724) and very high (more than 1724). According to the results, nearly 36% of the land area is classified as having a very high flood risk, 24% as high, 16% as moderate, 12% as low, and 11% as very low flood risk (Table 2). The majority of the study area's high-to-very highly vulnerable classes are located in the eastern, western, and southern regions (Figure 9). Higher runoff potential, poorly to very poorly drained soil, alluvial deposits, braided floodplains, lower slope gradients, lower elevations, and closer proximity to the main river are the characteristics of these high to very high flood susceptibility zones. These are crucial conditioning factors for flood susceptibility mapping using the FR model.

Discussion

The findings of this study provide a comprehensive evaluation of flood susceptibility in District Muzaffargarh using the Frequency Ratio (FR) model integrated with GIS-based spatial analysis. The FR model effectively quantified the relationship between flood occurrences and six key flood-triggering parameters: elevation, slope, aspect, curvature, rainfall and land use/land cover (Esteves, 2013). These parameters were categorised into sub-classes based on their spatial distribution and FR values, revealing distinct patterns of flood vulnerability across the study area. Elevation played a critical role in flood susceptibility, as water naturally flows from higher to lower regions, concentrating in low-lying areas (Acharya et al., 2019). The results showed that the lower elevation zones (<104 m) had the highest FR value (0.434), indicating a strong correlation with flood occurrence. Conversely, areas above 131 m had lower FR values, suggesting minimal flood impact. This aligns with previous research by Das (2018), which emphasised that lower elevations are more prone to water accumulation and runoff, increasing flood risk. Similarly, slope was another crucial factor, influencing runoff speed and infiltration. Steep slopes generally generate higher runoff and reduce infiltration time, which can lead to potential flash flooding. The highest

FR values for slope were found in flatter regions (<1.2 degrees) with significant runoff accumulation, supporting findings by Shafizadeh et al. (2018) on the role of slope in hydrological processes.

Aspect and curvature also showed notable impacts on flood susceptibility. The aspect influences solar radiation exposure, evapotranspiration and vegetation distribution, indirectly affecting moisture retention and runoff. The FR values for various aspect ranges (e.g., < -63.98 and 60.98 – 140.26) were relatively high (0.195 and 0.185, respectively), indicating their role in moisture dynamics and hence flood risk (Rajeev et al., 2025). The curvature parameter, describing the concavity or convexity of the landscape, also contributed significantly. Concave surfaces (with negative values) tend to collect water, thereby increasing the risk of flooding. The highest FR values in curvature were associated with slightly concave to flat surfaces, consistent with findings by Razandi et al. (2015) and Das et al. (2019). Rainfall emerged as a dominant parameter influencing flood risk. Higher rainfall zones (>366 mm) demonstrated elevated FR values (0.356), signifying greater flood susceptibility due to increased runoff (Hong et al., 2018). This aligns with global studies in semi-arid regions, where sudden heavy rains can trigger flash floods. Rainfall contributes not only to surface water accumulation but also affects soil saturation, runoff velocity and drainage efficiency. LULC patterns were directly correlated with flood occurrences. Areas under water bodies, built-up land, and dry land had higher FR values (0.091, 0.022, and 0.020, respectively), highlighting their reduced permeability and increased runoff potential. Forest and vegetation classes exhibited lower FR values, indicating better water absorption and flood mitigation capabilities (Khosravi et al., 2016). This supports the notion that urbanisation and land degradation intensify flood vulnerability by altering natural hydrological cycles.

Based on the FR scores, the study area was divided into five susceptibility classes: very low, low, moderate, high and very high. The spatial distribution revealed that about 36% of the area falls under the very high flood risk category, with another 24% under high risk. These zones are concentrated in the eastern, western and southern parts of Muzaffargarh. The spatial concentration of high-risk zones can be attributed to a combination of low elevation, gentle slope, proximity to rivers and poor drainage conditions (Devkota et al., 2013). This zonation approach is consistent with studies that highlight the utility of FR models in identifying flood-prone zones for disaster management. The integration of FR and GIS proves to be an effective tool for mapping regional flood risk. The identification of vulnerable zones offers critical insights for policymakers, urban planners and disaster management authorities. It highlights the need for flood-resilient infrastructure in high-risk areas, improved land-use planning, and enhanced drainage systems. Additionally, reforestation and soil conservation measures should be promoted in areas prone to erosion and vulnerable to flooding (Rahmati et al., 2016).

Conclusion

This study assessed flash flood vulnerability in Muzaffargarh, Pakistan, using the Frequency Ratio (FR) model, which was integrated with six conditioning factors: elevation, slope, aspect, curvature, rainfall, and land use/land cover. Monsoonal rainfall, river overflows, low-lying terrain and human activities such as deforestation and unplanned urbanisation primarily influence the region's flood risk. The FR model effectively identified varying degrees of flood susceptibility across the district. Results revealed that 36% of the land falls under very high vulnerability, with an additional 24% categorised as high. Moderate vulnerability accounts for 16%, low vulnerability for 12%, and very low vulnerability for 11% of the area. High-to-very high-flood-prone zones are mainly clustered in the eastern, western, and southern regions—areas characterised by lower elevations, poor drainage, and proximity to rivers. These findings highlight the importance of spatially informed flood risk assessments. Understanding how topographic and environmental parameters influence flood dynamics enables policymakers to design more targeted mitigation and adaptation strategies. The vulnerability maps developed in this study can guide local authorities in prioritising infrastructure development, resource allocation and community preparedness efforts in the most at-risk areas.

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