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Research Article

Hydraulic Modeling and Flood Mapping of Flood Plain Along Megech River, Upper Blue Nile Basin, Ethiopia

Masresha Tenaw Demamu*

Department of Hydraulic and Water Resources Engineering, University of Gondar, Gondar, Ethiopia

Abstract

Every year, devastating floods occur in numerous places around the world. Floods are also a daily occurrence in Ethiopia, wreaking havoc and claiming lives, especially in low lying areas such as cities. The Dembia floodplain is one of the most flood-prone districts in Ethiopia. Most victims of flood disasters are people who live in rural areas and make their living from agriculture and livestock near a floodplain. Due to the flooding on the Megech River in Ethiopia, the focus of the study was on hydraulic modeling and flood mapping. Combining the technologies HEC-HMS, HEC-GeoHMS, HEC-RAS and ArcGIS to create a regional model for floodplain identification and representation resulted in floodplain mapping. Using daily time series data, the hydrologic model HEC-HMS was calibrated for return periods of 2, 10, 25, 50, and 100 years. The model HEC-HMS provides 139.7 m^3s^{-1}, 228.2 m^3s^{-1}, 369.7 m^3s^{-1}, 437.8 m^3s^{-1}, and 568.8 m^3s^{-1} for return periods of 2, 10, 25, 50, and 100, respectively. A one-dimensional hydraulic model, HEC-RAS, with the HEC-GeoRAS tool extension in ArcGIS was used for flood mapping. The inundation mapping results in 19.92 km^2, 23.76 km^2, 25.32 km^2, 28.65 km^2, and 30.09 km^2 of inundation area for return periods of 2, 10, 25, 50, and 100, respectively. According to the study, floods have significant impacts as they inundate agricultural and pastoral lands, which has a direct negative impact on of the society. Moreover, flood hazards were evaluated based on the return period and water depth. Therefore, central and local governments should introduce appropriate policies and measures to address this problem.

Keywords

Flood Mapping, HEC-HMS, Flood Damage, HEC-RAS, Flood Inundation

1. Introduction

"Floods are among nature's most devastating disasters, causing loss of life, financial ruin, and destruction of livelihoods, particularly in developing countries [4]." Each year, they result in millions of casualties and extensive property damage. "Utilizing one- and two-dimensional (1D and 2D) modeling improves our understanding of river dynamics [12]". "Climate change and human-induced land use are exacerbating flood severity and frequency [5]". Therefore, implementing long-term flood forecasting, early warning systems, and control measures is essential.

"Flood mapping is a vital tool for professionals, developers, and organizations in metropolitan planning and urban development [7]". It informs decisions on resource allocation for emergency preparedness, flood insurance rates, and environmental studies, ultimately enhancing quality of life in flood-prone areas [8].

*Corresponding author: masreshatenaw21@gmail.com (Masresha Tenaw Demamu), masresha.tenaw@uog.edu.et (Masresha Tenaw Demamu)

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"Climate change, land degradation, and population growth worsen flooding, harming individuals and damaging property. Understanding flood risk reduction techniques can help mitigate these effects [13]". "One effective strategy is the controlled flooding of at-risk areas, identified through flood mapping that highlights regions along rivers prone to overflow [3]."

1.1. Statement of the Problem

Floods frequently occur in Ethiopia, leading to significant loss of life a property, particularly in lowland regions and urban areas. One flood-prone area is located downstream of the Megech River in the Dembia floodplain. "By flooding in 2010, 9200 people are affected and 4300 people are displaced in Dembia woreda [5]".

1.2. Objectives of the Study

The overall objective of this study is to identify the floodplains in the Megech River basin and to analyze the flood hazards along the Megech River.

1.3. Significance of the Study

This study aims to assist planners and decision-makers in understanding the impacts of floods on hydrological variables, particularly in the flood-prone Dembia and Gondar Zuria floodplain. It emphasizes the need for policymakers to consider these hydrological phenomena when developing policies for the area.

2. Research Methodology

2.1. Description of Study Area

The Megech River basin is one of the sub-basins of Lake Tana and is located in the northern part of the lake. The watershed is located between 12^{0}180" and 12^{0}45'0" north latitude and 37^{0}20'0" and 37^{0}40'0" east longitude. The Megech River flows south from north Gondar in the Gondar administrative area through the Dembia flood plain to Lake Tana. It has a total catchment area of 706.8 km^{2}, of which 195 km^{2} is in the Dembia flood plain. The Megech is one of the four perennial rivers that feed Lake Tana (Gilgil Abbay, Megech, Ribb, and Gumera). As shown in Figure 1, the Dembia floodplain is located in the northern Gondar zone of the Amharic region of Ethiopia. "Ninety-five percent of the catchment is cropland and Eutric and Leptosols cover about 82% of the area [2]". People use the water from these rivers to grow fruits, vegetables, and crops. During the rainy season, the Dembia floodplain is inundated by the Megech River.

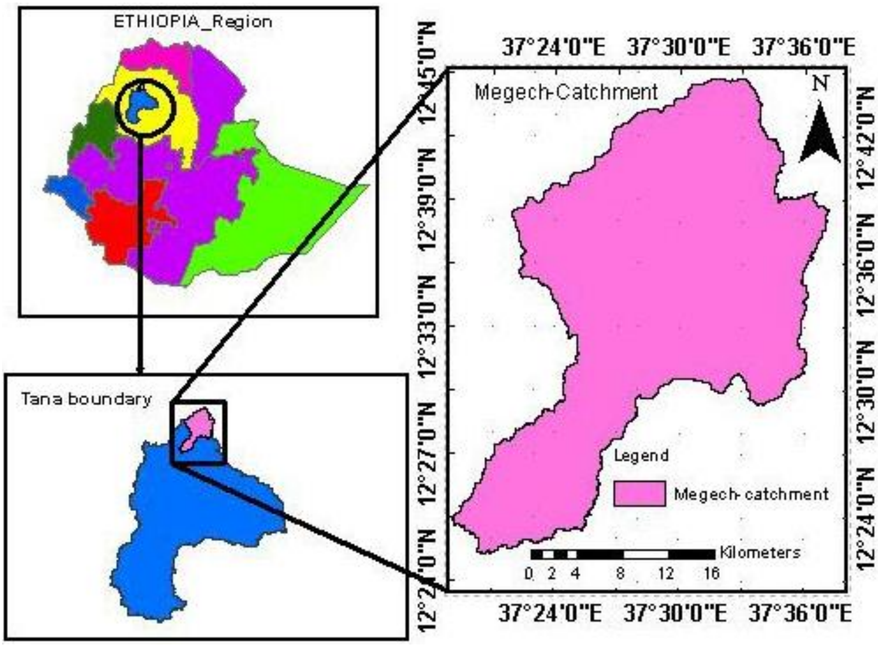


Figure 1. *The study area's location.*

2.2. Data Collection and Analysis

Primary and secondary data were used for this study. Interviews and conversations with elderly residents were conducted to collect the primary data. These people know when and where the river overflowed its banks and what hazards occurred, while the secondary data were collected from different institutions, as shown in Table 1.

Table 1. *Data collection and its sources.*

Data type	Data period	Resolution	Data sources
Digital elevation model (DEM)	2016	12.5m×12.5m	Vertex.daac.asf.alaska.edu
Megech river discharge	2000-2014	Daily	MoWE
Cross-section of the Megech River	——	——	MoWE (collected during the Megech dam project's study and design
Rainfall near meteorological stations	2000-2014	Daily	National Meteorology Agency of Ethiopia

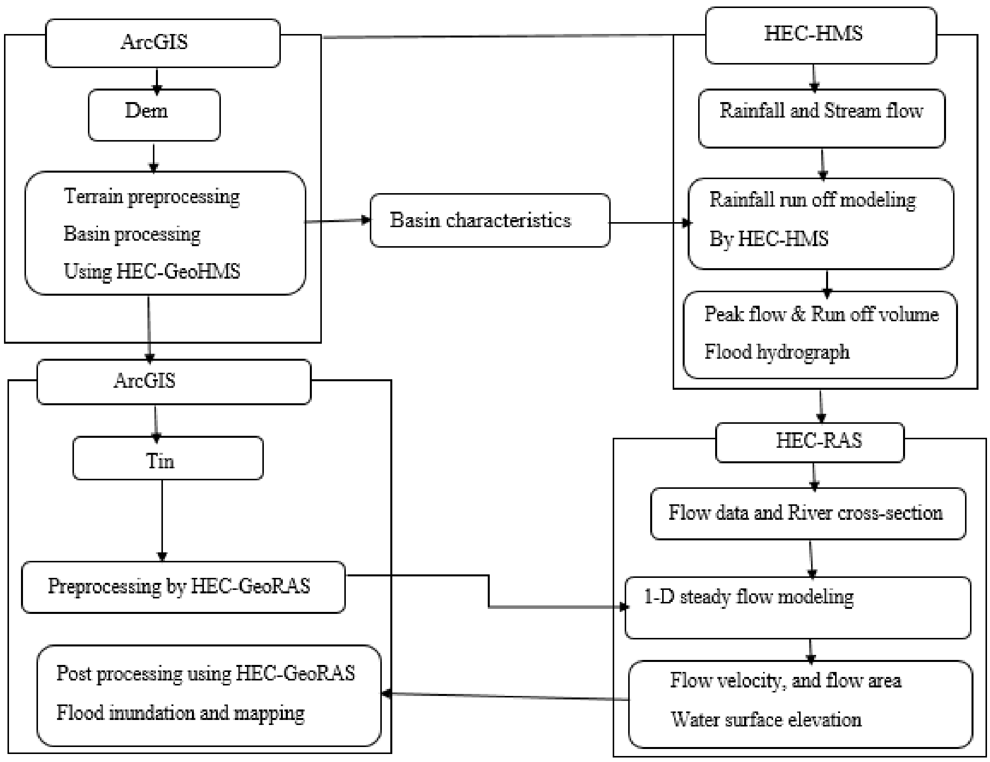


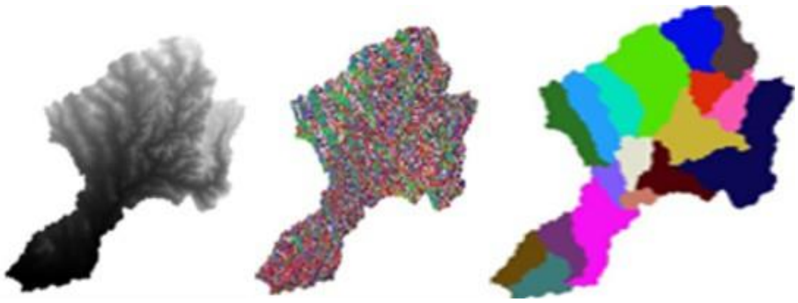
Figure 2. *Research framework.*

The main input data for "HEC-HMS includes actual precipitation, runoff, baseflow, and basin characteristics from HEC-GeoHMS. The simulation comprises three components: the catchment model, meteorological model, and control specifications [11]". "Daily modeling approaches utilize results from HEC-HMS through the gage weight and storm frequency methods. Using a refined DEM, physical properties such as river length, width, slope, watershed slope, longest flow path, and the elevation of the watershed's center of gravity were calculated [8]".

Table 2. *The Megech river HEC-HMS model`s basin parameters and constraints.*

Model	Method used	Parameter	Maximum	Minimum
Transform	Clark Unit Hydrograph	Time of concentration	500 hr.	0.1hr
		Storage coefficient	150 hr.	0hr
Loss	Initial and Constant	Initial loss	500 mm	0 mm

Model	Method used	Parameter	Maximum	Minimum
	Loss Rate	Constant loss Rate	300 mm/hr.	0 mm/hr.
Baseflow	Recession	Initial Discharge	100000 m^3/s	0 m^3/s
		Recession constant	1	0.00001
Routing	Muskingum	Muskingum-K	150 hr.	0.1 hr.
		Muskingum-X	0.5	0



a) 12.5×12.5 m DEM Flow direction➞c) Grid delineation

Figure 3. *HEC-GeoHMS watershed characterstics were imported.*

2.3. Validation and Calibration of Models

The "calibration process involves adjusting model parameters to align results with observed data. This study employed manual calibration to establish a practical range of parameter values while preserving the hydrograph shape and minimizing errors in peak discharges and volumes [9]". Calibration began with initial parameters, which were refined until simulated values matched observed data. A total of 15 years of historical data (2000-2014) were used, with calibration from year 2000 to 2009 (Figure 4) and validation from 2010 to 2014 (Figure 5) for the selected sub-basin watersheds.

2.4. Evaluation of Model Efficiency

Hydrologic model performance evaluation assesses the accuracy of simulated results by comparing them with observed data, primarily focusing on measured and simulated flows. In this study, model performance was evaluated during calibration and validation through visual inspections of flow plots and calculation of efficiency criteria, specifically the Nash-Sutcliffe Efficiency (NSE) coefficient of determination (R^2). NSE values range from -∞ to 1, with 1 indicating a perfect match between observed and simulated discharges. "Values between 0.9 and 1 signify very good performance, while values between 0.6 and 0.8 indicate acceptable performance [14]".

$$N\dot{S}E = 1 - \frac{\sum_{i=1}^{n}(Qoi - Qsi)2}{\sum_{i=1}^{n}((Qoi - \overline{Qo})^{\ 2}} \tag{1}$$

$$R^2 = \frac{\sum_{i=1}^{n}(Qoi - \overline{Qo})(Qsi - \overline{Qs})}{\sum_{i=1}^{n}((Qoi - \overline{Qo})^{\ 2})^{\ 0.5}\sum_{i=1}^{n}\ \overline{((Qsi -)^{\ 2})^{\ 0.5}}} \tag{2}$$

Where: Qoi = observed discharge

$\overline{Qo}$ = mean of observed discharge

Qsi = simulated discharge

$\overline{Qs}$ = mean of simulated discharge

Table 3. *Model performance indicators for calibration and validation year.*

Megech catchment model performances	Year of simulation	Nash-Sutcliffe Efficiency (NSE) in%	Coefficient of Determination R2 (%)
Calibration	(2000-2009)	71.9	79
Validation	(2010-2014)	72.5	84.5

GeoRAS primarily relies on terrain data, specifically the triangular irregular network (TIN), which is raster-based and can be processed in ArcGIS 10.4.1. The quality of this data is determined by its resolution; smaller cell sizes yield higher accuracy. To assess a DEM's utility for terrain modeling, both cell size and hydraulic evaluation levels were considered, with larger cell sizes enhancing analysis precision. ArcGIS converts point elevations from various sources into shapefiles, enabling further processing through interpolation and field surveys for areas with missing data. While previous studies utilized a 90×90 DEM, this research employs a high-resolution 12.5×12.5 m DEM to create an accurate TIN representing the entire floodplain, informed by extensive field data. Elevation values from the DEM were used to represent floodplain data collected during field surveys. Using ArcGIS triangulation methods, water surface TINs were generated for selected profiles based on cross-section water surface elevations. “Hydraulic analysis of the river system was conducted using HEC-RAS and the HEC-GeoRAS ArcGIS extension [10].”

2.5. Entering Flow Information and Boundary Conditions

Flows are defined at the headwaters of each river and at their confluences, with each river in HEC-RAS referred to as a profile. HEC-RAS offers various methods for determining flow conditions, categorized into steady and unsteady flow; this study employed a steady flow method. The model includes several boundary conditions, with critical depth at the downstream end being used in this analysis. A one-dimensional steady-state flow analysis was conducted using flow data calibrated in HEC-HMS for five flood periods: 2, 10, 25, 50, and 100 years, with flood discharge values entered manually for each return period. Manning roughness coefficients were manually applied to the model, with values of 0.03 assigned to the Megech River and 0.04 to its overflow banks and floodplains, “based on the Manning Roughness Coefficient Selection Guide for Natural Channels and Floodplains [16].”

2.6. HEC-RAS Calibration and Validation

Model calibration involves outlining the ideal principles of model factors that result in the smallest possible deviation between actual and simulated values. Due to the accessibility of the values, the main factor was adjusted with the roughness coefficient of the surface. Model validation is a method of analyzing the ability of the model to simulate with standard accuracy measurement data other than those used for calibration.

Calibration was always done by hand to improve factor values, starting with the specified initial values and continuing until the simulated variable matched the observed one. Calibration was assessed using a graphical explanation and other statistical methods. Calibration and validation were performed for this study using GPS coordinate points specifying a historic floodplain, information from older locals, and satellite overlays of floodplains.

2.7. Delineation of Floodplains Using ArcGIS

The DEM generated a TIN used to extract river cross sections, centerlines, shorelines, flow lines, and other geometries for the HEC-GeoRAS model. “Concurrently, land use/land cover data were analyzed to determine Manning's n values for each cross section. After preparing the River Analysis System (RAS) geometry data, the HEC-GeoRAS model created a RASGIS import file for input into HEC-RAS [4]”.

The HEC-GeoRAS research aimed to enhance spatial data for creating HEC-RAS import files with a 3D stream system and cross sections. The process involved three steps: first, training polyline themes to label river centerlines, banks, flow traces, and cross sections; second, utilizing HEC-GeoRAS; and third, distributing the technique. The Pre-RAS menu extracted 3D spatial data from TIN to generate polyline themes, which included river centerlines, banks, flow paths, and cross sections. These themes formed the foundation for geometric data required for HEC-RAS hydraulic analysis.

Three-dimensional details were computed and visualized within the system, leading to the creation of an inundation map using surface profiles integrated into the GIS/ArcView HEC-GeoRAS. This included river system diagrams and cross-section data, such as cross-section surface lines, bank stations, and designations for river reach and station coordinates.

3. Results and Discussion

3.1. Hydrological Simulation

HEC-HMS the model calibration performed at the lower gauging stations shows good agreement with NSE values of 71.9% and 79%, respectively, and R2 values for the megech watersheds. Model validation also shows good agreement with NSE values of 72% and 84%, respectively, and R2 values for the Megech watersheds, as described in Table 3.

“The frequency storm method utilizes statistical precipitation data to generate synthetic storms, producing peak discharges for various return periods [15]”. The output from the HEC-HMS model serves as well-calibrated peak streamflow for the HEC-RAS model, eliminating the need for further calibration of discharge data. Peak discharges for return periods of 2, 10, 25, 50, and 100 years were determined to be 39.7 m^3/s, 228.27 m^3/s, 369.77 m^3/s, 437.87 m^3/s, and 568.87 m^3/s. respectively.

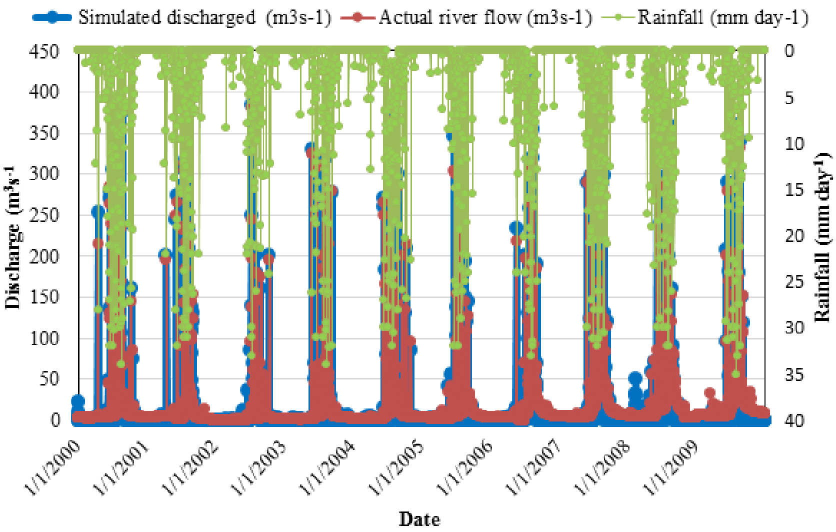


Figure 4. *Actual and simulated discharge during the calibration period (2000-2009).*

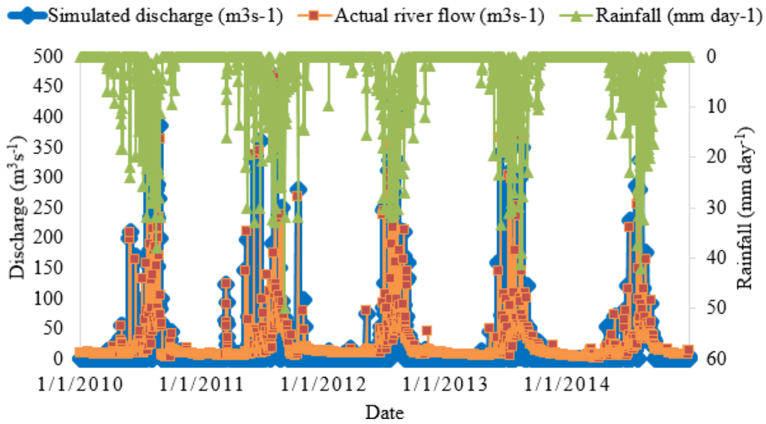


Figure 5. *Actual and simulated discharge during validation (2010-2014) year.*

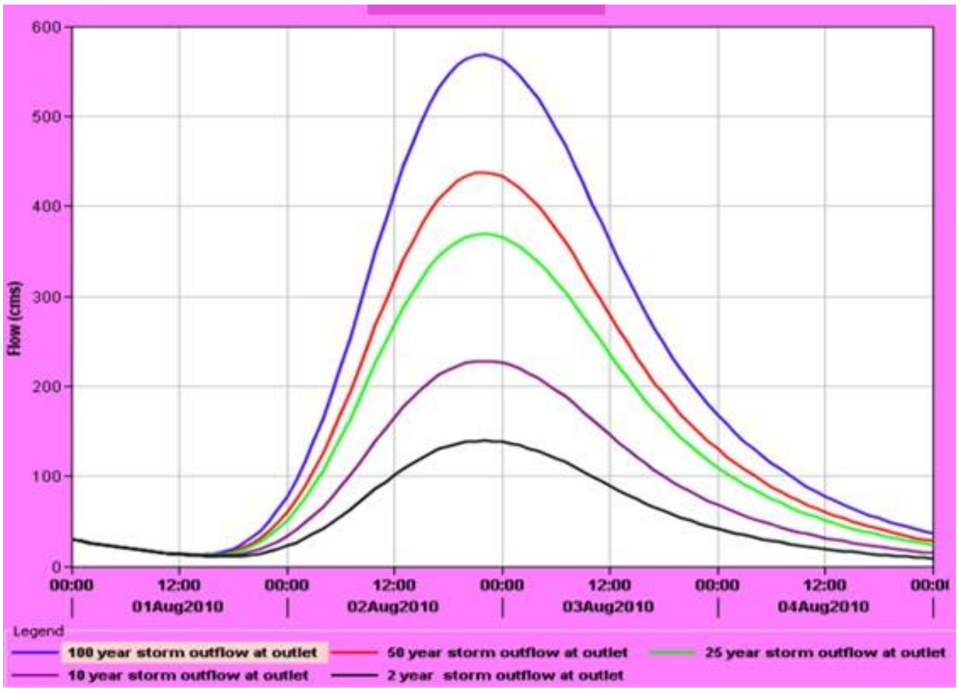


Figure 6. *Megech river peak flow hydrographs at 2, 10, 25, 50, and 100 years.*

3.2. Mapping and Delineation of Flood Inundation

When exporting an ArcMap geodataset to HEC-RAS, the right and left banks of a river were modified and named accurately. The right and left banks were matched in Arc-Map with the HEC GeoRAS extension, which did not match the actual right and left banks. The solution to these problems was to use a cross-section editor in HEC-RAS and manually select the right and left banks based on cross-section geometries. After using the correct steady-state flow analysis geometry to route flows of 39.7 m^3s^{-1}, 228.27-m^3s^{-1}, 369.77 m^3s^{-1}, 437.87 m^3s^{-1}, and 568.87 m^3s^{-1} through a stream, the steady-state flow analysis was formed from water surface profiles. With these two data sets, flow and topography, in appropriate form, the resulting model efficiency is high. The model provides a two-dimensional view of the water surface profile of the floodplain. According to the flood plan, the area was delineated as a buffer zone, as shown in Figure 7. Floodplains are created when the height of the flood exceeds the height of the land. Surface flooding and land surface elevations were used to delineate these areas. The floodplains were shown as a calculated area in HEC-RAS. "These elevations, as well as the distances from the stream centerline to the left and right floodplain boundaries, were imported into the Gis software during data import [1]".

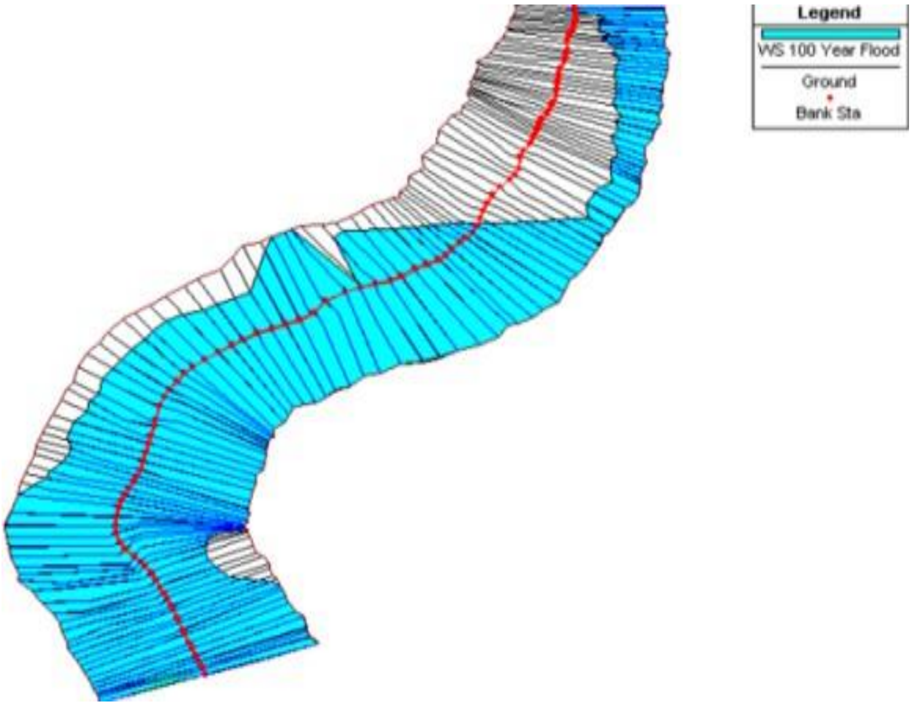


Figure 7. *HEC-RAS 3D floodplain and channel perspective (100 year peak flood).*

Five flow regimes were studied and mapped with Arc-Map to create floodplain maps along the Megech River. Floodplains were mapped with specific shapefile features to provide a thorough examination of floodplains and affected areas. The extent of the floodplains was also 1.5 km, with 0.6 km on each side.

3.3. Flood Affected Areas

According to the results of this study, two woredas in the central Gondar zone were affected by flooding. The Dembia and Gondar Zuria woredas are examples of these. Eight kebeles in Dembia were inundated by floods, while three kebeles in Gondar Zuria were inundated. For each of the modeled flood events, vulnerability maps were created for the flooded areas by intersecting the floodplain land use map with the floodplain polygon. This model shows the aspect of vulnerability to flood risk in a given area in relation to flooding during a given return period. According to the analysis, 90%, 5.17%, 2.25% and 2.76% of the floodplain are covered by cropland and 0.83 km^2 and 0.83 km^2 are covered by cropland, grassland and aquatic and shrubland, respectively, which means that the extent of the area increases as the flood intensity increases. The vast majority of irradiated land around the floodplain is cropland, with a smaller percentage of shrubland, wetlands, and pasture. Nearly 90% of the flooded land is agricultural or cropland. The remaining 10% is in agricultural and pastoral use near the confluence of Lake Tana.

Table 4. *Flood affected areas with different return period.*

Flooded kebeles Dembia woreda	2 Year Inundated Area (Ha)	10 Year Inundated Area (Ha)	25 Year Inundated Area (Ha)	50 Year Inundated Area (Ha)	100 year Inundated Area (Ha)
Sufan Gubia	38.6	54.3	56.4	62.5	86.2
Wekerako	305.0	412.1	485.2	534.08	601.05
Guramba Jankra	198.6	198.6	327.4	398.02	417.05
Arebia Dibatsge	135.0	317.0	289.4	312.5	319.05
Seraba dablo	83.70	265.4	108.4	121.3	139
Achera	405.8	454.08	495.8	516.5	587.5
Debirzuria	327.9	574..2	584.4	598.5	615.8
Guramba Bantana	18.60	28.5	47.5	96.6	1228.05
Total Area (km^2)	18.60	22.04	23.43	26.4	28.94

Table 5. *Flood inundated kebeles in Gondar zuria kebeles.*

Kebeles flooded	2-Year Flooded Area (Ha)	10-Year Flooded Area (Ha)	25-Year Area (Ha)	50-Year Flooded (Ha	100-Year Flooded Area (Ha)
Minyicher	31.2	37.8	39.7	45.6	50.5
Tachetabriha	31.8	35.7	45.8	58.2	62.9
Hamasafe	68.4	89.5	93.5	121.7	125
Total Area (km^2)	1.314	1.63	1.79	2.25	2.38

3.4. Discussion

With Limited River, geometric, topographic, and hydrologic data available in developing countries such as Ethiopia, hydraulic models and GIS are of limited use for floodplain analysis and risk mapping. River flooding in Ethiopia is also quite different from other countries where floods, flows, and rivers are completely unregulated. Flood control structures on riverbanks, such as dikes and levees, are inadequate, and boundary lines need to be clarified.

The flood discharge for different return periods is calculated by a different method. In this work, the result of the model HEC-HMS is considered representative of the correct discharge value. According to the model results, even with a flood discharge from a 2- year storm, significant flooding occurs in the area. For a 100-year storm, the flood depths and extents range from 0.0002 to 3.26 m. The flood risk and hazard maps show that cropland, agricultural land, and rivers with large water depth and area are at high risk. These are the most flood-prone areas in the floodplains, so additional flood protection measures are needed. This study identified the flood-prone areas of Debrezuria, Wekerako, Achara, Guramba Jankara, Arabia Dibatsge, Seraba dablo, Guramba Bantana, and Sufan Gubia, which have corresponding flood susceptibility of 21.3%, 20.8%, 20.3%, 14.4%, and 11.04%, respectively. Flood discharge during a 100-year storm was 4.8%, 4.4%, and 3%, respectively. Three kebeles in Gondar Zuria were affected by flooding, with Hamasafe Kebele being the most affected, followed by Mincher and Tachetabriha.

According to research“ investigated flood risk mapping and vulnerability analysis in the Dembia floodplain using 2D hydrodynamic modeling [17, 6]”. The main strengths of the research are that the 2D flow is dynamically simulated without specifying flow patterns; there is flexibility in adjusting the grid resolution within the model; and there is detailed information on velocity, depths, and other floodplain parameters. Raw streamflow data that had not yet been calibrated or refined to high resolution were used for this study. Despite the use of a one-dimensional model, the best aspect of our research is that one-dimensional discharge is accurate for hydraulic description of rivers and channels and can be easily analyzed and results extracted [18]. In addition, It has been calibrated and validated discharges and identified flood-prone areas down to the kebele level.

4. Conclusion and Recommendation

4.1. Conclusion

This study utilized the numerical models HEC-RAS, HEC-HMS, HEC-GeoHMS, HEC-GeoRAS, and ArcGIS 10.4.1 for flood modeling of the Megech River. The floodplain map was created by processing geometric input data from a DEM using HEC-GeoRAS. The hydrologic model HEC-HMS was calibrated using daily time series data for return periods of 2, 10, 25, 50, and 100 years, producing peak flows of 139.7 m^3/s, 228.2 m^3/s, 369.7 m^3/s, 437.8 m^3/s, and 568.8 m^3/s, respectively. The flood mapping results indicated inundation areas of 19.92 km^2, 23.76 km^2, 25.32 km^2, 28.65 km^2, and 30.09 km^2 for the same return periods.

The largest inundated area occurred during the 100-day return period due to increased runoff. Model results indicated that flood depths peaked at 3.26 meters in the lower reaches of the river, decreasing from upstream to downstream. The severe flooding significantly impacted life and property, particularly affecting agricultural and pastoral lands. The study assessed land use patterns in flooded areas concerning flood risk and vulnerability, revealing that even a two-year storm can inundate Dembia and Gondar Zuria Woreda. This highlights the need for engineering structures, such as levees and dams, along the river channel and lower floodplain.

Topographic analyses using ArcGIS and field survey data provided accurate terrain depiction, with a high-resolution DEM (12.5m × 12.5m) enabling more precise hazard and risk mapping. Extreme rainfall during the main rainy season leads to significant flooding in low-lying areas, particularly in Kebeles Achara, Wekerako, Debrizuria, and Guramba. Consequently, central and local governments should develop effective measures and policies to address this issue in the future.

4.2. Recommendations

To prevent flooding and siltation caused by sediment deposition along the river course, river engineering measures such as the construction of dams, slope protection, dikes, or other nonstructural measures are recommended. To reduce flood damage, areas inundated by the 100-year return period should not be used for agricultural activities, infrastructure development, settlements, or other capital projects during the rainy season, as this would result in property and infrastructure damage. To reduce the extent of flooding, sediment transport, and siltation, soil conservation measures should be implemented in both the upstream and downstream portions of the area. To reduce flood risk, efforts must also be made to implement effective land use planning in flood- prone areas. For flood emergencies, the government should raise public awareness and establish an emergency plan. Researchers and students should have access to qualitative and quantitative data from educational and research institutions to produce relevant problem-solving scientific research.

Abbreviations

DEM	Digital elevation model
HEC-HMS	Hydrologic Engineering Center's Geographic Hydrologic Modeling System
HEC-GeoHMS	Hydrologic Engineering Center's Hydrologic Modeling System
HEC-RAS	Hydrologic Engineering Center's River Analysis System
ArcGIS	Arc Geographic Information System
km^2	Square kilometers (unit of area)
m^3/s	Cubic meters per second (unit of flow rate)
MoWE	Ministry of Water, and Energy Ethiopia
ENTRO	Eastern Nile Technical Regional Office

Author Contributions

Masresha Tenaw Demamu is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

I declare that there are no conflicts of interest regarding the publication of this article titled "Hydraulic Modeling and Flood Mapping of Flood Plain along Megech River, Upper Blue Nile Basin, Ethiopia." The research was conducted independently, and the findings presented in this study are based solely on the data collected and analyzed by the sole author.

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