GIS-based hydrological modelling for watershed analysis and flood control in Mokwa, Niger State, Nigeria.

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Keywords: Flood, Vulnerability, Curve number, and Watershed

SUMMARY

This study evaluates the hydrological dynamics and flood vulnerability of the Mokwa watershed in Niger State, Nigeria, through an integrated GIS and HEC-HMS modelling approach. Utilizing SRTM DEM for delineating the watershed, along with HWSD soil data, land use, and land cover data, the SCS-CN method was applied to simulate rainfall-runoff processes. The findings revealed that the watershed primarily consists of the Hydrologic Soil Group B (sandy loam), with curve numbers of 55 for forest, 61 for rangeland, 78 for croplands, and 85 for built-up areas. Simulation of a 57.17mm rainfall event showed that 40.39mm was lost to infiltration, while 16.68mm was excess rainfall, nearly all of which (16.58mm) was converted into direct runoff. The model generated a peak discharge of 4.2 m^3/s at 10:20 a.m. on May 29, 2025, with a lag time of 209.44 minutes.

The results highlight that while the watershed has moderate infiltration capacity overall, built-up areas and agricultural zones show a significant potential of runoff, rendering Mokwa somewhat vulnerable to flooding. To address this concern, the study recommends integrating flood management strategies, including improved drainage systems, flood control structures, stopping the blocking of waterways, and soil conservation practices to reduce curve numbers and delay peak discharge. While dependence on secondary datasets presents a limitation, the approach demonstrates the utility of GIS and hydrological modelling for flood risk assessment in semi-arid regions. The findings provide valuable insight bolstering early warning systems, informing land use planning, and enhancing flood resilience in Mokwa and Nigeria Watershed.

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1.0 INTRODUCTION

Flooding is one of the significant natural hazards worldwide, leading to damage to infrastructure, livelihoods, and the environment. Their causes are diverse depending on the affected region, encompassing heavy rainfall, coastal flooding, inland flooding, snowmelt, and structural failure.

Flooding in Nigeria presents multiple hazards, including the destruction of infrastructure, displacement of populations, loss of lives, and outbreaks of waterborne diseases (Babati et al., 2022). The recent flooding in Mokwa, Niger state, Nigeria, which occurred on May 28, 2025, after several hours of rainfall, led to the loss of 250 lives, submerging the town, washing away houses, and collapsing the bridge, leaving motorists stranded and disrupting vehicular movement. Mokwa is particularly susceptible to recurrent flooding due to its proximity to the River Niger and its tributaries, coupled with expanding agricultural activities and urbanization. This calls for a working approach or techniques for adequate planning to mitigate flooding.

In recent times, Geographic Information System-based hydrological modelling has emerged as a powerful tool for watershed analysis and flood risk management. It enables researchers and practitioners to visualize, analyze, and interpret complex hydrological phenomena within a watershed context. This approach enables the assessment and integration of spatial data such as topography, land use/land cover, soil properties, and rainfall to simulate hydrological processes and predict areas at risk of flooding with high spatial precision. Also, these techniques have been effectively used in a variety of studies to support hydrological models and the prediction of floods, including (Lempert et al., 2013; Long et al., 2010; Samarasinghea et al., 2010; and Wanga et al., 2008). Hydrological modelling specifically, GIS can be used to construct flooding projection models in catchments, and to prepare and analyse multiscale and multi-source spatial data(Gallegos et al., 2009; Merwade et al., 2008).

The application of GIS-based hydrological modelling has become a powerful tool in watershed analysis and assessing flood vulnerability, owing to its capacity to integrate topography attributes, land use, soil type, and rainfall data. For example, Akinbobola et al., (2015) employ a GIS and watershed-based approach using Digital Elevation Model (DEM) and precipitation to identify areas susceptible to flooding along the Niger-Benue River Basin.

Also, Adeogun et al., (2014) employ SWAT (Soil and Water Assessment Tool) hydrological modelling in the watershed upstream of Nigeria's Jebba Reservoir to demonstrate the value of GIS-coupled models in predicting streamflow with good calibration, highlighting the sensitivity of curve number parameters.

Notwithstanding studies on vulnerability, few studies have comprehensively evaluated flood risk in Mokwa employing a GIS-based hydrological modelling approach. The existing flood management system is primarily based on multi-dimensional social and environmental lenses rather than simulation of hydrological processes, leaving the communities unprepared for future extreme events (Ndanusa et al., 2022). Mokwa, in Niger State, Nigeria, continues to experience flooding as a result of insufficient predictive modelling and control strategies in place.

This study seeks to apply GIS-based hydrological modelling to delineate the Mokwa watershed, especially using the soil conservation curve number (SCS-CN) method, to simulate hydrological processes, assess flood risk, and inform targeted flood control strategies. This approach addresses the knowledge gap in flood risk prediction, supporting actionable flood control intervention by considering objectives such as delineating the Mokwa watershed along with its subbasin using the Digital Elevation Model (DEM), integrating DEM, soil, Land use/Land cover, and rainfall data to derive hydrological parameters implementing and calibrating hydrological models (SCS-CN) for the simulation of runoff and assessment of flood risk, and mapping flood-prone areas and recommend a context-specific flood management strategy for Mokwa.

2.0 MATERIALS AND METHODS

2.1 Study Area

Mokwa is a local government area and market town located in the western part of Niger State, Nigeria, and situated along the Niger River, which forms its southern border. The town is located at approximately 9.295° N latitude and 5.054° E longitude, with a population of 244,937 at the 2006 census and a land area of $4{,}338 km^2$. The study area experiences a tropical wet and dry climate, with a mean annual rainfall of approximately 1,100 - 1,200 mm concentrated between May and October (Mamman, 2018). The area's geography is characterised by a transition from cropland and shrubs near the town to a landscape with varied elevations within a wider radius. Seasonal flooding has grown frequent, especially in low-lying floodplains where settlements and agricultural land are concentrated. Mokwa's economy is driven by agriculture, with key features including the Mokwa-Jebba Bridge over the Niger River, which is down, and proximity to the Jebba Hydroelectric power station.

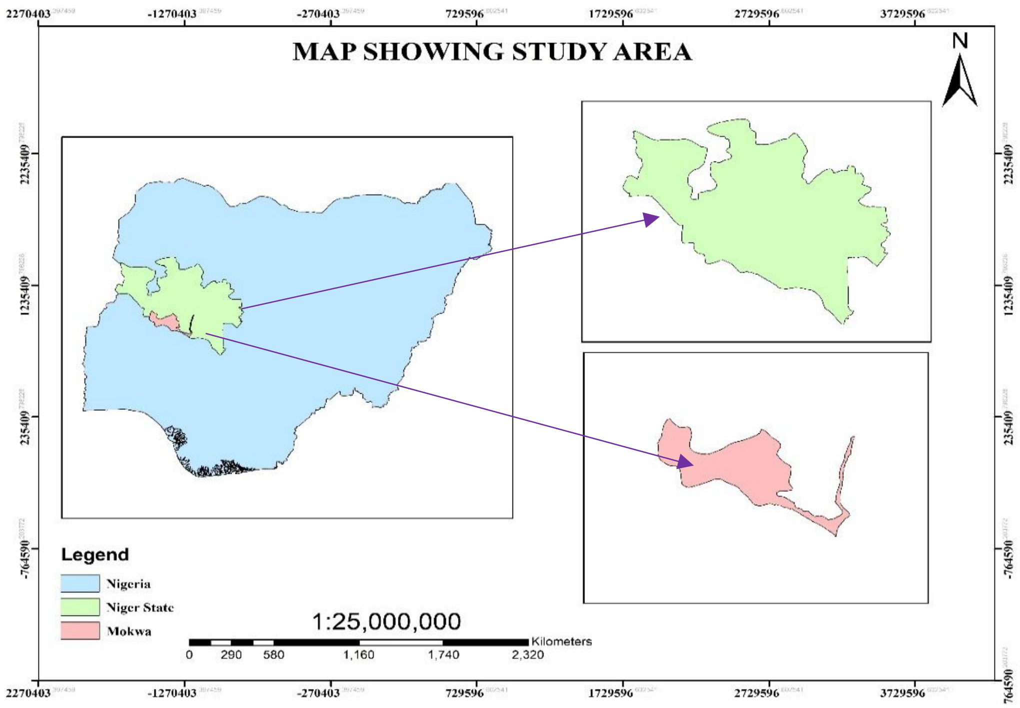

Figure 1. Map of the study areas

2.2 Data Source

Four main data sets used in this study are:

2.2.1 Digital Elevation Model (DEM)

The Shuttle Radar Topography Mission (SRTM) DEM used for this study was acquired from OpenTopography. The Shuttle Radar Topography Mission (SRTM) obtained data on a near-global scale to generate the most complete high-resolution digital topography database of the Earth (NASA Jet Propulsion Laboratory, 2025). SRTM consisted of a specially modified radar system that flew onboard the space shuttle Endeavour during an 11-day mission in February of 2000. SRTM is a project spearheaded by the National Geospatial Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA). The DEM was used for watershed delineation, stream network extraction, and terrain analysis.

2.2.2 Land Use Land Cover Data (LUCL)

Land use is commonly defined as a series of operations on land, carried out by humans, with the intention of obtaining products and/or benefits through using land resources. Land cover is commonly defined as the vegetation (natural or planted) or man-made construction that occurs on the Earth's surface. Land use significantly influences the degree of flood vulnerability. Land use changes affect the discharge and volume of sub-watersheds, and mismanagement without consideration of the environmental aspect often results in disasters.

LULC data for 2025 were obtained from Landsat 8 imagery by supervised classification using ArcMap 10.5. The land cover was categorised into water, trees, flood vegetation, crops, built area, bereland, and rangeland. **Figure 2** shows the Land use and Land cover classification of the study area.

2.2.3 Soil Data

The rate of infiltration can be determined by the soil texture. More permeable soil has more infiltration capacity and therefore reduces surface run-off, whereas less permeable soil has less infiltration capacity and is prone to waterlogging. Soil compactness significantly reduces infiltration and consequently increases the flood depth and duration.

The infiltration process of an integrated catchment model needs information about soil hydraulic properties (SHP), such as saturated hydraulic conductivity (Ksat), porosity, and field capacity, as well as the influence of compaction on these properties (Umer et al., 2019).

Hydrologic soil groups are based on estimates of runoff potential. Soils are assigned to one of four groups according to the rate of water infiltration when the soils are not protected by vegetation, are thoroughly wet, and receive precipitation from long-duration storms.

According to USDA, (1999), Soils in the United States are assigned to four groups (A, B, C, and D) and three dual classes (A/D, B/D, and C/D). The groups are defined as follows:

2.2.3.1 Group A: Soils having a high infiltration rate (low runoff potential) when thoroughly wet. These consist mainly of deep, well-drained to excessively drained sands or gravelly sands. These soils have a high rate of water transmission.

2.2.3.2 Group B. Soils having a moderate infiltration rate when thoroughly wet. These consist chiefly of moderately deep or deep, moderately well-drained or well-drained soils that have a moderately fine texture to moderately coarse texture. These soils have a moderate rate of water transmission.

2.2.3.3 Group C. Soils having a slow infiltration rate when thoroughly wet. These consist chiefly of soils having a layer that impedes the downward movement of water or soils of moderately fine texture or fine texture. These soils have a slow rate of water transmission.

2.2.3.4 Group D. Soils having a very slow infiltration rate (high runoff potential) when thoroughly wet. These consist chiefly of clays that have a high shrink-swell potential, soils that have a high water table, soils that have a claypan or clay layer at or near the surface, and soils that are shallow over nearly impervious material. These soils have a very slow rate of water transmission.

If a soil is assigned to a dual hydrologic group (A/D, B/D, or C/D), the first letter is for drained areas and the second is for undrained areas. Only the soils that, in their natural condition, are in group D are assigned to dual classes.

The soil texture and hydrologic soil group data used for this study were obtained from the Food and Agriculture Organisation (FAO) soil database. These were used to calculate Curve Number (CN) parameters. **Figure 2** shows the soil classification of the study area, and **Table 1** shows the soil classification used to classify the soil of the area.

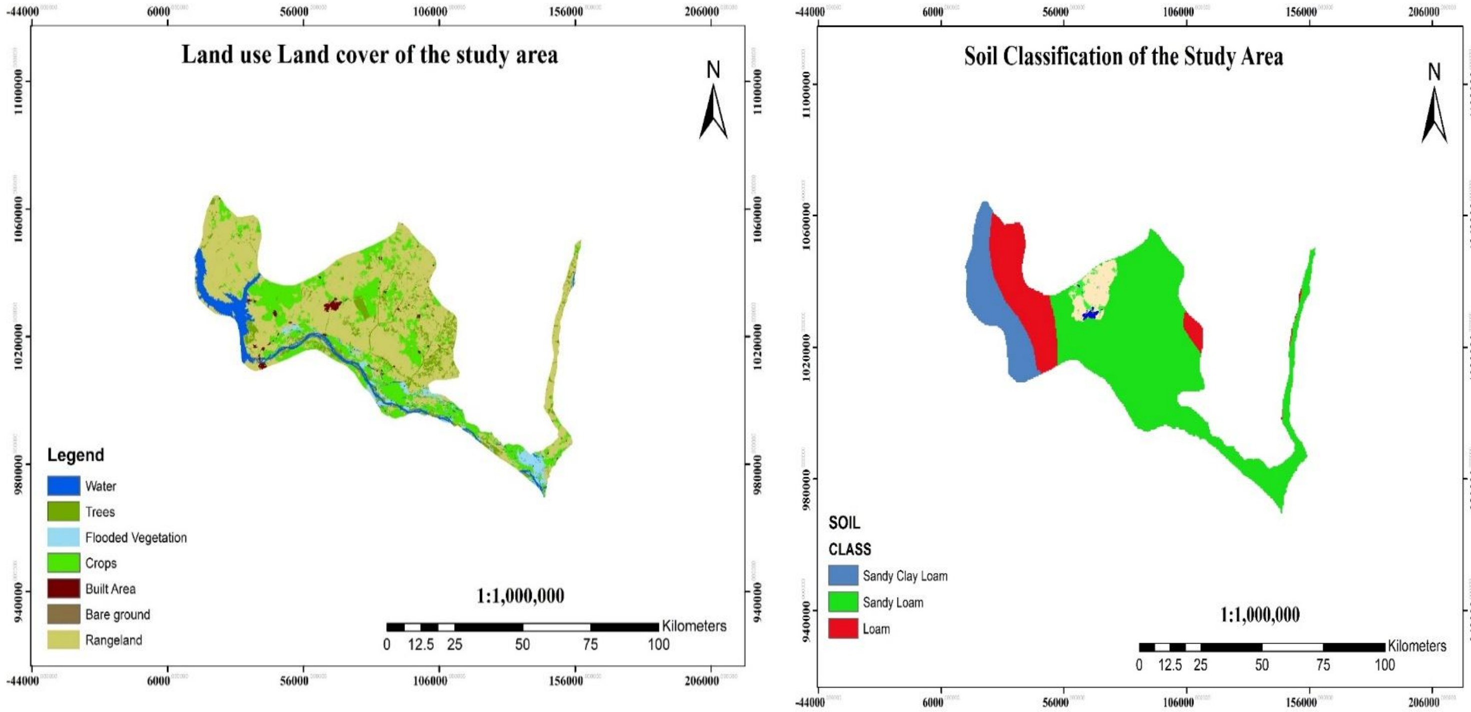

Figure 2. Map of land use land cover, and soil classification of the study area

Table 1. Classification scheme used to develop hydrologic soil groups (HSGs).

HSG	Soil Texture Class	Run-Off Potentials	SoilGrids250m texture class value
A	Sand	Moderately low	12
B	Sand loam, Loamy Sand	Moderately high	9,11
C	Clay loam, Silty clay loam, Sandy clay loam, Loam, Silty loam, Silt	High	4, 5, 6, 7, 8, 10
D	Clay, Silty clay, Sandy clay	High	1, 2, 3
A/D	Sand	High	12
B/D	Sandy loam, Loamy sand	High	9, 11
C/D	Clay loam, Silty clay loam, Sandy clay loam, Silty loam, Silt	High	4, 5, 6, 7, 8, 10

D/D	Clay, Silty clay, Sandy clay	High	1, 2, 3

2.4 Rainfall Data

Rainfall is a key factor in controlling the hydrological cycle of a watershed area, and it also contributes to the triggering of flash floods, thereby making it a mandatory parameter in hydrological model studies. The size of the water resources in a watershed depends on the amount of rainfall that occurs along the watershed. Also, to determine the occurrence of a flood, the value of peak discharge is compared to the values of bankfull discharge, with flooding occurring if the peak discharge exceeds the bankfull discharge.

Meteorological fields were obtained from the fifth-generation ECMWF reanalysis (ERA5; (Hersbach et al., 2020), which provides high-resolution atmospheric data. Variables retrieved include specific humidity, u and v wind components, vertical velocity, potential velocity, specific rainwater content, and vapour flux. In this study, the hydrological model was applied to investigate the rainfall-induced flood phenomenon. It is a method that can be used to forecast both runoff and peak discharge in small sub-catchments. To determine flood occurrence, we compared the values of peak discharge to the values of bankfull discharge, with flooding occurring if the peak discharge exceeded the bankfull discharge. This required calculating peak discharge and bankfull discharge.

2.5 Data processing and Modelling

2.5.1 Sub-Basin delineation

The Shuttle Radar Topography Mission (SRTM) DEM was processed in ArcGIS using the hydrology toolset. The following processes were undergone to delineate the Mokwa watershed.

2.5.2 Fill sinks

Filling sinks in a surface raster helps to remove small imperfections in the data. Sinks are considered to have undefined flow directions and are assigned a value that is the sum of their possible directions. To create an accurate representation of flow direction and, therefore, accumulated flow, it is best to use a dataset that is free of sinks. The digital elevation model (DEM) was processed to remove all sinks using the hydrology toolset (Fill)

2.5.3 Flow Direction

The fill sink raster was used to create a raster of flow direction from each cell to its steepest downslope neighbour using the hydrology toolset (Flow Direction).

2.5.4 Flow accumulation

The flow direction raster was used to create a raster of accumulated flow into each cell.

2.5.5 Stream Order

Map Algebra using raster calculator was performed on the raster flow accumulation to create a stream order raster using the hydrology toolset (Map Algebra and Stream order). This enables us to see small tributaries and larger streams as well in different colours. This was then converted into a network of rivers using the “Stream to Feature” tools in the hydrology toolset.

2.5.6 Outlet

The outlet point was digitised using the shapefile point created.

2.5.7 Watershed delineation of the study area

The watershed for the study area was delineated by inputting the flow directions raster, and the outlet point digitised using the hydrology toolset (Watershed). The watershed formed the boundary used for clipping the study area.

2.5.8 Curve Number

Curve number (CN) in hydrology is a parameter used in the USDA-NRCS (formerly SCS) to estimate the depth of runoff from the depth of rainfall in a given event. It is a dimensionless value between 0 and 100 that quantifies a watershed’s runoff potential, with higher numbers indicating greater runoff potential. It is determined by the use of the hydrologic soil group (HSG), land use, land treatment, and antecedent soil moisture condition (AMC) of a drainage basin.

The curve number (CN) for the study area was calculated to estimate water leakages in the soil and was generated based on land use and hydrological soil groups. This was done in a GIS environment using the formula below. Therefore, data used to estimate curve number for the study area includes land use land cover (LULC), soils with hydrologic soil groups, and Sub-basin polygons. The composite curve number was finally calculated using the formula below.

$$CcN = \frac{\sum_i^n CN_i * A_i}{\sum_i^n A_i} \dots\dots\dots\dots (1)$$

CcN = Composite Curve number

CN= Curve number

A_i = Area

2.5.9 Lag Time

Lag time is the measure of the speed at which a watershed responds to a run-off-producing event; specifically, it represents the delay in time between a watershed’s rainfall and its peak runoff discharge. In hydrology, lag time is mostly calculated using the National Resources Conservation Service (NRCS), which is based on the physical characteristics of a specific watershed. This is calculated using the formula below.

$$T_l = \frac{L^{0.8}(S+1)^{0.7}}{1{,}140Y^{0.5}} \ldots\ldots\ldots\ldots (2)$$

$$Lag = 0.6T_C \ldots\ldots\ldots\ldots. (3)$$

where

T_c = time of concentration, h

l = Flow length, ft

Y = average watershed land slope, %

S = maximum potential, in

2.6 Peak Discharge

Peak discharge refers to a point on a flood hydrograph when the river discharge is at its greatest. In order to estimate the peak discharge (Q_p), the Hydrologic Engineering Centre-Hydrologic Modelling System (HEC-HMS) software was used to determine the peak discharge. This approach transforms excess rainfall into direct runoff hydrographs.

2.6.1 Hydrological modelling of the study area

Hydrological modelling plays a critical role in understanding watershed reaction to rainfall and in formulating flood control in flood-prone areas. Among the most commonly used modelling tools is the Hydrologic Engineering Centre-Hydrologic Modelling System (HEC-HMS). HEC-HMS is a critical tool that offers a framework for simulating the rainfall-runoff relationship across various geographic areas. HEC-HMS, therefore, includes models for runoff volume, direct runoff, and base flow, allowing for comprehensive simulation of hydrological processes (**Makena & Kau, 2016).**

The prepared inputs used in the HEC-HMS were Sub-basins & reaches, composite curve number, lag time and rainfall data. All parameters used in the HEC-HMS were ensured to be in the same projection coordinate system and were used for the basin model, meteorological model, and control specifications in the HEC-HMS software.

3.0 RESULTS

The result of the watershed clip raster for the study's soil was sandy loamy HSG B. This was used in equations 1, 2, and 3 to calculate the curve numbers, composite number, and lagtime, with the result summarised below.

This study utilised the SCS-CN method within the HEC-HMS environment to estimate surface runoff and peak discharge in the Mokwa watershed. The analysis of the Hydrologic Soil group (HSG) identified it as predominantly HSG B (Sandy loamy) using equations (1, 2, and 3) with derived curve number (CN) values of 55 (trees/forest), 78 (cropland), 85 (Built-up areas), 61 (rangeland), and a composite of 64.85. These CN values reflect the varying infiltration potentials and runoff capacities across different landuse. Built-up areas and croplands exhibited the highest CN values, indicating reduced infiltration and increased vulnerability to rapid runoff generation.

Additionally, the lag time was estimated to be 209.44 minutes (approximately 3.5 hours). The lag time signifies the interval between the center of rainfall excess and the peak discharge at the watershed outlet. This value indicates that, considering the current landuse and soil conditions, Mokwa exhibits a moderate response time, giving a limited window for flood warning and preparedness before peak flow occurs.

Based on a design storm, the model estimated a direct runoff depth of 16.58mm, indicating the proportion of rainfall converted into surface flow. The peak discharge of 4.2 m^3/s indicates the watershed's rapid reaction to rainfall input occurring on 29 May 2025 at 10:20. Also, the model generated a precipitation depth of 57.17mm over the catchment. Of this, 40.39mm was lost to infiltration and other abstraction, while 16.78mm constitutes excess rainfall available for direct runoff. **Figure 3** shows the vulnerability map prepared from HEC-RAS and ArcMap software.

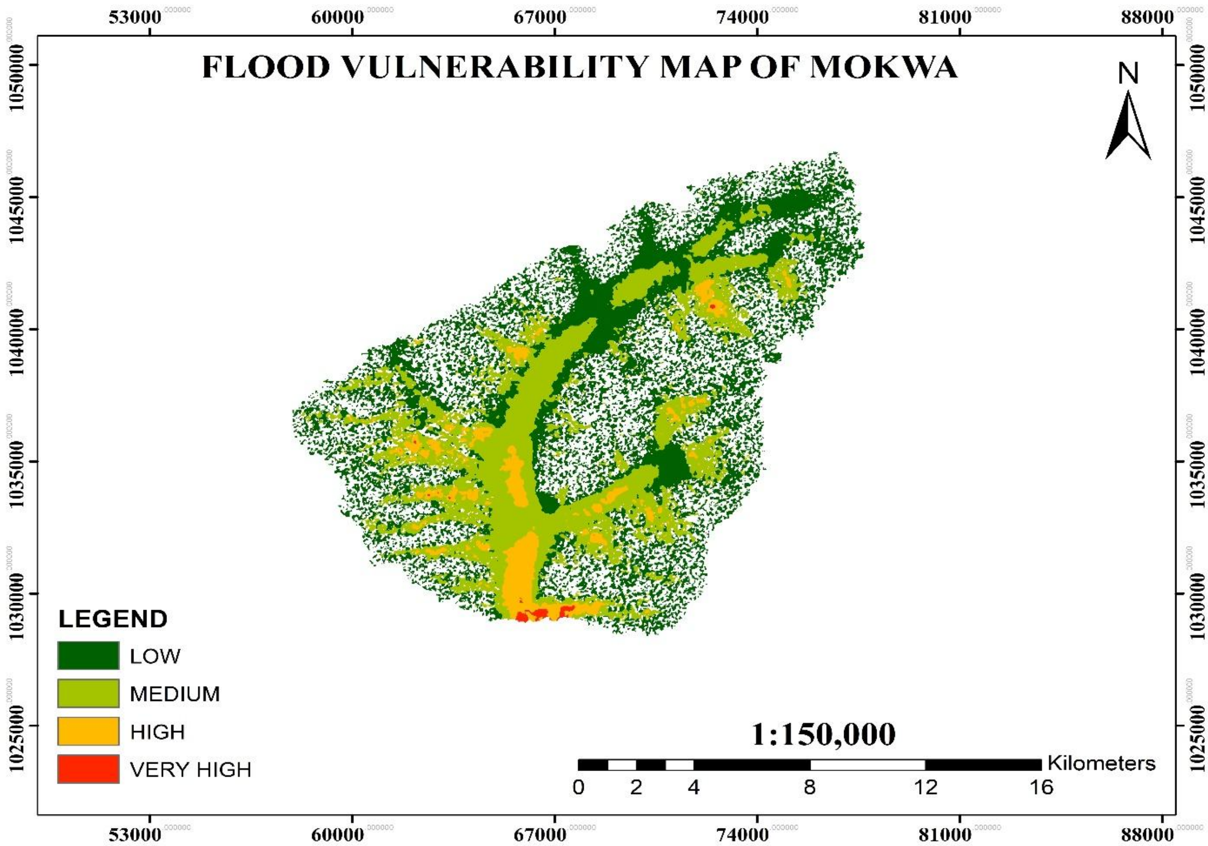

Figure 3. Vulnerability map of Mokwa watershed

4.0 DISCUSSIONS

The results offer a clear insight into Mokwa's hydrological response to rainfall events and its implications for flood vulnerability. The precipitation input of 57.17mm produced a notably high volume loss of 40.39mm, primarily attributed to the prevalence of HSG B soils (Sandy loam), which permit infiltration (Sartika et al., 2020). However, the remaining excess rainfall of 16.78mm swiftly converted into direct runoff of 16.58mm, illustrating the limited capacity of the catchment to buffer against intense rainfall. This aligns with the findings of Mishra & Singh, (2013)**,** who indicated that cultivated and built-up areas, typical of Mokwa reduce infiltration and accelerate surface flow.

The peak discharge of 4.2, occurring at 10:20 am on 29 May 2025, underscores the relatively fast response of the watershed to rainfall. The lag time of 209.44 minutes suggested that while Mokwa is not classified as an ultra-rapid response basin (flashy watershed), the timeframe for flood is still limited to less than four hours. This corroborates a similar study in semi-arid Nigerian watersheds, where lag time of 2-4 hours has been linked with recurrent flooding incidents. The disparity between loss volumes indicates that while infiltration plays a significant role, the land cover and soil distribution are insufficient to mitigate flooding under severe rainfall events. Also, the Built-up area curve number value of the study area is especially critical, as it significantly reduces infiltration and increases surface runoff. Furthermore, croplands further compound this issue, leaving forests and rangelands to provide hydrological resilience.

5.0 CONCLUSION AND RECOMMENDATIONS

This study illustrates that the combination of GIS and hydrological modelling yields valuable insights into flood vulnerability in Mokwa, Niger state, Nigeria. By applying the SCS-CN method within HEC-HMS. It was revealed that the watershed possesses a moderate infiltration capacity (HSG B soil) but exhibits a high potential runoff in built-up areas and cultivated areas, resulting in a direct runoff volume of 16.58mm, a peak discharge of 4.2 m^3/s, and a lag time of 209.44 minutes. These findings suggest that Mokwa is to a certain extent prone to flooding, with limited time for flood preparedness once rainfall occurs.

It is therefore recommended that local authorities implement sustainable land use practices such as afforestation, soil conservation, and control urban expansion, especially building on waterways to lower curve number, while also investing in improved drainage and flood forecasting systems to effectively utilise the lag time. Future studies should integrate high-resolution LIDAR, ground-based rainfall data, as there was no Nimet station at Mowa at the time of undertaking this research, and climate change scenarios to improve predictions and strengthen long-term flood resilience planning.

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BIOGRAPHICAL NOTES

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