Integrating GIS and Remote Sensing for Comprehensive Flood Risk Zonation in Tehsil Shah Alam (Peshawar)

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Abstract

A comprehensive assessment of flood risk in tehsil Shah Alam, district Peshawar, Pakistan, was conducted using GIS and remote sensing techniques. Flooding in Pakistan is often exacerbated by human activities like deforestation and urbanization, posing significant socio-economic and environmental challenges. The study utilized 30-meter Landsat imagery, a 12.5-meter Digital Elevation Model (DEM), and rainfall data from the meteorology department to analyze critical factors influencing flood risk, including slope, river proximity, flow length, land use, and precipitation. Data processing included DEM generation, stream order classification, Euclidean distance calculation, flow length measurement, slope analysis, satellite imagery classification, and rainfall data interpolation. The Weighted Overlay Analysis (WOA) technique integrated these parameters to create a detailed flood risk zonation map. The findings highlighted areas with steep slopes, proximity to rivers, long flow lengths, high levels of built-up and barren land, and high rainfall as the most at risk. The study delineated the flood risk zones into five categories, identifying 23.28 square kilometers as very high-risk and 39.46 square kilometers as high-risk, with other areas classified into varying levels of risk. This GIS-based model offers essential insights for targeted interventions in high-risk regions, enhancing flood management and mitigation efforts.

Keywords: Flood Risk, Susceptibility, Digital Elevation Model, Weighted Overlay Analysis.

Introduction

Flooding, defined as the overflow of water onto dry land often occurs due to excessive water from severe rainfall or other natural events. It is a natural phenomenon, frequently exacerbated by human activities like deforestation and urbanization. Severe floods, characterized by rapid and hazardous water rise, lead to significant socio-economic and environmental impacts, including loss of life and property damage (Ali et al., 2024a; Watson & Haeberli, 2004). Predicting floods is challenging due to the rapid onset and intensity of water rise (Borga, 2011), with events becoming more common due to climate change (Groisman et al., 2005; Mason et al., 1999). Contributing factors include poor land management, deforestation, and uncontrolled land use (Romshoo & Rashid, 2014). Floods are generally categorized into river floods, which cause significant property damage, and flash floods, which result in more fatalities. Flash floods occur quickly after heavy rainfall, especially in arid regions with little vegetation, while river floods develop more slowly but affect larger areas.

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In Pakistan, floods are the most common natural disaster, often resulting in extensive infrastructure damage and loss of life (NDMA, 2012; Kirsch et al., 2012). The country experiences regular riverine and flash floods, particularly during the monsoon season. Notable floods include the 2010 event, which caused over two thousand deaths and extensive damage, and the 2022 floods, which displaced 32 million people and resulted in an estimated $30 billion in economic losses (Federal Flood Commission, 2012; NDMA, 2022; Ullah et al., 2024; UNICEF, 2022). Urban flooding is well-documented, but there is a need for improved understanding and measurement tools for flood risk (Fedeski & Gwilliam, 2007). This study aims to propose a robust methodology for assessing flood risk, focusing on urban areas in Pakistan. Risk assessment, crucial for disaster risk reduction, involves identifying vulnerabilities and building resilience. Initially defined as the interaction between hazard and vulnerability, risk assessment now also includes exposure and capacity factors (Schneiderbauer & Ehrlich, 2015). Various models and frameworks, such as the "Risk Triangle" and the Pressure and Release model (PAR), help explain these relationships, integrating disaster risk management and climate change adaptation (Davidson & Shah, 2013). Empirical studies use indices for hazard, exposure, sensitivity, and capacity to assess risk and vulnerability (Fedeski & Gwilliam, 2007; Ahsan & Warner, 2014).

GIS and Remote Sensing (RS) technologies play a critical role in wildlife, tourism, urban planning, water management and flood risk assessment (Ali et al., 2024b). They are used to create Digital Elevation Models (DEM), monitor floods, and map flood risk zones (Sanyal & Lu, 2004). These technologies enable the delineation of drainage networks and basin extents and help manage emergencies post-disaster. Additionally, they support probabilistic approaches and flood vulnerability mapping using hydrological and stochastic methods (Horritt & Bates, 2002). The versatility of GIS and RS in handling multi-dimensional spatial data makes them invaluable tools for comprehensive flood risk assessment (Coppock & Sharma, 2018).

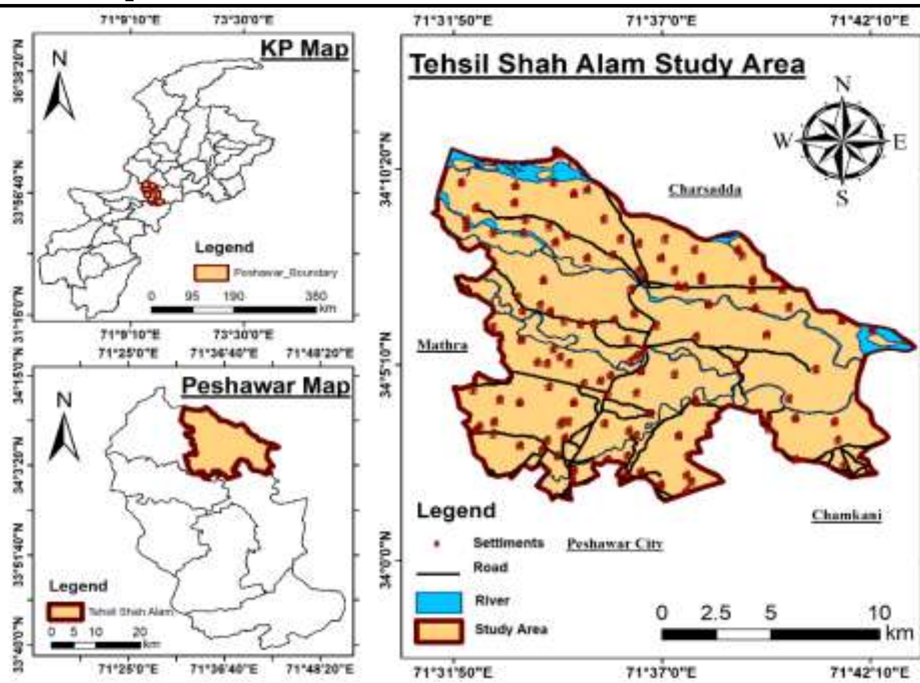
Importance

The importance of this work lies in its ability to provide a scientifically robust and spatially explicit framework for flood risk management in tehsil Shah Alam. By integrating various geospatial and hydrological data through advanced GIS and remote sensing techniques, the study delivers a comprehensive flood risk zonation map that is crucial for policymakers, urban planners, and disaster management authorities. This targeted identification of high-risk areas enables more efficient allocation of resources and implementation of mitigation strategies, potentially reducing the socio-economic impacts of flooding. Pakistan experiences significant flooding almost every year, with severe floods in 2010 affecting 20 million people and causing damage worth $10 billion, highlighting the need for effective flood risk management. In Khyber Pakhtunkhwa (KP) province, where tehsil Shah Alam is located, flooding has led to substantial human and economic losses. For example, the 2015 floods in KP resulted in over 200 deaths and displaced thousands of people. According to the World Bank, the financial losses due to floods in Pakistan amount to approximately 3% of the country's GDP annually. Effective flood risk zonation can significantly reduce these losses by guiding infrastructure development and disaster preparedness. Rapid urbanization and deforestation in regions like tehsil Shah Alam exacerbate flood risks, with studies showing that urban areas are particularly vulnerable due to impervious surfaces increasing runoff and flood intensity. Climate change is expected to increase the frequency and intensity of extreme weather events, including floods. This study's methodology can help adapt to these changes by providing updated and accurate flood risk assessments, promoting sustainable land use practices and resilience against future flood events.

Study Area

Peshawar, the provincial capital of Khyber Pakhtunkhwa, is centrally located within the province and spans an area of approximately 1,267 km² between the latitude of 33°44′ and 34°15′ North and longitudes of 71°22′ and 71°45′ East. The district comprises seven tehsils: Peshawar city, Mathra, Shah Alam, Badbher, Peshtakhara, Chamkani, and Hassan Khel (FR Peshawar). The climate in Peshawar features mean winter minimum temperatures of 1.28°C and maximums of 30.25°C, while in summer, maximum temperatures can reach 47.45°C with minimums around 15.60°C. The region receives an average annual precipitation of 400 mm, with more rainfall occurring in the winter months compared to summer. The specific study area, Shah Alam tehsil, is situated in the northern part of district Peshawar, between the latitudes of 33° 59' 13.68" and 34° 10' 33.86" north of the equator and longitudes of 71° 30' 59.20" and 71° 44' 29.93" east of the prime meridian. Shah Alam tehsil is bordered by district Nowshera to the east, district Charsadda to the north, Mathra and Peshawar city tehsils to the west, and Chamkani tehsil to the South.

Figure 1: Study area map



Data Collection

This study utilizes two distinct data types: open data sources and departmental data. The open data sources include 30 meter resolution satellite imagery provided by the United States Geological Survey (USGS) and a 12.5 meter Digital Elevation Model (DEM) extracted from earth data. The departmental data comprises detailed rainfall records obtained from the Meteorology Department, providing essential information for the study's analysis.

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Table 1: Data &Data Source

Data layer		Resolution	Data Source
Satellite Imagery	Landsat	30m	https://earthexplorer.usgs.gov/
DEM	Alos Palsar	12.5m	https://search.asf.alaska.edu/#/?dataset=ALOS

Source: Rainfall Data, Meteorological Department of Khyber Pakhtunkhwa

Data Processing

In order to achieve reliable and accurate flood risk zonation, the methodology presented in the flowchart offers a methodical and thorough approach to tehsil Shah Alam flood risk assessment. It does this by combining a variety of data sources and analytical tools inside a GIS framework. Digital elevation models (DEMs), satellite imaging, and rainfall data are all incorporated into the data collection process, which uses departmental data as well as information from public sources. Table 1: Detail of data sources used in analysis

Digital Elevation Model (DEM) and Hydrological Analysis

The DEM is the starting point for the extraction of important topographic elements, which makes it possible to compute the slope, flow length, and stream order that are necessary for hydrological modelling. Creating stream orders aids in the classification of streams and sheds light on the hydrological structure and how it affects flood danger. A critical metric for evaluating flood exposure based on closeness to water bodies is river distance computation, which uses the Euclidean Distance Tool to calculate the straight-line distance from each place in the study area to the closest stream. Using ArcGIS's Flow Length Tool, one may determine the length of the flow and identify locations that are more likely to flood due to possible water accumulation and extended flow. Another crucial stage in understanding runoff dynamics is slope analysis, which finds the steepest downhill routes; steeper slopes cause faster runoff, which increases downstream flood risk.

Satellite Imagery and Land Use Classification

High-resolution Landsat 8 data, in particular, is preprocessed using ArcGIS's Composite Bands and Extract by Mask tools to get it ready for additional study. By classifying land into distinct LULC classes by supervised classification using the Maximum Likelihood approach, information about the ways in which different forms of land cover affect flood risk is obtained.

Rainfall Data Interpolation

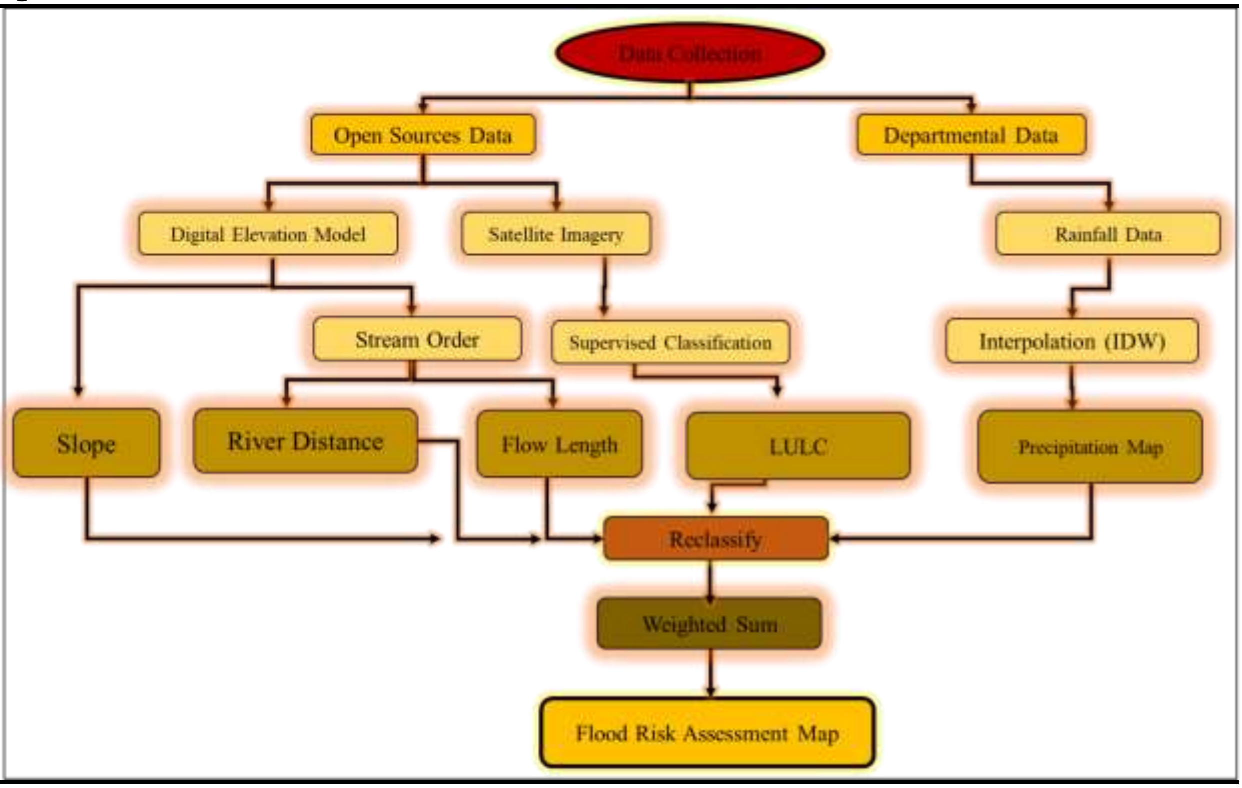
The Peshawar Regional Meteorological Department provides rainfall data, which is interpolated using the Inverse Distance Weighted (IDW) method to construct a continuous surface of precipitation distribution. This process is crucial for comprehending how differences in rainfall over space affect the danger of flooding.

Reclassification and Weighted Overlay Analysis

By combining related values into more inclusive groups, reclassification streamlines data layers and concentrates on important elements for analysis that is easier to understand and apply. These classed data layers are then integrated using the Weighted Overlay Analysis (WOA), which assigns

weights depending on their relevance to flood risk. The result is a full map of flood risk assessment. This final output provides important information for flood management and mitigation activities by identifying zones with varied levels of flood risk (high, moderate, and low).
Its thorough data integration from many sources, which provides a comprehensive flood risk assessment, justifies this methodology. In order to accurately evaluate and understand the connections between topography, hydrology, and land use, advanced GIS techniques including Euclidean Distance, Flow Length, and IDW interpolation are used. For the purpose of identifying minute changes in flood risk, high-resolution data guarantees precise geographical information. Accuracy in approach is ensured by the solid framework, which uses well-known methods such as weighted overlay analysis and stream ordering. In order to help policymakers, disaster management authorities, and urban planners make educated decisions, an actionable flood risk assessment map that provides precise and spatially explicit insights is generated. Accurate flood risk assessment is crucial for, and this thorough and scientifically sound methodology makes use of cutting-edge GIS and remote sensing technology to providing accurate flood risk assessment vital for enhancing preparedness and resilience against flooding in tehsil Shah Alam.

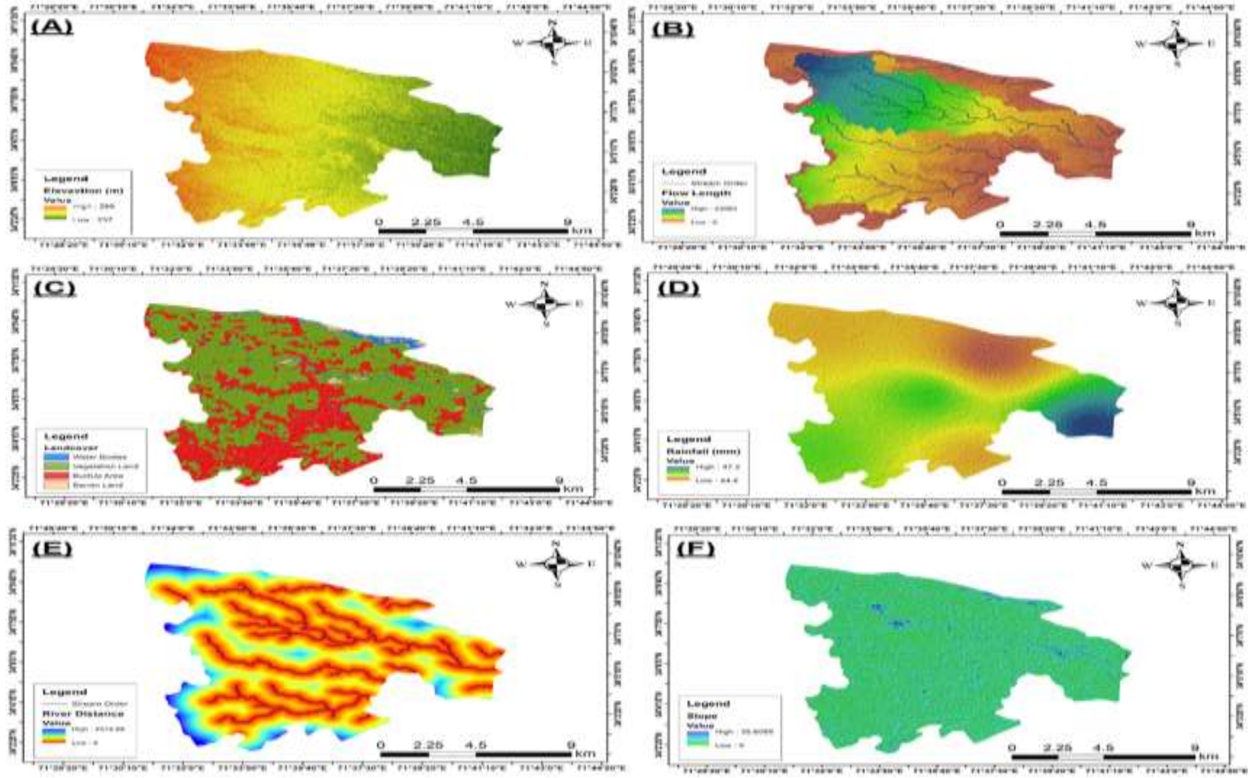
Figure 2: Flow chart



Results and Discussion

The study's analysis revealed critical factors influencing flood risk within tehsil Shah Alam. The slope analysis showed that the steepest slopes reached up to 35.6 degrees. These areas are particularly susceptible to erosion and rapid surface runoff during rainfall events, increasing flood risk. The river distance analysis highlighted regions within a 500-meter buffer of the streams as high-risk zones. The flood risk decreases as the distance from the stream network increases, underscoring the importance of proximity to water bodies in assessing flood vulnerability.

Figure 3: (A) Digital Elevation Model, (B) Flow Length, (C) LULC, (D) Rainfall, (E) River Distance (F) Slope. Parameters used for the assessment of flood risk zones



In the flow length analysis, areas with longer flow paths were identified as having heightened susceptibility to flooding. This finding emphasizes the significance of hydrological connectivity and flow pathways in determining flood-prone regions within the study area. The land use and land cover (LULC) analysis provided insights into the spatial distribution of different land cover types, including built-up areas, croplands, water bodies, and barren lands. The spatial distribution of LULC in tehsil Shah Alam includes 3.6 sq km of water, 99.8 sq km of vegetation cover, 53.45 sq. km of built-up area, and 2.19 sq km of bare ground.

Finally, the rainfall analysis revealed average precipitation ranging from 44.2 mm to 47.2 mm across the study area. This data is crucial for understanding the intensity and distribution of rainfall, which directly impacts flood occurrence and severity. Together, these analyses provide a comprehensive assessment of the factors contributing to flood risk in tehsil Shah Alam, guiding flood prevention and management strategies.

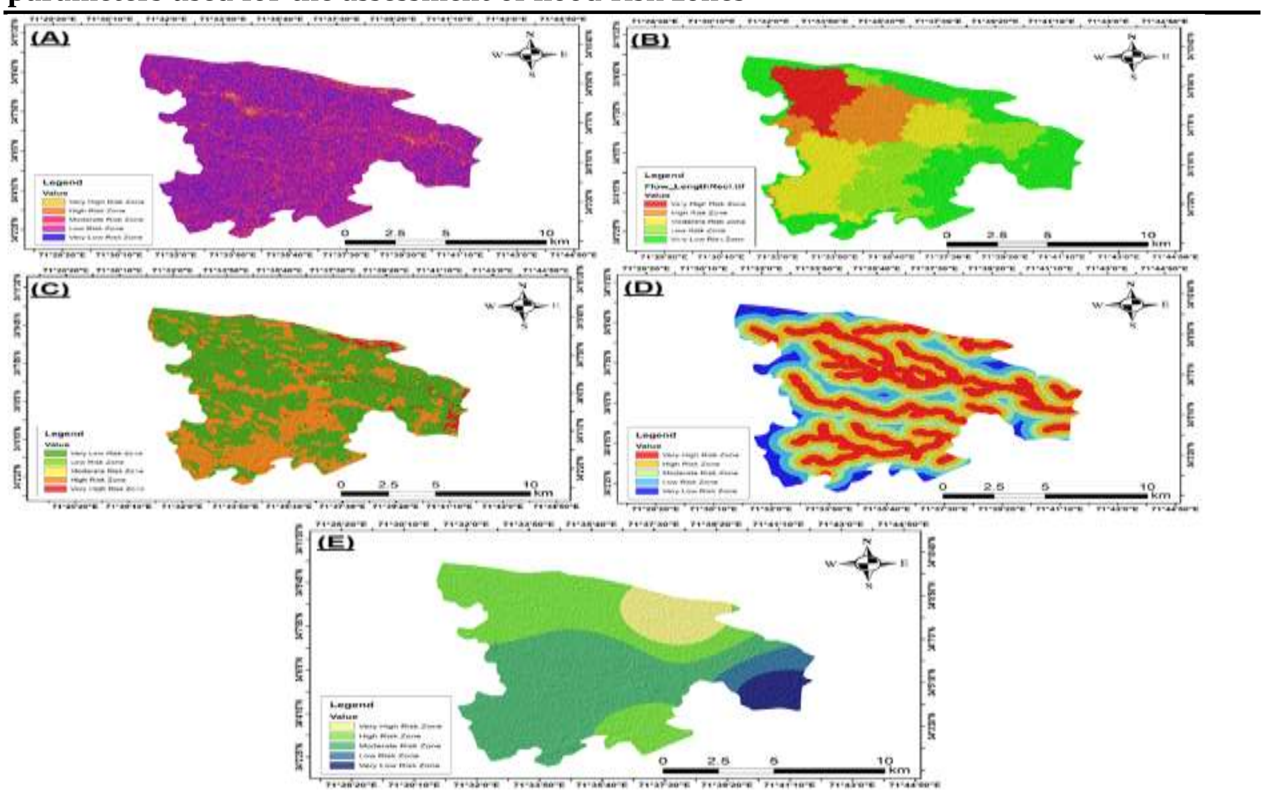
Reclassification

After conducting a detailed analysis of slope, river distance, flow length, land use, and precipitation data, each parameter was categorized into five distinct classes to streamline the data for easier management and interpretation. This reclassification helped to group similar areas, making it easier to understand the various flood risk levels across the study area. The findings indicated that areas with steeper slopes in tehsil Shah Alam, marked by yellow and orange hues on the map, are at a higher risk of flooding due to rapid water runoff. In contrast, areas with gentler slopes, shown in purple and blue, are less prone to flooding because water moves more slowly and can be better absorbed. This differentiation emphasizes the need for improved flood management strategies in steeper regions and highlights the role of topography in assessing flood risk.

Proximity to rivers was also identified as a critical factor, with areas closest to rivers (shown in red) being at very high risk, especially during heavy rainfall events. Areas marked in orange and yellow also face significant to moderate risks, with the threat decreasing as the distance from rivers increases. The light and dark blue areas, which are further from the rivers, were found to have a lower flood risk. The analysis of flow length revealed that regions with longer overland flow paths, represented in red and orange, are more prone to flooding due to significant runoff accumulation. In contrast, areas with shorter flow lengths, shown in light and dark green, face a lower flood risk, indicating that the northern and central parts of tehsil Shah Alam are more vulnerable compared to the relatively safer southern and eastern areas.

In terms of Land Use Land Cover (LULC), the study found that areas with a high concentration of built-up and bare land, marked in red and dark red, are at greater risk due to urbanization and environmental pressures. Conversely, areas with more vegetation, shown in green, are less susceptible, highlighting the importance of maintaining green spaces to mitigate risk and support environmental stability. The reclassification of rainfall data identified zones at various risk levels based on rainfall intensity. Areas with very high risk, shown in yellow, are particularly vulnerable to heavy and erratic rainfall, which can negatively impact infrastructure, agriculture, and the environment. Other zones, ranging from moderate (light green) to very low risk (dark blue), provide a detailed picture of rainfall hazards across the region, offering crucial information for regional planning and mitigation measures.

Figure 4: (A) Slope, (B) Flow Length, (C) LULC, (D) River Distance (F) Rainfall. Reclassified parameters used for the assessment of flood risk zones



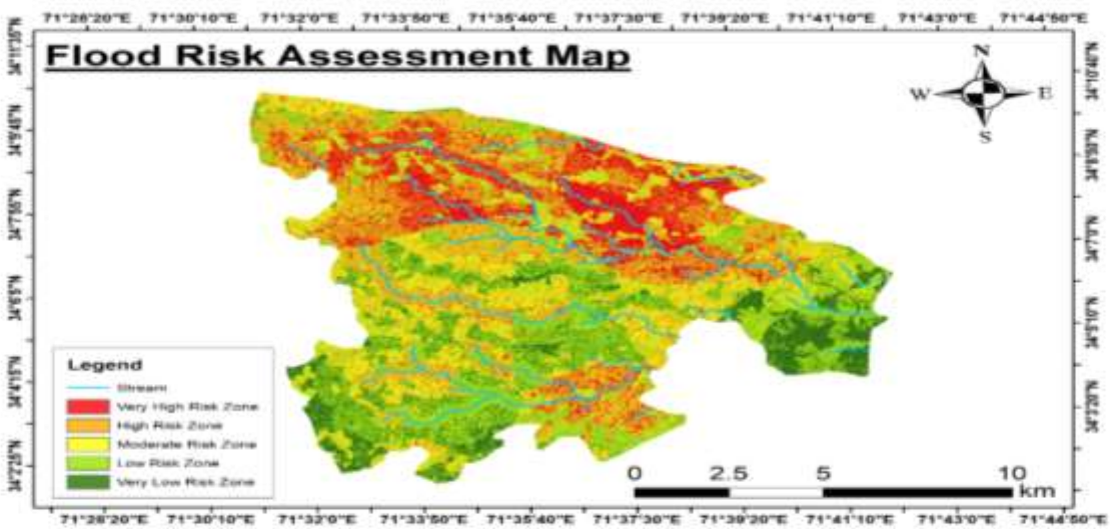
Flood Risk Zones

The study's findings reveal that flood risk in tehsil Shah Alam is significantly influenced by several key factors. Areas with high steepness, close proximity to rivers with longer flow lengths, increased coverage of built-up and barren land, and higher rates of rainfall consistently show elevated flood risk. In contrast, regions characterized by gentle slopes, greater distances from rivers with shorter flow lengths, and predominantly vegetated land cover exhibit lower flood risk. Quantitatively, the flood risk assessment identifies specific areas within tehsil Shah Alam based on their risk levels:

- Very High-Risk Zone: Approximately 23.28 square kilometers
- High-Risk Zone: Approximately 39.46 square kilometers
- Moderate Risk Zone: Approximately 39.87 square kilometers
- Low-Risk Zone: Approximately 39.58 square kilometers
- Very Low-Risk Zone: Approximately 16.30 square kilometers

The results indicate that areas in close proximity to rivers are particularly susceptible to flooding, emphasizing the critical role of water proximity in flood risk assessment. The developed GIS-based flood risk model effectively identifies and prioritizes these at-risk areas, providing a valuable tool for flood management and mitigation efforts in tehsil Shah Alam.

Figure 5: Flood Risk Zonation Map



Conclusion

The findings from the flood risk assessment in tehsil Shah Alam, district Peshawar, offer valuable insights into the spatial distribution and underlying factors influencing flood vulnerability. The use of GIS and remote sensing techniques enabled a detailed analysis, highlighting areas with varying levels of flood risk. The study revealed that regions with a high concentration of built-up and barren land are more vulnerable to flooding, aligning with the land use transition theory, which posits that urbanization significantly alters hydrological processes by increasing impervious surfaces and reducing infiltration rates. The proximity to water bodies was another critical factor, with areas closer to rivers at higher risk, consistent with the concept of hydrological connectivity. This reflects the natural flow of water towards lower elevations and river channels, increasing the likelihood of inundation in adjacent areas. Slope analysis identified steep gradients as high-risk due to the potential for rapid surface runoff, supporting geomorphological principles that steeper slopes facilitate faster water movement and increase flash flood risks. The study also found that areas with higher average rainfall are more susceptible to flooding, supporting the environmental Kuznets curve theory, which suggests that environmental degradation initially rises with economic development but can decline with sustainable practices. Additionally, regions with longer flow paths were found to have increased flood susceptibility, linked to watershed management concepts and the role of hydrological pathways in distributing surface water. The findings are theoretically justified by the land use transition theory, environmental Kuznets curve, and principles from geomorphology and hydrology. This study emphasizes the importance of using GIS and remote sensing technologies in flood risk assessment, providing comprehensive data analysis and visualization capabilities. The results highlight the need for targeted flood management strategies, such as improved urban planning, sustainable land use practices, and enhanced infrastructure, to mitigate flooding impacts. Implementing these measures can balance economic development with environmental sustainability, reducing flood risks and enhancing community resilience in tehsil Shah Alam.

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