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Geospatial Analysis for Flood Vulnerability and Risk Assessment: A Case Study of Omdurman and Um Badda Localities Khartoum State- Sudan

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ABSTRACT

Flooding is one of common sort of natural disaster facing Sudan. Recently, frequency and gravity of large-scale flood disasters have increased globally, resulting in casualties, destruction of property and huge economic loss. The destructive flood disaster devastated many areas in Sudan especially, in urban area such as Khartoum State. This study employs advanced geospatial analytical techniques to assess and maps the flood vulnerability and risk in Omdurman and Um Badda localities within Khartoum State, Sudan. The study's objective is to utilize integrated geospatial data to determine and map the trend, location, and magnitude of land use affected by flooding in the study area. The study uses satellite imagery and geographic information system (GIS)-based hydrological modeling to delineate regions susceptible to flooding, integrates topographical and hydrological data to classified areas into vulnerable flood categories. The findings indicate that approximately 7.83 square kilometers of the study area is classified as least vulnerable, while a substantial 2503.44 square kilometers is highly vulnerable to flooding. The study area presents critical areas at high to very high flood risk, encompassing 64.21% of the study area at high risk and 4.97% at very high risk, this highlights the urgent necessity for intervention and mitigation Measurement to reduce flood risks and build resilience in such region. This research highlights the role of geospatial technology in natural disaster management and enhancing community resilience against increasing flood frequencies and changing climate.

Keywords: Geospatial analysis, Climate change, flood vulnerability, risk mapping, Omdurman localities, Khartoum State, Sudan

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INTRODUCTION

Floods, exacerbated by climate change, pose significant threats to communities worldwide, particularly in vulnerable regions like Sudan. Understanding the factors that contribute to flood vulnerability is crucial for effective disaster risk reduction as well as security, personal behavior and sustainable development (Nguyen *et al.*, 2023). Sudan, situated in a region highly vulnerable to climate change, has experienced frequent and severe flooding in recent decades. These floods, often triggered by intense rainfall during the rainy season, have had significant impacts on the lives of millions of Sudanese

people. Historical records indicate that major floods have occurred in Sudan in 1962-1965, 1978-1979, 1988, 1994, 1998, 1999, and 2006. These events have resulted in widespread damage to infrastructure, displacement of populations, and loss of livelihoods. The types of floods in Sudan can be categorized into three main types: urban flash floods, riverine floods, and valley floods. Urban flash floods are caused by intense rainfall in urban areas, while riverine floods occur when rivers overflow their banks. Valley floods result from the accumulation of rainwater in valleys and floodplains. Research has shown that many regions in Sudan are at high risk of flooding (Hassan *et al.*

2023). Climate change, on the other hand, is projected to exacerbate these risks, leading to more frequent and intense flood events in the future.

Flooding is a recurring challenge in Sudan, often exacerbated by climate change. These events disproportionately impact vulnerable populations, particularly women and marginalized groups. Socioeconomic disparities, limited access to resources, and cultural norms can amplify the vulnerability of women to flood-related risks. Women may face challenges in accessing information, decision-making processes, and relief aid, leaving them more susceptible to the consequences of flooding (Jerin *et al.*, 2023).

Furthermore, floods can exacerbate gender-based inequalities by disrupting livelihoods, increasing domestic burdens, and exposing women to heightened risks of violence and exploitation. To effectively address the impacts of flooding in Sudan, it is crucial to recognize and mitigate these gender-specific vulnerabilities (Jerin *et al.*, 2023).

Vulnerability is a complex concept encompassing a system's susceptibility to harm and its capacity to cope with and recover from adverse events. It is influenced by a range of factors, including physical, social, and economic conditions (Berry, 2006; Füssel, 2006). Physical vulnerability is linked to geographic factors such as topography, hydrology, and land use patterns. Social vulnerability is shaped by socio-economic factors, including poverty, inequality, and access to resources (Karimzadeh *et al.*, 2014). Moreover, climate change is exacerbating flood risks in many regions worldwide. In Asia, for example, storms and floods have caused significant loss of life and widespread damage. Flooding can lead to erosion, destruction of infrastructure, and loss of livelihoods (Senapati, 2022).

Land use changes are a major driver of increased flood risk. Urbanization, deforestation, and agricultural intensification can alter hydrological processes, reduce infiltration, and increase runoff, leading to more frequent and severe floods. It is imperative that land use policies ensure sustainable development and improve quality by balancing demand and supply, needs and interests, or between conflicting uses of the land (Karimzadeh *et al.*, 2014). Usually, or more often than not, a poorly developed planning process leads to the transformation of natural land surfaces into artificial ones designed for human activities, which increases social vulnerability. Therefore checking the process of land use change is very important for evaluating its effectiveness (Ponce, 2013; Naranjo *et al.*, 2020).

In the recent past, the frequency and gravity of large-scale flood disasters have increased globally, resulting in casualties, destruction of property and huge economic loss. The destructive flood disaster devastated many areas in Sudan including Khartoum State. Developing countries in Africa such as Benin, Ghana, Nigeria, Senegal, and Sudan have recently experienced severe flooding, leaving a considerable number of human

casualties and thousands displaced. The ability to accurately identify, measure and evaluate the various vulnerabilities of affected people and communities is the right step toward reducing disaster risk. The lack of services in the study area resulted in poor quality of life for the people affected by flooding, such as the vulnerability of housing, access to water, and other services. Geospatial data information and Remote Sensing are provided with a system for collecting, managing, storing, analyzing, manipulating, and presenting geographic or geographical data. Together, remote sensing and GIS enable the collection, archiving, analysis, and visualization of allows comprehensive analysis of flood risks across vast geographical regions. Therefore, this study aimed to assess the flood of vulnerability factors in the Ombadda and Omdurman localities. The specific objectives of the study are:

1. Assess and determine the trend, location, and magnitude of flood impact in Omdurman and Ombadda localities.
2. Map land use/land cover affected by flood inundation during flood period.
3. Identify and evaluate the main factors affecting land use change and flood vulnerability.

METHODOLOGY

The methodologies are based on the integration of different data sources and other geospatial data such as Landsat8, Digital Elevation Model (DEM), land use and land cover, and climatic data. The study applied GIS/RS software for mapping flood extent and inundation, assessing the flood impact on land-cover and producing flood risk maps that could be used for decision support system. The study is carried out in Omdurman and Umbadda, two localities situated in Khartoum State, Sudan.

Study area

Khartoum State, the most populous state in Sudan, comprises seven localities: Khartoum, Jebel Awlia, Bahri (Khartoum North), Omdurman, Karari, Um Badda, and Sharg El-Neel (East Nile). According to the 2008 population and housing census, the state's population is 21% rural, 68% urban, and 11% internally displaced (Khartoum State Government, 2011; UNDP, 2011; CBS, 2008). This study focuses on flood vulnerability assessment in Omdurman and Um Badda, two localities within Khartoum State, Sudan. The study area, situated between longitudes 31° 45' 00" E and 32° 30' 00" E and latitudes 16° 30' 00" N and 15° 10' 00" N (Figure 1), covers approximately 3898.60 km². Khartoum State's climate falls within the desert and semi-desert ecological zone, characterized by hot to very hot summers, a short rainy season, and warm to cold, dry winters (UNDP, 2011). The rainy season typically extends from July to October, with a

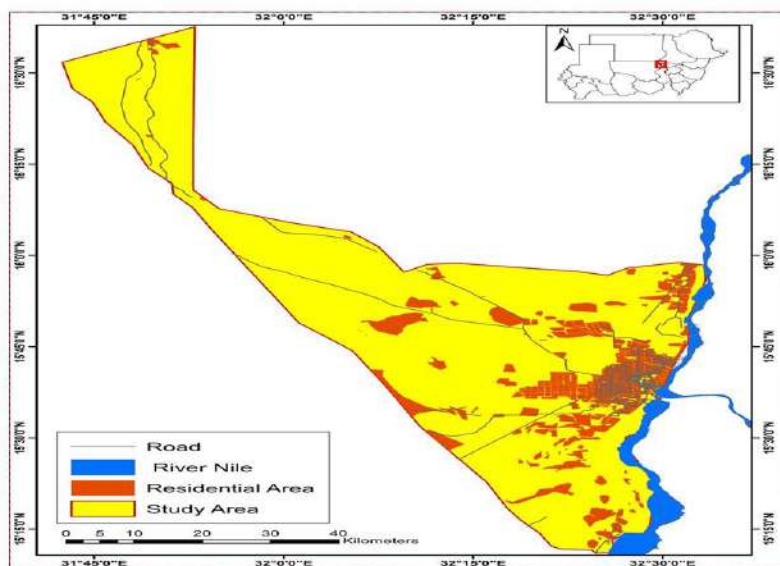


Figure 1: Location of the study area

Table 1: Data description and Sources.

| Data Layer | Source/Reference |
|-------------------------------|--|
| Digital Elevation Model (DEM) | United States Geological Survey (USGS) (https://glovis.usgs.gov/) |
| River Nile | Dams Implementation Unit (DIU) |
| Roads | Sudanese Survey Authority |
| Land Use/Land Cover | Food and Agriculture Organization (FAO) |
| Urban Areas | Ministry of Infrastructure |
| Soil Data | Geological Research Authority |
| Rainfall Data | USGS FEWS NET Data Portal |

mean seasonal (June–September) rainfall of approximately 121 mm and an average of 15 rainy days. August is the wettest month, accounting for 48.3% of the mean rainfall (WMO, 2023). Rainfall in the state is characterized by high-intensity, short-duration storms. Khartoum State experiences a very high potential evaporation rate (2.2–7.0 mm per day), with evapotranspiration significantly exceeding rainfall amounts (Soil Conservation Administration, 2000). The topography of Khartoum State is generally flat, with slight slopes towards the banks of the Blue Nile, White Nile, and River Nile, interspersed with a few rocky outcrop hills. The topography is further characterized by the terraces and floors of the Nile valleys in the northeastern part (Hamid and Elhassan, 2014). The drainage pattern in Khartoum State is dominated by the Nile River, its tributaries, and ephemeral watercourses (wadis) (Soil Conservation Administration, 2000).

Data Description and Acquisition

Data was gathered during the data collection process from many sources using a variety of methods, including surveys and data portals. These techniques were utilized to get additional data quickly and easily. Specific data layers were gathered to determine the study area (Table 1).

Digital elevation model (DEM)

A DEM is a digital representation of the Earth's bare ground topography, excluding vegetation, structures, and other surface features (USGS). DEMs are crucial for flood vulnerability assessment as they provide insights into elevation variations within the study area, which directly influences flood risk.

River Nile

Omdurman's location on the west bank of the Nile significantly impacts its development, transportation, and water resources. Understanding Nile's flow patterns, historical flood events, and potential for future flooding is crucial for urban planning and disaster preparedness. The Nile serves as a primary source of water for drinking, irrigation, and industrial use. Data on water quality and availability is essential for sustainable water management.

Roads

Road networks influence urban growth patterns, accessibility, and economic activities. Analyzing road density, connectivity, and traffic flow can inform transportation planning and urban development strategies. Road networks determine how easily people and goods

can move within and outside Omdurman, impacting economic opportunities and social interactions.

Land Use/Land Cover

Monitoring changes in land use/land cover over time can reveal the extent and pace of urban sprawl, highlighting areas of rapid development and potential conflicts with natural ecosystems. Understanding land use patterns helps in managing natural resources like water, soil, and vegetation, ensuring their sustainable use. Analyzing land cover changes can assess the impact of urbanization on the environment, such as deforestation, soil erosion, and biodiversity loss.

Urban Areas

Data on urban areas can reveal population density and distribution within Omdurman, informing urban planning and service provision. Analyzing urban areas helps identify areas with inadequate infrastructure, such as water supply, sanitation, and transportation, guiding development priorities. Urban data can provide insights into socioeconomic disparities within Omdurman, such as access to education, healthcare, and employment opportunities.

Soil Data

Soil data is crucial for assessing agricultural productivity and identifying suitable areas for different crops. Analyzing soil properties can help monitor land degradation, such as soil erosion and salinization, and implement appropriate mitigation measures. Soil data can reveal potential environmental risks, such as soil contamination and pollution, guiding environmental protection efforts.

Rainfall Data

Rainfall data provides insights into the region's climate variability and potential for droughts and floods, influencing water resource management and agricultural practices. Rainfall patterns significantly impact agricultural productivity, informing crop selection and irrigation strategies. Rainfall data is essential for hydrological modeling, predicting river flows, and assessing flood risks.

Data collection

A quantitative approach was employed for this research, involving the collection and analysis of numerical data. This method facilitates the identification of trends, averages, potential causal relationships, and the extrapolation of findings to broader contexts. Specifically, a correlational research design was adopted within the quantitative framework. This non-experimental approach involves measuring two variables – flood vulnerability drivers and flood occurrences which means flood affected

areas – to understand the relationships between them without introducing external factors that might influence the results. Data was collected from various sources using diverse methods, including surveys and online data portals. These strategies enabled efficient data acquisition for the study area, as detailed in (Table 1).

Data Analysis

The study applied integrated process of image processing, images classification and DEM hydrological analysis using ArcGIS 10.7.1 (2020) for generating flood vulnerability maps that identify high-risk areas within Omdurman and Um Badda localities. Image enhancement and supervised classification were applied to generate the land use and land cover map of the study area. Hydrological analysis, Multi Criteria Analysis MCA as well as weighted overlay were also applied to generate the flood risk and vulnerability maps. The classification process for flood mapping, with initial pre-processing carried out to improve visualization and interpretation for flood mapping (Figure 2). The raster image support very strong to the rainwater flow in the study area, since is the area drainage pattern in Khartoum State is characterized by the dominance of the Nile, its tributaries and the ephemeral water courses (Wadies).

RESULTS

Based on image classification and hydrological analysis the study area is considered highly vulnerable to flooding taking into account factors like land use, elevation, and soil type which make most of areas susceptible to flooding. Integration of GIS analysis tools and image classification results expressed with maps figures.

Digital elevation model (DEM)

Using ArcGIS, the DEM was transformed into elevation raster layers, depicting the topography of the study area. Low-lying areas were identified as highly vulnerable to flooding, while elevated regions exhibited reduced susceptibility. This differentiation highlights the role of elevation in flood vulnerability and is presented in the DEM map (Figure 3).

Slope factor

The slope of the study area, derived from a 90-meter contour interval using a Digital Elevation Model (DEM), was categorized into five classes based on its influence on flooding. Areas with low slopes, ranked highest in vulnerability, are more prone to water accumulation and flooding. Conversely, steep slopes, ranked lowest, are less susceptible due to faster water runoff. This classification is visually represented in re-categorized slope raster layers (Figure 4).

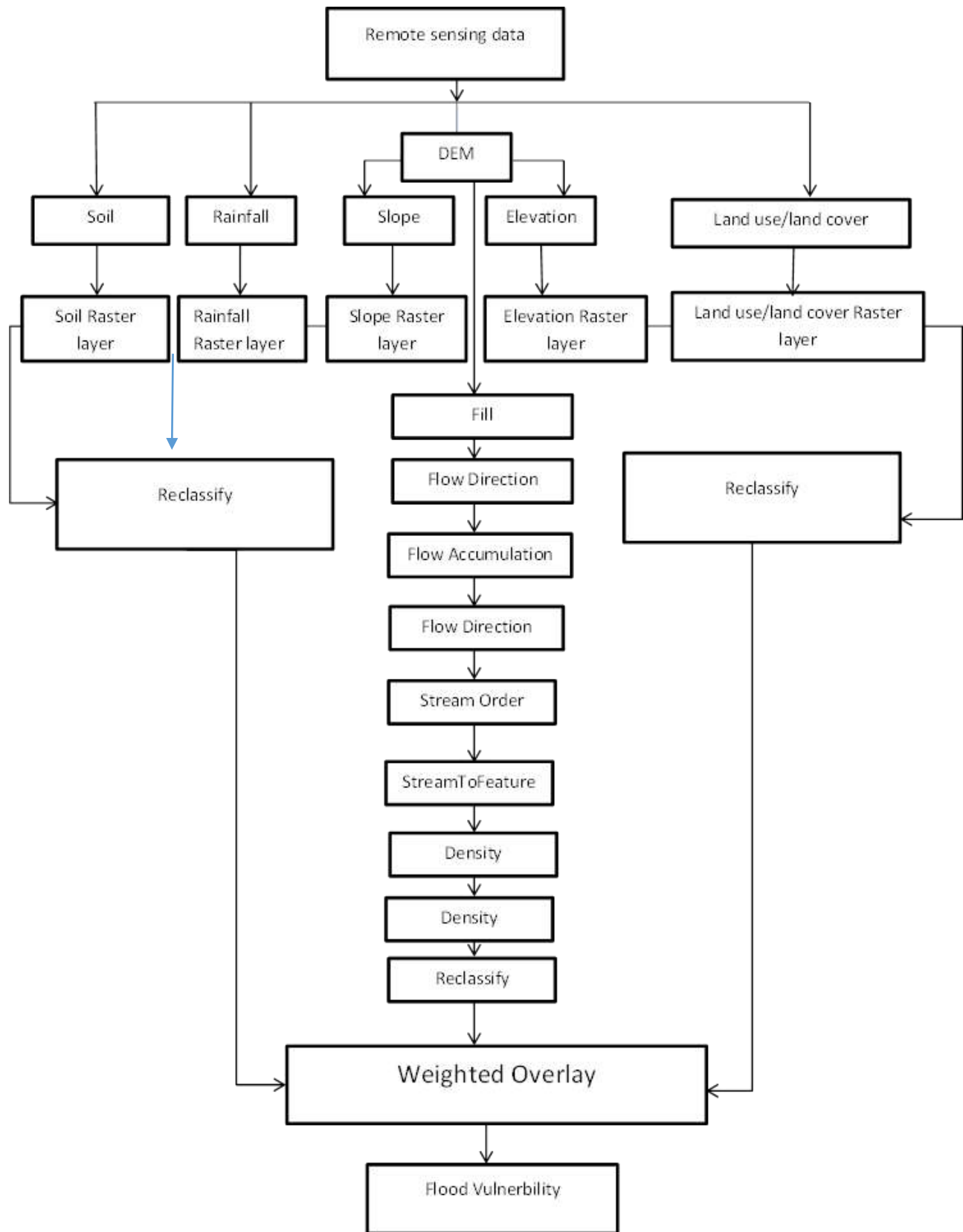


Figure 2. The methodological flow chart of flood mapping

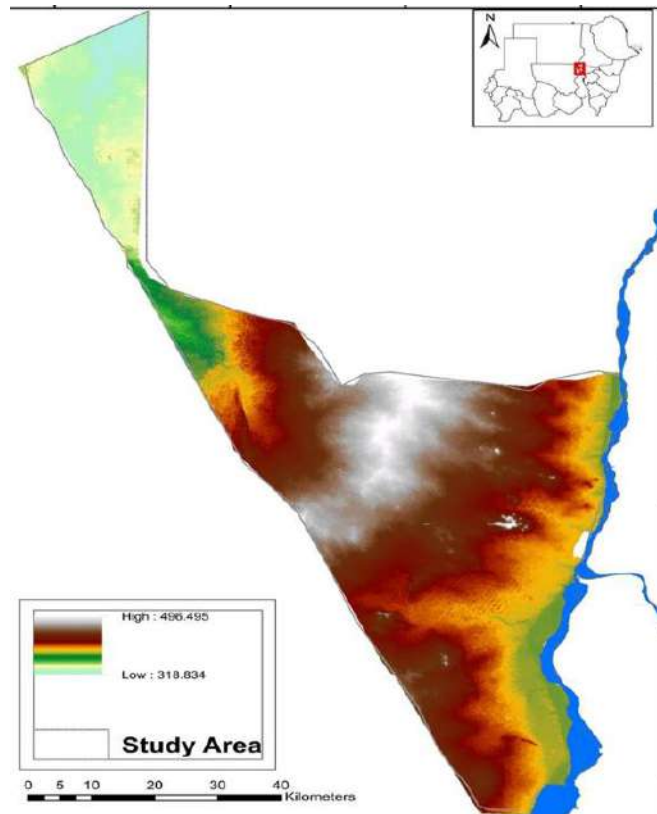


Figure 3: Digital Elevation Model (DEM) of the study area

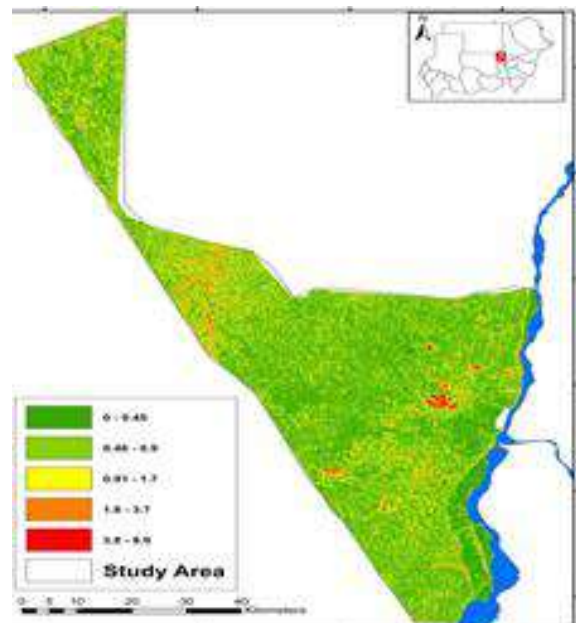


Figure 4: The slope of the study area

Rainfall factor

Rainfall data, collected from the USGS FEWS NET Data Portal, were interpolated using the Inverse Distance Weighting (IDW) method to create a spatial rainfall map. This interpolated data was represented as a raster image

for use in thematic maps. The precipitation data were categorized into five classes, with areas of higher rainfall indicating increased flood vulnerability. Areas receiving the heaviest rainfall were ranked highest, as shown in the reclassified precipitation map (Figure 5).

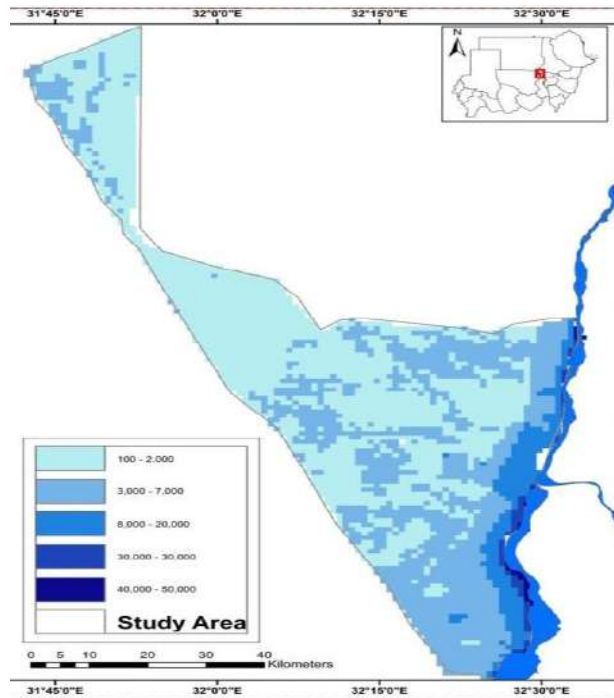


Figure 5: Rainfall map of the study area

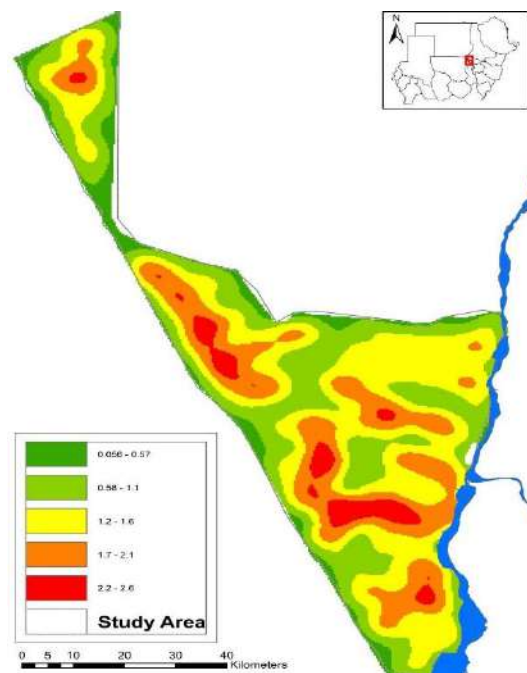


Figure 6: Drainage density of the study area

Drainage density factor

Drainage density, calculated as the total length of streams divided by the drainage area, was mapped to evaluate water flow patterns. All layers were overlaid to create the

final flood map. Areas with high drainage density were classified as highly vulnerable due to their rapid water accumulation, which increases flood risk. This is illustrated in the drainage density map and the reclassified drainage density map (Figures 6 and 7).

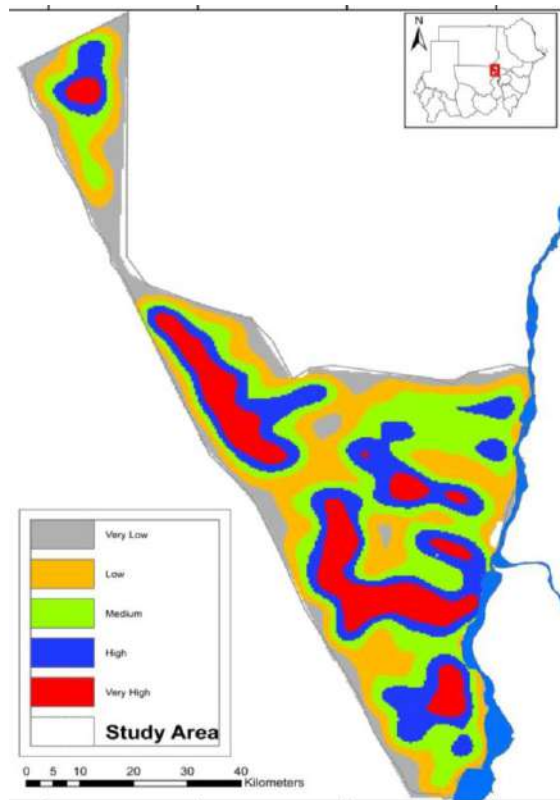


Figure 7: Reclassified Drainage density map of the study area

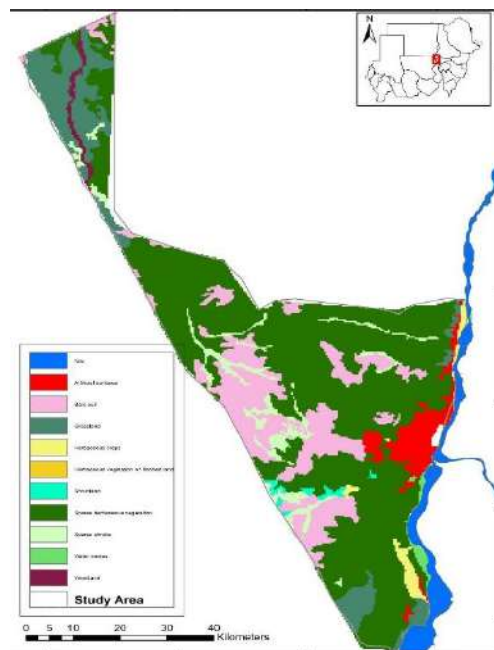


Figure 8: Land use/land cover map of the study area

Land use/land cover factor

Land use and land cover types were analyzed and reclassified into five categories based on their potential to influence flooding. Urban and agricultural areas were identified as vulnerable due to reduced natural absorption

and increased surface runoff. This categorization is illustrated in the land use/land cover maps (Figures 8 and 9). The land use map shows the range of affected areas, with high and medium vulnerability recognized in settlement areas.

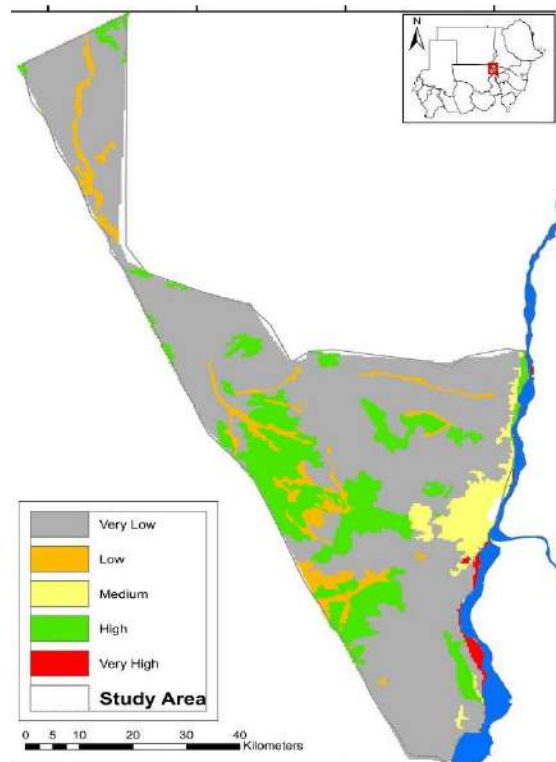


Figure 9: Re-categorize Land use/land cover classified map of the study area

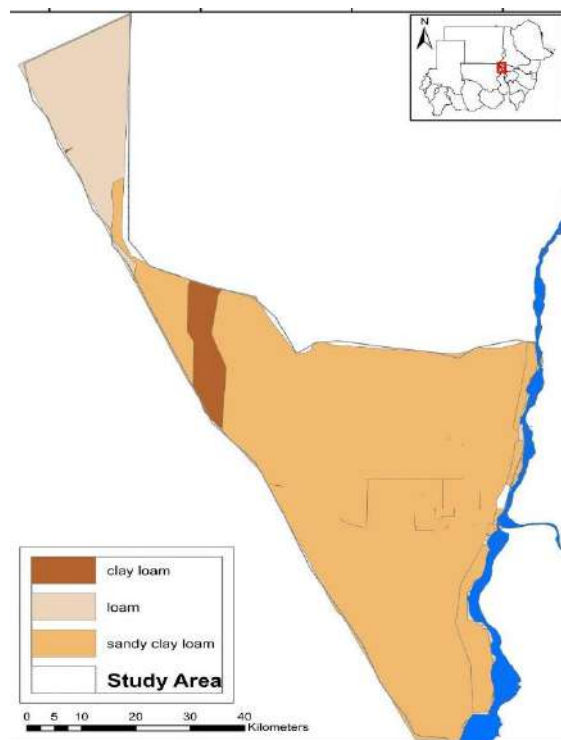


Figure 10: Soil types map of the study area

Soil factor

The study area contains three major soil types. The soil map obtained from national soil map of Sudan, then the classified maps was overlaid on their drainage maps of

the study area (Figure 10). Poorly draining soils, such as clay, were ranked as highly vulnerable, whereas sandy soils, with better infiltration rates, were ranked lower. The spatial distribution of soil types is presented in (Figure 10).

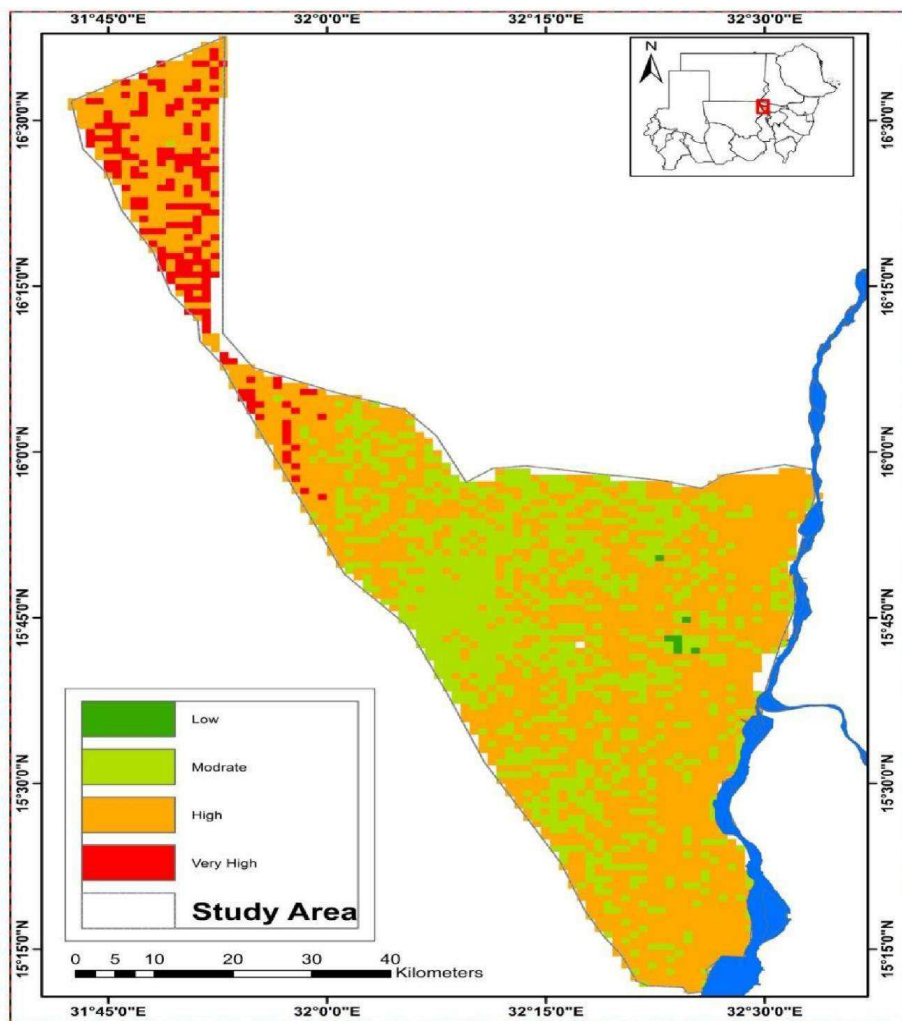


Figure 11: Flood vulnerability map

Table 2: Shows flood vulnerability level, area coverage, and percentages.

| Flood vulnerability Level | Area (km ²) | Percent of Area Coverage % |
|---------------------------|-------------------------|----------------------------|
| Low | 7.83 | 0.2 |
| Moderate | 1,193.25 | 30.61 |
| Very High | 2,503.44 | 64.2 |
| High | 194.06 | 4.97 |

Flood vulnerability map

Using a weighted overlay method in ArcGIS 10.7.1 (2020) a flood vulnerability map was developed by integrating all factors—slope, elevation, rainfall, drainage density, land use/land cover, and soil types. The results reveal four vulnerability levels: low, moderate, high, and very high. The results clearly show that moderate and high flood vulnerability levels covered the largest areas of the study area, encompassing 1193.25 km² and 2503.44 km², respectively, for a combined coverage of 64.2%.

In contrast, very high flood vulnerability areas covered approximately 194.06 km² (4.97%), while low flood vulnerability areas were limited to only 7.83 km² (0.21%) (Figure 11, Table 2).

DISCUSSION

The results, derived from overlaid maps of population distribution, precipitation, slopes, elevations, drainage density, land use/land cover, and soils, are presented in the flood susceptibility map, which delineates the

geographical distribution of flooding in the Omdurman and Um Badda localities. These localities experience varying degrees of flood impact. The smallest area, estimated at 7.83 km², exhibits the lowest flood vulnerability, while the largest, covering 2503.44 km², and is the most vulnerable. Satellite imagery and GIS-based analysis have proven to be powerful tools for analyzing and mapping flood risks. By integrating diverse spatial data layers, GIS facilitates the identification of flood-prone areas, the assessment of vulnerability, and the development of effective mitigation strategies. This study utilizes these methods, aligning with the broader application of GIS in flood risk assessment and its significance in informing decision-making (Osman and Das, 2023). The cross-mapping revealed that settlement areas, a land use category indicative of higher social vulnerability due to population density and often less robust construction, are predominantly located within the high and moderate flood vulnerability zones, supporting Cutter *et al.* (2003) observation.

Influence of topography and rainfall

This study confirms the disproportionate impact of floods on low-lying areas and regions experiencing high precipitation. This aligns with observations in other locations. For instance, urban expansion into natural floodplains in Romania has been shown to exacerbate social vulnerabilities to flooding (Ajtai *et al.*, 2020). Furthermore, the correlation between rainfall intensity and flood risk, as documented in Accra, Ghana (World Weather Attribution, 2024), is also apparent in the current study, underscoring the critical role of precipitation in determining flood patterns. Recently World Weather Attribution (2024) concluded that Sudan's ongoing conflict and fragility have exacerbated existing challenges such as poverty, rapid urbanization, and aging infrastructure. The displacement crisis has left millions vulnerable, particularly those living in makeshift shelters, who are at heightened risk during extreme rainfall events. The 2024 floods in Sudan highlight the region's susceptibility to severe weather events. The low return period of the rainfall that caused such significant damage underscores the deep-rooted vulnerabilities that amplify the impact of these events (World Weather Attribution, 2024).

Impact of land Use and urbanization

Unregulated urban expansion, as highlighted by Ferreira *et al.* (2015) contributes significantly to flood risks. The replacement of natural land cover with impervious surfaces like roads and rooftops increases surface runoff, reducing the land's capacity to absorb rainfall. This was also documented in Nigeria, where land use changes led to higher flood hazards in 2015 as reported by Ferreira *et al.* (2015). The study area's rapid urbanization without proper drainage planning mirrors these global trends, calling for stricter land-use policies.

Socio-economic vulnerabilities

Marginalized communities, particularly those in informal settlements near riverbanks, because the settlements are located by river site or on floodplains, face heightened risks. This finding is consistent with Holand and Lujala's (2011) assertion that poverty exacerbates vulnerability by limiting access to resources and safer housing. Furthermore, the poor are often the most affected post-disaster, given the high relative costs of recovery. Addressing these vulnerabilities requires targeted interventions, such as resettlement programs and equitable resource distribution.

Integrated flood risk management

The study reinforces the importance of a multi-faceted approach to flood risk management, as suggested by Armaş (2008). Early warning systems, improved drainage, and land-use planning are crucial for mitigating risks. Adopting a holistic flood management framework, as proposed by Krakowka *et al.* (2012), can help reduce vulnerabilities and build resilience in flood-prone areas like Omdurman and Ombadda.

Climate change implications

Climate variability, characterized by erratic rainfall and extreme weather events, amplifies flood risks. The IPCC (2007) underscores that countries like Sudan, already grappling with institutional and economic challenges, are particularly vulnerable. This study supports the need to integrate climate adaptation strategies, such as sustainable urban planning and infrastructure development, into broader disaster management policies.

Conclusion

The study demonstrates the effective application of Remote Sensing (RS), Geographic Information Systems (GIS), and Digital Elevation Models (DEM) in identifying areas susceptible to flooding due to water drainage, streams, natural precipitation, or low-lying residential locations. Within Omdurman and Ombadda localities, varying degrees of flood vulnerability have been identified, with areas ranging from 7.83 km², representing the least vulnerable zones, to 2,503.44 km², which are the most vulnerable. These findings provide valuable insights into flood risk distribution across the region. The research underscores the importance of understanding flood-prone areas and their contributing factors. By leveraging these insights, policymakers and communities can implement proactive measures to mitigate flood risks, enhance resilience, and develop targeted adaptation strategies. This study contributes significantly to the broader efforts of flood risk management and disaster preparedness within the region.

Recommendations

The following recommendations should be established such as:

1. Planning for land use can significantly reduce vulnerabilities and raise property values planning for land use is therefore encouraged.
2. It is important to improve flood forecasts and early warning systems.
3. The adaptation to climate change plan needs to be included in programs and policies related to natural disasters.

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