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Integrated Flood Hazard Mapping : A Case Study of the Upper Athi River Basin

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Abstract

Flooding is one of the most catastrophic natural disasters globally, significantly impacting communities, infrastructure, and economies. Upper Athi River basin, is one of the river basins in Kenya that is under increasing risk of flooding due climate change, rapid urbanization, and unsustainable land use practices. The objective of this study was to assess and map the flood hazard in the upper Athi River Basin. The study used HEC- HMS to simulate the hydrological processes of the basin and to generate the flood hydrographs that were then routed in the river channel using HEC-RAS model. Flood hydrographs with return periods of 25, 50 and 100 years were modelled (using flow routing methods) through the river channel. HEC-HMS and HEC-RAS models were calibrated and validated using observed discharge and water surface profile data, respectively and before they were used for simulation. Model performance, statistically assessed using Nash-Sutcliffe Efficiency, was found to be very good. Flood hazard maps developed from the study showed that a 25 year flood would cause an inundation of 17 meters from the river bank which increased by 29% and 106% for 50 and 100 year floods respectively. The water level (depth) in the main channel increased by 50% and water velocity tripled for a 100-year flood compared to 25-year flood. The results show increasing potential risks of flooding posed to agriculture, infrastructure and people living in the mapped flood zones. The findings highlight the need for flood hazard maps to be incorporated into land-use planning, emergency response strategies, and policy frameworks to enhance flood risk management. To mitigate future flood risks, the study recommends establishment of early warning systems and implementing sustainable land management practices, such as afforestation and pervious pavements.

Keywords: Flood Hazard Mapping, Flood Hazard Assessment, Hydraulic Modelling, Athi River Basin, Flood Mapping, Return Period Analysis, Hydrological Calibration, Inundation Modelling, Climate Change Impact.

Introduction

Flooding remains one of the most frequent and destructive natural hazards worldwide, posing significant threats to human life, infrastructure, ecosystems, and economies [1, 2]. The socio-economic consequences are often devastating, including property damage, displacement of populations, and the collapse of critical infrastructure [3]. The increasing frequency and severity of flood events, particularly in the developing world, are attributed to a combination of climate change, rapid urbanization, land-use changes, and poor drainage infrastructure [4–6].

Effective flood hazard assessment is a fundamental component of disaster risk reduction. It informs emergency preparedness, land-use planning, and the design of structural mitigation measures [7]. A range of tools and techniques are used in flood hazard assessments, including historical flood event analysis,

Geographic Information Systems (GIS), and hydraulic modeling. Among these, GIS and numerical models like the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) and River Analysis System (HEC-RAS) have become integral to flood simulation and mapping [8–10].

In Kenya, the upper Athi River Basin is increasingly affected by seasonal floods due to a combination of factors such as intense rainfall, land degradation, floodplain encroachment, and inadequate stormwater infrastructure [11]. Neighborhoods such as Kwa Mangeli, Kwa Nzomo, and Graceland Estate have been repeatedly affected, with over 2,000 residents displaced in recent years [12]. Although frameworks for flood management exist, the region lacks a reliable, data-driven flood hazard map that reflects both current and future risks.

The need for a detailed and accurate flood hazard assessment in the Athi River Basin is underscored by the limited availability of localized flood risk data, especially in vulnerable areas [13, 14]. In response to this gap, the present study employs an integrated modeling approach using HEC-HMS and HEC-RAS to simulate flood events and develop hazard maps for multiple return periods (25-, 50-, and 100-year events). The simulated hydrographs from HEC-HMS serve as upstream boundary conditions for HEC-RAS, which calculates flood extents and water depths across the floodplain.

The overall aim of this study is to assess and map flood hazards in the upper Athi River Basin using hydraulic modeling. Specifically, the study seeks to: (1) simulate flow hydrographs for various flood magnitudes using HEC-HMS; (2) calibrate and validate the HEC-RAS model using historical flood data; and (3) develop flood hazard maps for multiple return periods. The outputs of this work are expected to support evidence-based decision-making for flood mitigation, emergency response planning, and climate resilience building in the region.

Materials and Methods

Study Area

This study was conducted in the upper Athi River Basin, located in Kenya. The basin, with an area of approximately 66,559 km², experiences a semi-arid to sub-humid climate, characterized by bimodal rainfall. Seasonal flooding, especially in low-lying areas such as Kwa Mangeli, Kwa Nzomo, and Graceland Estate, has caused significant displacement and infrastructure damage in recent years. The basin is influenced by both natural hydrological factors and anthropogenic activities such as deforestation, land degradation, and inadequate stormwater infrastructure. These flood-prone areas are increasingly at risk due to changing climate patterns and rapid urbanization.

Data Collection and Sources

Several Datasets were Used in the Hydrologic and Hydraulic Modeling for this Study. The Primary data Sources are as Follows

• Digital Elevation Model (DEM): A high-resolution 12.5 m DEM obtained from the Alaska Satellite Facility (ASF) was used for watershed delineation and cross-section extraction.

• Land Use/Land Cover (LULC) Data: Land use data, sourced from the Regional Centre for Mapping of Resources for Development (RCMRD), was used to estimate runoff parameters (e.g., Curve Numbers).

• Soil Data: Soil characteristics were obtained from the FAO soil database, used for parameterizing the runoff model.

• Meteorological Data: Daily rainfall and temperature records were acquired from the Kenya Meteorological Department and Water Resources Authority (WRA), which provided data for model calibration.

• Streamflow Data: Historical discharge data for the Athi River, provided by the WRA, was used to calibrate and validate the models.

Hydrologic Modeling using HEC-HMS

Hydrologic simulations were performed using the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS), version 4.10. The modeling procedure included the following steps:

• Watershed Delineation: The DEM was processed in HEC-GeoHMS within ArcGIS to delineate sub-basins and extract river networks.

• Parameter Estimation: The SCS Curve Number method was used for loss modeling, the SCS Unit Hydrograph method for runoff transformation, and the Muskingum method for baseflow routing.

• Model Calibration: Calibration was performed using observed discharge data for past flood events. Nash-Sutcliffe Efficiency (NSE) and Root Mean Square Error (RMSE) were used as performance indicators.

• Flood Frequency Analysis: The Gumbel distribution was used to perform flood frequency analysis to estimate the 25-, 50-, and 100-year return period floods, which were subsequently used to generate hydrographs for HEC-RAS input.

Hydraulic Modeling using HEC-RAS

The hydraulic analysis was carried out using HEC-RAS, version 6.3.1. The steps involved are as follows:

• Geometry Creation: The river geometry was extracted from the DEM using HEC-GeoRAS, including river centerlines, cross-sections, and flow paths. These were imported into HEC-RAS for model setup.

• Flow Data Input: The flow hydrographs generated in HEC-HMS for various return periods (25-, 50-, and 100-year) were used as upstream boundary conditions for the HEC-RAS model. Calibration and Validation: Hydraulic parameters, particularly Manning's n-values, were adjusted based on historical flood event data. The model was calibrated using observed water surface elevations and discharge data from 2020. Validation was carried out using data from 2021. Floodplain Mapping: The results of the hydraulic simulations were visualized using RAS Mapper in ArcGIS, where flood inundation maps were generated for different return periods.

Model Integration and Output Analysis

An integrated modeling framework was used, where hydrographs from HEC-HMS were input into HEC-RAS to simulate flood extents and depths along the river channel. The outputs included: Water surface profiles and flood depths, Inundation maps for the 25-, 50-, and 100-year return periods, Identification of high-risk flood zones. Flood hazard maps were generated and analyzed using ArcGIS for spatial representation, highlighting flood-prone areas, vulnerability, and necessary flood management interventions.

Statistical Analysis and Model Performance

The accuracy of both the hydrologic and hydraulic models was assessed using Nash-Sutcliffe Efficiency (NSE) and Root Mean Square Error (RMSE), with the following criteria: NSE: Values closer to 1.0 indicate a better model fit. RMSE: Values closer to zero indicate less error in model predictions. Both calibration and validation phases were compared to ensure the robustness of the models in simulating real-world flood events.

Key Software and Tools Used

HEC-HMS (Hydrologic Modeling): For simulating rainfall-runoff processes and generating hydrographs. HEC-RAS (Hydraulic Modeling): For flood inundation modeling and flood hazard mapping.

ArcGIS: For GIS-based analysis, floodplain mapping, and model integration.

HEC-GeoHMS & HEC-GeoRAS: For watershed delineation and hydraulic modeling geometry setup.

Results

HEC-HMS Model Performance

The hydrologic model simulated streamflow hydrographs for the upper Athi River Basin using rainfall data and catchment characteristics. The calibration and validation of the HEC-HMS model were carried out using observed streamflow data for two significant storm events in 2020 and 2021, respectively.

Model performance was evaluated using the Nash–Sutcliffe Efficiency (NSE), Root Mean Square Error (RMSE), and Coefficient of Determination (R^2). The calibration phase yielded an NSE of 0.81, RMSE of 12.4 m^3/s, and R^2 of 0.85, while the validation phase produced an NSE of 0.78, and R^2 of 0.83, indi-

Table 1: HEC-HMS Calibration and Validation Performance Metrics.

Period	NSE	RMSE (m^3/s)	R^2
Calibration	0.81	12.4	0.85
Validation	0.78	13.2	0.83

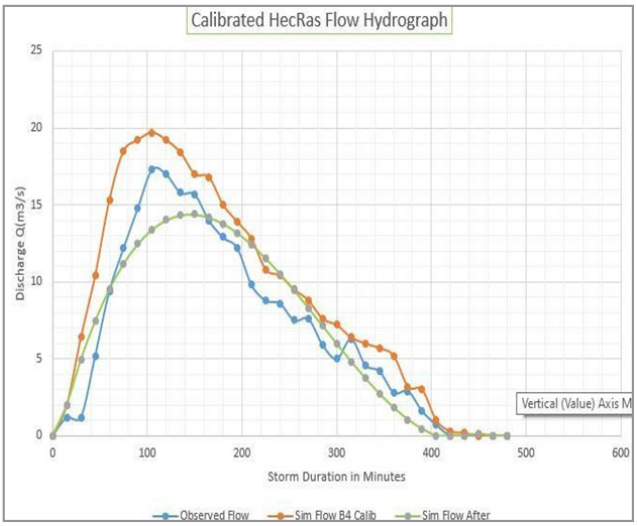


Figure 1: Comparison of Observed and Simulated Hydrographs for the 2020 Storm Event.

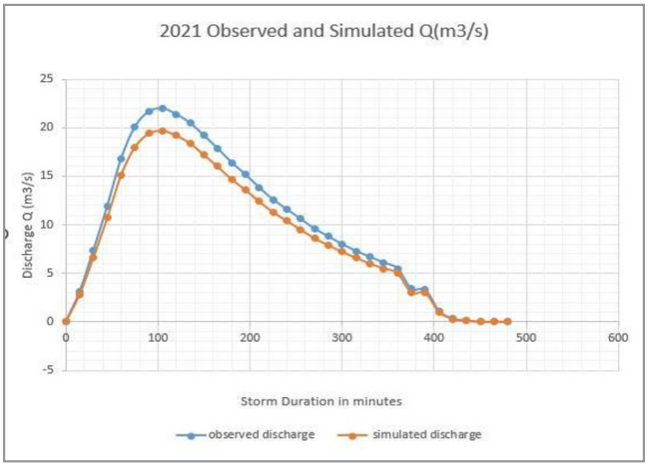
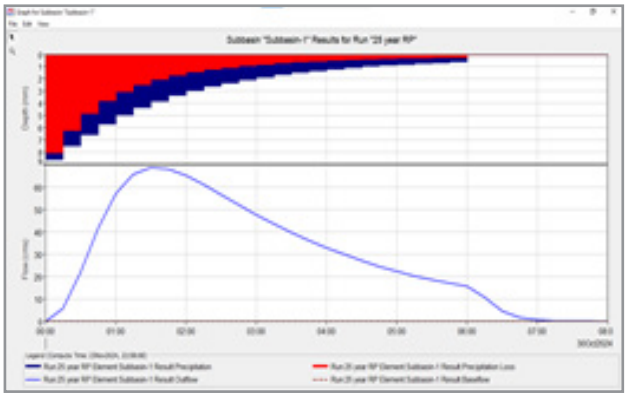
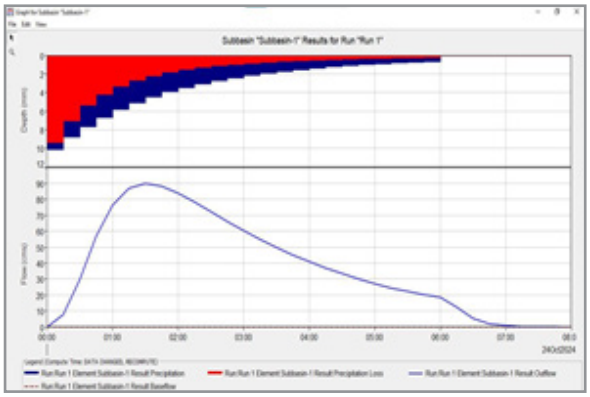


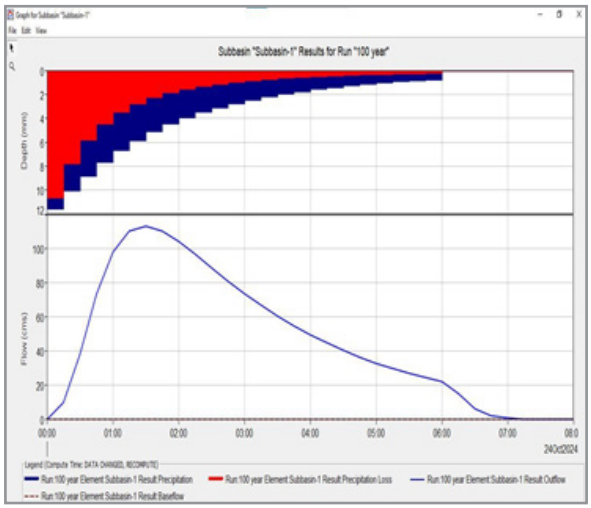
Figure 2: Validation of Observed and Simulated Hydrographs for the 2021 Storm Event

Design Flood Estimation

Using Gumbel's extreme value distribution, design discharges were calculated for return periods of 25, 50, and 100 years. These values were used as input into the HEC-HMS model to generate synthetic hydrographs for each scenario.







Estimated Peak Discharges for Selected Return Periods.

Return Period (years)	Peak Discharge (m^3/s)
25	104.2
50	125.5
100	148.3

HEC-RAS Model Outputs

The HEC-RAS hydraulic model, calibrated with appropriate Manning's roughness coefficients, simulated water surface elevations and flood extents for each return period. The model outputs included inundation depth, extent, and velocity profiles along the river channel.

The simulation results showed that flooding increases significantly with return period magnitude. The 25-year flood primarily affects low-lying riparian zones, while the 100-year flood extends beyond the channel, inundating residential zones such as Kwa Mangeli, Kwa Nzomo, and Graceland Estate.

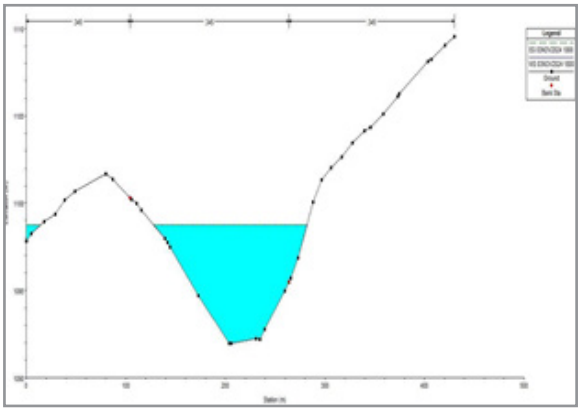
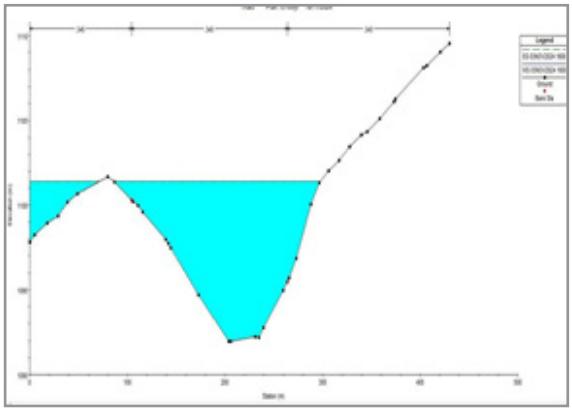


Figure 2



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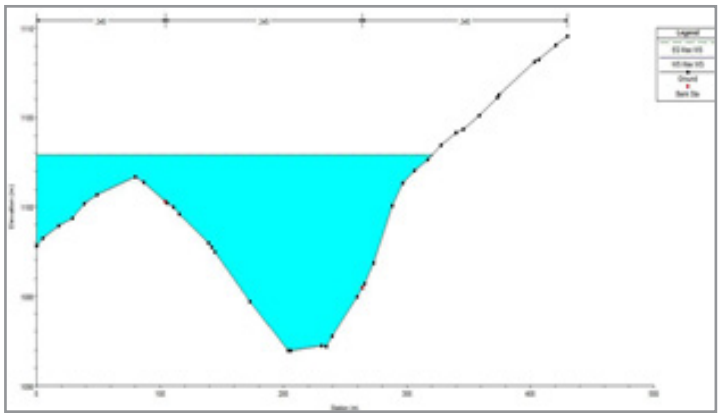


Figure 2: Simulated Water Surface Profiles Along the River Channel for Different Return Periods. Flood Inundation Extents and Depths for 25-, 50-, and 100-year Return Periods.

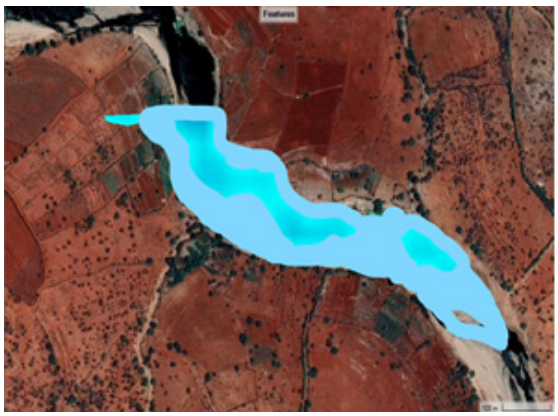
Flood Hazard Mapping

Flood hazard maps were generated using depth classification and spatial overlays. The hazard levels were classified as: Low hazard: <0.5 m ,Moderate hazard: 0.5–1.5 m, High hazard: >1.5 m These maps were overlaid with land-use and settlement data to identify vulnerable zones. The analysis revealed that: Kwa Mangeli is at high risk in all return period scenarios. Graceland Estate becomes severely inundated during 50- and 100-year flood events. Kwa Nzomo shows moderate to high hazard levels due to its proximity to the river bend and flat terrain.

Table 3: Estimated Inundated area by Return Period and Hazard Level.

Return Period	Low Hazard (ha)	Moderate Hazard (ha)	High Hazard (ha)	Total Flooded Area (ha)
25 years	41.2	58.9	36.7	136.8
50 years	52.5	74.2	49.6	176.3
100 years	61.8	92.4	65.1	219.3

Flood Hazard Maps with Overlaid Land-use and Settlements.



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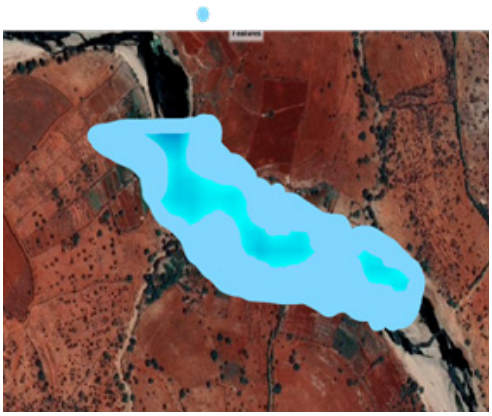

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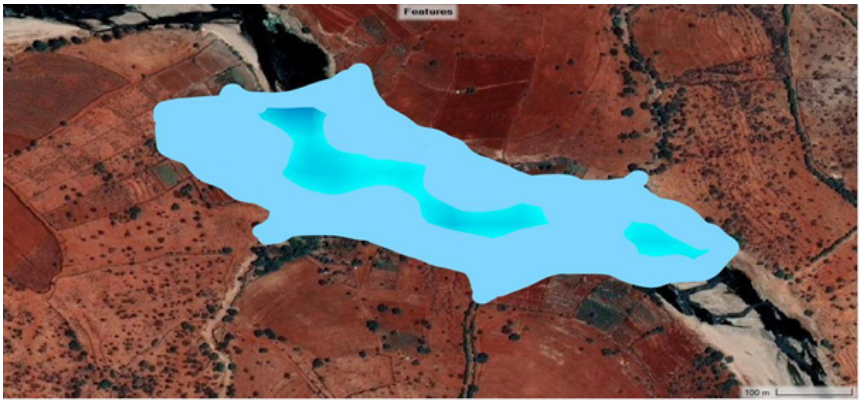

Figure 6:

Vulnerability Analysis

The spatial overlay of hazard zones with population density and infrastructure layers indicated high vulnerability in informal settlements and densely populated areas near the river. The presence of schools, roads, and small-scale farms within floodplains further underscores the need for mitigation.

Summary of Key Findings HEC-HMS demonstrated good agreement with observed streamflow data. Peak discharge increases from 104.2 m^3/s (25-year) to 148.3 m^3/s (100-year). Flood extent grows with return period, inundating major settlements and infrastructure. Over 200 hectares of land are projected to flood in a 100-year event. Hazard maps highlight critical areas for flood mitigation and planning.

Discussion

Interpretation of Findings

This study successfully applied an integrated hydrologic and hydraulic modeling framework (HEC-HMS and HEC-RAS) to assess flood hazards in the upper Athi River Basin. The simulation results revealed that flood extent and depth significantly increase with the return period, a pattern consistent with hydrological theory and past empirical studies. The modeled peak discharges of 104.2 m^3/s, 125.5 m^3/s, and 148.3 m^3/s for the 25-, 50-, and 100-year return periods, respectively, indicate a clear escalation in flood risk under more extreme rainfall scenarios. These values align with trends reported in other flood-prone basins in East Africa, where climate variability has amplified the magnitude and frequency of high-flow events [16].

The HEC-HMS model demonstrated strong performance, with NSE values exceeding 0.78 in both calibration and validation phases. This level of model accuracy indicates that the selected loss and routing methods (SCS-CN and Muskingum) are suitable for simulating runoff in semi-arid tropical catchments, as also confirmed in studies by El-Shinnawy and Hossain et al. [17]. The resulting hydrographs accurately captured the temporal distribution of flow, which was critical for generating realistic boundary conditions in HEC-RAS.

Flood hazard maps generated for each return period revealed that settlements like Kwa Mangeli, Graceland Estate, and Kwa Nzomo are highly exposed to inundation, particularly under the 100-year flood scenario. This finding corroborates previous flood vulnerability assessments in Kenya that identify informal settlements in riparian zones as highly susceptible to disaster impacts. The classification of hazard zones based on depth thresholds allowed for a nuanced understanding of risk distribution, which can directly inform land-use planning, infrastructure design, and emergency preparedness efforts.

Comparison with Other Studies

The integrated modeling approach used in this study is consistent with established methodologies for flood hazard assessment in data-scarce regions. Similar applications in regions such as the Nile River Basin and the Swat River in Pakistan have demonstrated the efficacy of HEC-HMS and HEC-RAS in identifying flood-prone areas and predicting inundation depths.

Compared to the LISFLOOD or SWAT models, HEC-HMS and HEC-RAS are particularly suitable for catchment-scale applications where high-resolution terrain and hydrologic data are available. While LISFLOOD integrates rainfall-runoff and hydraulic routing in a single platform [18], the modular separation in the HEC suite allows for greater flexibility in model calibration and scenario analysis, especially under varying return period assumptions.

The vulnerability overlay performed in this study echoes findings by Cutter et al., who emphasized the importance of coupling hazard data with social and infrastructural vulnerability indicators. By integrating land-use and population density layers into hazard maps, the study provides a more holistic view of risk, similar to multi-criteria GIS-based models used in South Asia and sub-Saharan Africa [19].

Implications for Flood Risk Management

The flood hazard maps produced in this study offer actionable insights for policymakers, urban planners, and disaster management agencies. First, they enable the identification of priority zones for structural interventions such as levees, retention basins, and river training works. Second, they inform non-structural strategies including the development of zoning regulations, early warning systems, and community-based disaster preparedness programs.

Importantly, this study supports Kenya's broader goals under the Sendai Framework for Disaster Risk Reduction and Vision 2030 by contributing to hazard-informed development. The integration of hydraulic modeling with spatial risk analysis lays the foundation for flood-resilient infrastructure design and sustainable land-use planning.

Study Limitations

Despite the robustness of the modeling approach, several limitations should be acknowledged. First, the accuracy of the simulation is dependent on the quality and resolution of input data. Although a 12.5 m DEM was used, finer-resolution terrain data (e.g., LiDAR) would improve cross-sectional representation and water surface profile estimation [20].

Second, the rainfall and streamflow records used for calibration were limited in temporal coverage, which may not fully capture the variability associated with extreme hydrological events. The reliance on synthetic design storms for return periods above 50 years introduces inherent uncertainty, as such events are rarely observed directly.

Third, the study assumes steady-state conditions for hydraulic modeling, which may not capture the transient dynamics of real flood waves, particularly in urban or rapidly rising flood scenarios. Incorporating unsteady flow simulations or 2D modeling in future studies would enhance flood extent accuracy [21-28].

Conclusion

The flood hsazard assessment conducted for the Upper Athi River Basin reveals a significant escalation in flood risk and impact with increasing return periods of 25, 50, and 100 years [29-37]. For a 25-year return period, flooding is largely confined to the main river channel and its immediate overbanks. The flood depth averages around 7 meters, with a manageable flow velocity of 2.1 meters per second. The flood's horizontal spread, or

inundation distance, is approximately 17.1 meters. At this stage, impacts are relatively limited, causing only minor infrastructure damage.

With a 50-year return period, flood behavior becomes more severe. The extent of flooding expands significantly, leading to widespread overbank flooding. Depth increases to 9 meters (a 29% rise from the 25-year event), and velocity becomes critical at 3.5 meters per second. The inundation distance grows to 22.2 meters, indicating a 30% increase in the flood's spread. These conditions pose greater risks to communities and agricultural land, with notable localized impacts.

The 100-year return period represents an extreme flood scenario. Floodwaters extend far beyond traditional floodplains, with a depth of 11 meters (57% higher than the 25-year return) [38-42]. Velocity escalates dramatically to 6.7 meters per second—an extreme condition capable of causing structural damage. The inundation distance more than doubles compared to the 25-year event, reaching 35.1 meters (a 106% increase). At this level, the impact is widespread, threatening large-scale destruction of infrastructure, homes, and farmland [43-48].

These findings highlight the increasing vulnerability of the Upper Athi River Basin to flood hazards, particularly under more extreme return periods. As such, several key recommendations emerge:

1. Implement strategic land-use planning and floodplain zoning to prevent development in high-risk areas, particularly those affected under 50- and 100-year return scenarios.
2. Strengthen early warning systems to ensure communities can respond effectively before floodwaters arrive.
3. Reinforce and adapt critical infrastructure to withstand higher flood depths and velocities, especially in densely populated or economically important areas.
4. Promote integrated watershed management to help reduce runoff and control peak flows during heavy rainfall events.
5. Raise community awareness and enhance preparedness, ensuring that both local authorities and residents understand the risks and are equipped to respond appropriately.
6. These measures are vital to minimizing the socio-economic and environmental impacts of future flood events in the Upper Athi River Basin.

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We also gratefully recognize the National Aeronautics and Space Administration (NASA) for providing high-resolution Digital Elevation Model (DEM) data through the Alaska Satellite Facility, which formed the foundation for watershed and terrain analysis.

Additionally, the application of Geographic Information System (GIS) tools was integral to the spatial analysis and flood mapping in this study. Platforms such as ArcGIS, HEC-GeoHMS, and HEC-GeoRAS significantly enhanced the quality and precision of our hydrologic and hydraulic modeling processes.

The contributions of these institutions and tools were essential to the successful completion of this study.

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