International Journal on Engineering Technology (InJET)

www.kec.edu.np/kec-journal/
Volume 3, issue no. 1, Dec 2025, Page 230-239
Received Date: Aug 28. 2025
Accepted Date: Sep 21, 2025
ISSN: 3021-940X (Print)
DOI: https://doi.org/10.3126/injet.v3i1.86985

Flood Management and Inundation Mapping: A Case Study of Khando River Basin of Saptari District, Nepal

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Abstract

Flooding is increasingly recognized as one of the most significant water-related hazards globally. The extent of damage inflicted on various components escalates over time. This study aims to examine the frequency of flooding, develop flood maps for the Khando River Basin corresponding to various recovery periods, and pinpoint hazardous areas within the basin. The Khando River Basin, encompassing an area of 117.3 km², has been selected for this analysis. Frequency analysis is conducted utilizing the Gumbel calculation method alongside HEC-RAS software. The creation of Flood Hazard Maps is essential for assessing flood levels. These maps were generated using HEC-RAS version 5.0.7 and integrated with ArcGIS 10.1 and HEC-GeoRAS extensions. A Digital Elevation Model (DEM) with a spatial resolution of 20 m × 20 m was employed for the research. The discharge data utilized in this study have been validated against field measurements. Discharge and flood depth increased with return periods (2–100 years), reaching 3 m at the 100-year event in the Chure Range, where shorter cross-sections had greater depths, while other areas showed lower depths. Flood depths in the Khando River were classified as high, medium, and low risk by the Department of Hydrology and Meteorology (DHM). The flood zone indicates population vulnerability, making this study helpful in valuable study for planning and managing future natural disasters.

Keywords: Flood hazard maps, HEC-RAS, frequency analysis, Gumbel calculation method, ArcGIS, Digital Elevation Model (DEM), discharge data, return periods

1. Introduction

Floods are common hydrological disasters worldwide and occur in Nepal, during flood lives and property. Growing population density and informal riverbank settlements lead to increased floodplain encroachment and vulnerability (Dangol, 2015); Floods are a recurring hazard in Nepal due to intense monsoon rains, steep terrain, and narrow river valleys prone to mass wasting. Each year, floods cause deaths, displacement, and significant damage to public and private property, severely impacting national development (Hemant R. Ojha et al, 2016); The majority of rivers and streams in Nepal flow from the north towards the south, typically exhibiting high velocity due to the steep river gradient. River system of Nepal based on topography and many rivers are originate from higher Himalayan and Mahabharat. Khando is one of the important rivers of Saptari that originates from Siwalik range and carry large amount of water in monsoon season. This paper is based on a case study of the Khando River in the Saptari district of Nepal's Terai region, which is a flat area in the southern part of the country, located in Madhesh Province in Nepal. The Khando River originates from the Churia region, and flooding in the Tilathi-Rajbiraj area occurs nearly every year. River flooding is a significant in Nepal during the monsoon season, which lasts from June to September. The primary causes of flooding include continuous heavy rainfall during this season, a large catchment area for the river, and the fact that the elevation of the river, fertile land, and villages are nearly the same (Saraswati Thapa, 2020); Therefore, this study focus in identifying the problems associated in the Khando River.

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Chure-origin rivers are ephemeral in nature, exhibiting high discharge and substantial sediment transport and deposition during the monsoon period. Deforestation, grazing, and poor farming practices increase soil exposure, making the erosion-prone region even more vulnerable due to its weak geology (DHM, 2014). In the flat Terai, sediment builds up along rivers, blocking waterways and causing meandering and floods. Along with rising temperatures, intense rainfall, and poor land use, threatens lives and livelihoods in the Chure and Terai regions. (Shrestha et al., 2014); The Khando River, which originates in the Churia Range. The rivers in this area become wide, inundating and damaging agricultural lands, landslides in Chure. The damages are further characterized by bank erosion and the deposition of infertile coarse material on cultivated land, as well as the cutting down of roads and bridges. The RL of the river and the RL of village nearly equal. Therefore, there is a huge inundation problem in the river basin. This river also affects huge area in Nepal as well as India also. This study aims to identify the flood-affected areas of the Khando River basin and mitigate to flood (Saraswati Thapa, 2020).

2. Literature Review

Floods frequently strike in monsoon season at Nepal, causing deaths, displacement, and significant damage to property and infrastructure. Steep terrain, intense monsoon rains, and narrow valleys increase vulnerability, hindering national development (Chow et al., 1988); Floods are a recurring monsoon disaster in Nepal, causing deaths and damage to key infrastructure. This paper reviews national and international studies on flood hazard mapping, noting that Province 2 in the Terai is most affected. Most research focuses on steady flow models and hazard analysis, with less emphasis on vulnerability and risk assessment **(**Buddhi Raj Shrestha **et** al**.**, 2020**).**

Major glacier rivers like the Koshi, Gandaki, Karnali, and Mahakali flow through mountains and the Terai. Their large catchments and fast flows cause annual floods, damaging infrastructure and claiming lives **(**Hari Dhungana et al**.**, 2016**);** Climate change scenarios project warmer temperatures and changed precipitation with negative impacts on water supply (Santos et al., 2016); Floods are one of the most devastating disasters, especially in Asia (Whitehead et al., 2012); Economically disadvantaged people are most vulnerable, living in high-risk areas with limited capacity to cope. Developing countries face greater flood risks due to weak disaster response systems (Bowyer et al., 2014).

2.1 Flood

For many human societies, flooding is becoming a more growing concern. Floods affected approximately half of the individuals affected by natural disasters and accounted for nearly one-third of all disasters globally between 1900 and 2006. Recent studies have shown that increased greenhouse gas emissions and global climate change contribute to more frequent and severe flooding (S Birkholz et al., 2014); Flood risk management involves three key steps: risk analysis (identifying potential risks), risk assessment (evaluating and categorizing those risks), and risk reduction (implementing measures to control or minimize hazards) (L Wang et al., 2022).

2.2 HEC-RAS

Numerous features of the HEC-RAS computer model include quasi-2D velocity distribution, pipeline and bridge routines that permit various kinds and sizes of openings, x-y-z graphic of the river channel system, and mixed flow regime analysis, which enables the analysis of both subcritical and supercritical flow regimes in a single computer run (U.S.; US Army Corps of Engineers, 1995); A single river, a branch system, or an entire channel network can all be handled using the HEC-RAS model. The water surface profiles of subcritical, supercritical, and mixed flow regimes can be modeled by the stabilized flow component. The Manning one-dimensional equation was used to determine the flow rate of both natural and artificial channels (Chow 1959).

The Geometric Data Module defines the river system layout, including cross-sections, structures, and water flow paths, while the Flow Data Module provides steady or unsteady flow conditions, boundary conditions, and hydraulic structures. Steady Flow Analysis calculates water surface profiles for steady-state conditions, and Unsteady Flow Analysis simulates time-dependent flow changes like flood wave propagation. Sediment Transport Modeling examines sediment movement, deposition, and erosion, and Water Quality Analysis evaluates parameters such as temperature and dissolved oxygen. Advanced features include 2D Flow Modeling for enhanced floodplain mapping and Dam Breach/Levee Failure Analysis to assess downstream impacts (U.S.; US Army Corps of Engineers, 2020);

2.3 Flood management

In the UK, Defra handles flood risk policy, while the Department for Communities and Local Government oversees spatial planning. The Environment Agency is the leading authority in England and Wales. Private water companies manage flood risks linked to poor sewerage, and internal drainage boards (farmer-run) operate drainage in lowlands. Local authorities are responsible for emergency planning and disaster response. Private insurers cover most homes against floods and related hazards (P. Bubeck et al., 2017); Switzerland has managed floods since the Middle Ages, using engineering technology. Despite many policies, flood risks and damages have increased since the 1970s. The WSL has tracked data since 1972, recording eight major flood years (F Metz et al., 2019); The Damodar River catchment sees seasonal floods from South-West Monsoon rains, influenced by regional depressions. The DVRRC and CWC use five stations for flood forecasting, with data from three reference points and two reservoirs. A 1986 mathematical model and CWC manual support flood control. DVRRC also mediates among states, DVC, and stakeholders through annual meetings with public input (Suresh Chandra 2003).

2.4 Flood management in national context

Accurate data is crucial for flood risk management, while its absence hinders modeling, forecasting, and planning. Satellite data (optical, LiDAR, radar) and Earth observation support GIS mapping, hazard assessment, and modeling, which are essential for Nepal's flood analysis. (Sudeep Thakuri et al., 2022); The August 2008 Koshi flood affected 2.64 million people in Nepal and India, impacting 700 hectares of fertile land and 65,000 people in Nepal. Eight years later, 25% of cultivated land in Sunsari district's Shreepur, Haripur, and Kushaha villages remains unusable due to flood sediment (Kafle et al., 2017);

2.5 Flood Inundation Mapping

Flood models are crucial for minimizing flood impacts by providing forecasts on flood magnitude and depth, which aid in developing accurate hazard maps. These maps assess risks to life and property in flood-prone areas (Pender and Faulkner, 2010); Among the various non-structural measures necessary for disaster mitigation, hazard maps are among the most important(Mahato et al., 1996); The area of land at risk of flooding can be defined based on hydrological studies of selected flood peak magnitudes and topographic information (Joshi, 1987).

3. Research Methodology

3.1 Study area

Khando river which is originate from Chure Parbat. The geographical coordinate of Khando river are 26° 37'35.341" N Latitude and 86° 43' 37.368 " Longitude (GPS-coordinates.net); The Khando river catchment area cover very large in the Churiya region as well as the terai region. During the monsoon season there is many destroy in the prone area of the Khando river. Around the Khando river, many properties are damaged during the monsoon season. The Figure given below shows the study area for this research.

The Khando River catchment encompasses an area of 117.3 km², with elevations varying from 67 to 419 meters above the sea level. According to long-term climate data collected from 1986 to 2015 within the catchment, the annual average precipitation is approximately 1800 mm. Annual maximum and minimum temperatures in the catchment area are approximately 33.7 °C in May and around 8 °C in January, according to long-term climate data spanning from 1981 to 2012. The river extends for 25.246 km. The Khando River is recognized as one of the most problematic rivers concerning flooding and the resulting damages, as indicated by flood records from recent decades. Most of the river's course is situated within the Indo-Gangetic plain, resulting in a flat profile with an average bank height of about 0.8 m (Fig.1).

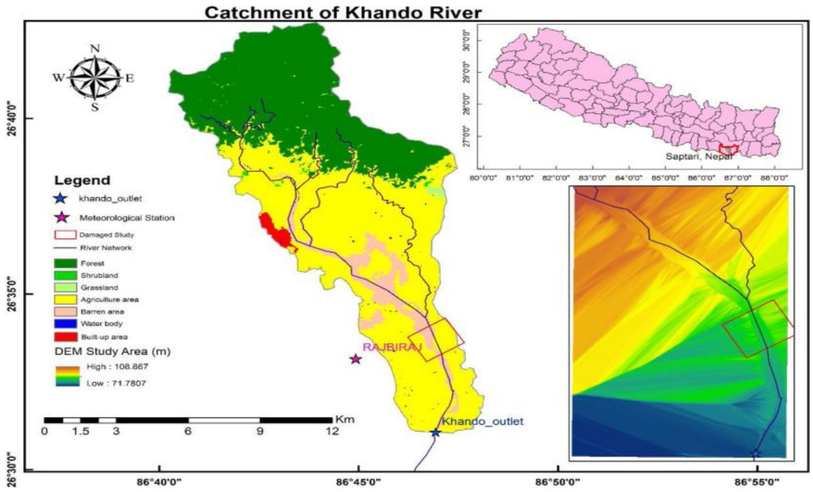

Figure 1. Map of study area (Source Saraswati Thapa, 2020)

3.2 Data collection

Data collection involves acquiring and analyzing information to study outcomes and address concerns. It's essential in research to connect findings to reality. For flood impact studies, both primary and secondary data are needed. Primary data were collected through field surveys, while secondary data, including DEM and HEC-RAS inputs, were provided by DHM, Kathmandu.

Data were collected from primary and secondary sources for accuracy. Primary data included surveys of the Khando River with depth measurements at ten sites, questionnaires from households on both banks, and river outflow data. Secondary data, from government reports and academic sources, provided historical context. Hydrological and meteorological data are collected from DHM stations covered 30 years of rainfall and precipitation. Combining both data types enabled a thorough analysis and solid conclusions.

3.3 Frequency Analysis

Flood frequency analysis used the Gumbel distribution to predict peak floods. The method is suitable for the Khando river because it has limited human interference, consistent flow data over 10 years, and no major tributaries influencing flood peaks, which ensues reliable flood frequency estimates. The equation for Gumbel's distribution, as well as the procedure with a return period T, is

Given as,

$$XT = Xav + K * SDV \qquad \text{(Equation 1)}$$

where;

XT = value of the variate with a return period

Xav = mean of the variate

SDV = Standard deviation of the sample

K = Frequency factor expressed as $K = (yT - 0.577)/1.2825$; yT = reduced variate expressed

by *"YT = -ln(ln(T / (T-1)))"* ; T = return period

3.4 Hydraulic Analysis

HEC-RAS is used to determine the depth and extent of flooding. Software called HEC-RAS was utilized. The stream morphology is represented by a sequence of cross sections indexed by river station in the 1D flow model HEC-RAS. A set of lateral and elevation coordinates, usually derived from the DEM, defines each cross section.

3.5 Theoretical Background of HEC-RAS

HEC-RAS, developed by the U.S.; US Army Corps, was used for 1D steady flow analysis in this study, computing water surface profiles using the energy equation between cross-sections.

$$z_2+y_2+\frac{\alpha_2 V^2{}_2}{2g} = z_1 + y_1 + \frac{\alpha_1 V^2{}_1}{2g} + h_e \qquad \text{(Equation 2)}$$

Where Z_1, Z_1: Datum head at two different sections

y_1, y_2: water depth at sections1 and 2

v_1, v_2: velocities at sections1 and 2

h_e = Energy Head loss

α_1, α_2 = Velocity weighting coefficients

g = gravitational acceleration

4 Results and Discussion

4.1 Flood Flow Analysis

As explained earlier, the Khando River has not been gauged so far. The catchment area of this river exhibits diverse topography, mountains, hills forests in its upper reaches to terai region. In the absence of a gauging station on the river, it is not possible to obtain accurate information or conduct a precise analysis of the flood flows. It is a well-known fact that flood hydrology is a dynamic and complex science. Continuous refinement of data by continued observation and analysis is always necessary.

The figure shows the maximum 24-hour rainfall for the Khando River (1976–2021), with an overall rise in extreme events. Peaks in 2002, 2018, and 2021 mark exceptionally high rainfall. Values fluctuate, with sharp increases after lower years. Recent records are the highest, suggesting a rise in extreme weather linked to climate change, shifting monsoons, or catchment changes. This highlights the need for more comprehensive flood risk assessment, improved infrastructure planning, and enhanced disaster preparedness.

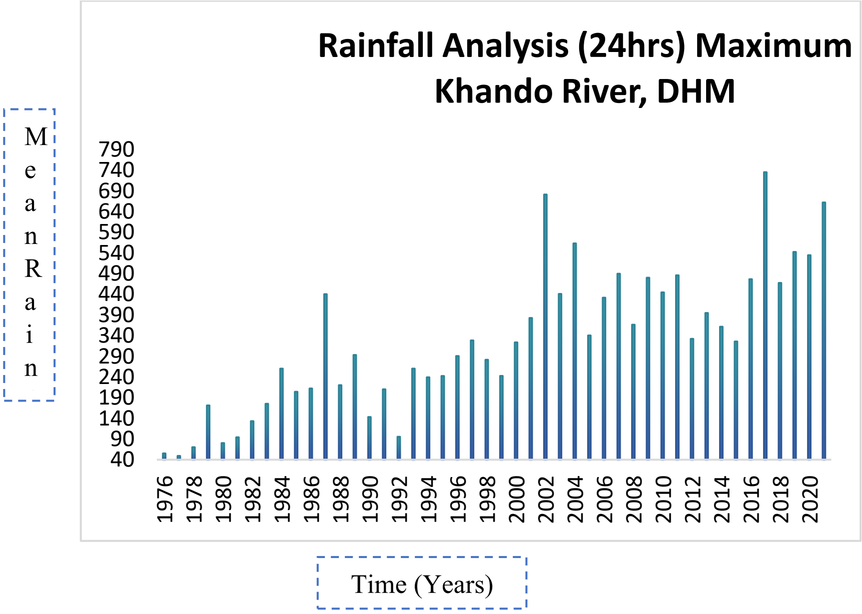

Figure 2. Rainfall Analysis (Rainfall Analysis (24hrs) Maximum Khando River, DHM)

- **Maximum Monthly Temperature**

Table 1. Maximum Monthly Temperature

Months	Best Temperature (°C)	Low Temperature (°C)	High Temperature (°C)
January	7.56	1.06	14.06
February	9.10	2.79	15.41
March	13.11	6.52	19.70
April	18.15	10.87	25.42
May	20.78	13.14	28.43
June	22.54	15.33	29.76
July	22.82	16.03	29.61
August	22.44	15.60	29.28
September	21.47	14.55	28.38
October	18.97	11.61	26.32
November	12.59	5.96	14.13
December	8.16	2.19	14.13
Mean	**16.47**	**9.64**	**23.31**

The table shows monthly maximum temperatures varying from January to a peak in April–May and then declining toward December. The mean maximum, low, and high estimates (27.43°C, 19.88°C, and 34.98°C) indicate a wide temperature range. Moderate standard errors (mean 3.85°C) reflect some variability, especially in March–May. Low bias values (mean 0.70°C) show good model accuracy. Overall, the data indicates warm conditions, with the highest temperatures in the pre-monsoon months.

4.2 Hydraulic Simulation

The implementation of the HEC-RAS model under three different scenarios related variations in key hydraulic parameters such as water surface elevation, channel flow velocity, and flow area. The result of the case for 2yr, 5yr, 25yr & 100yr of return period.

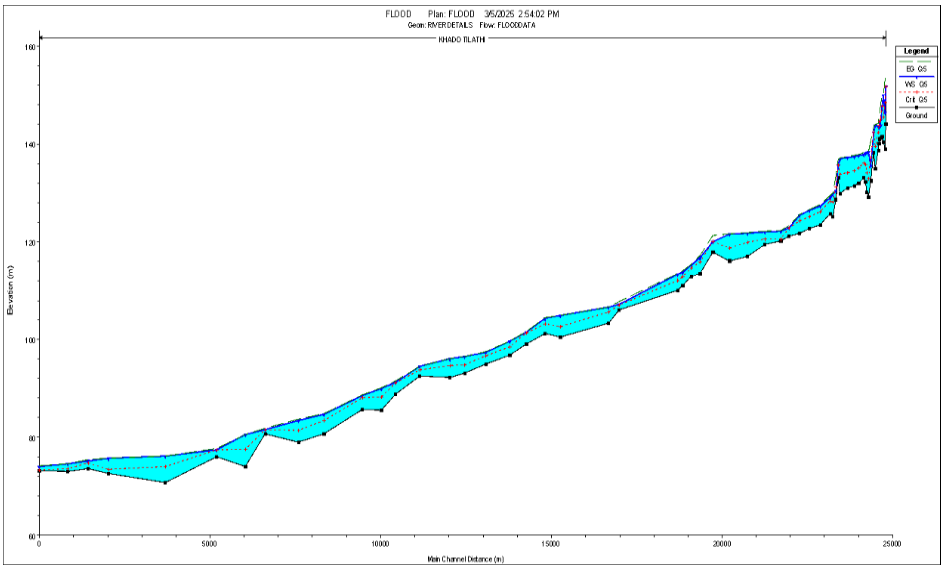

Figure 3. Hydraulic Simulation

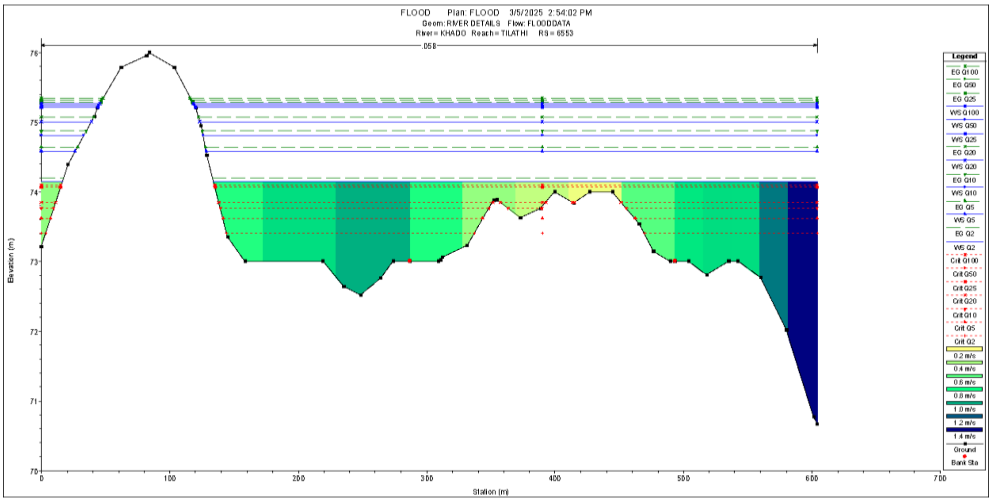

Figure 4. Hydraulic Simulation

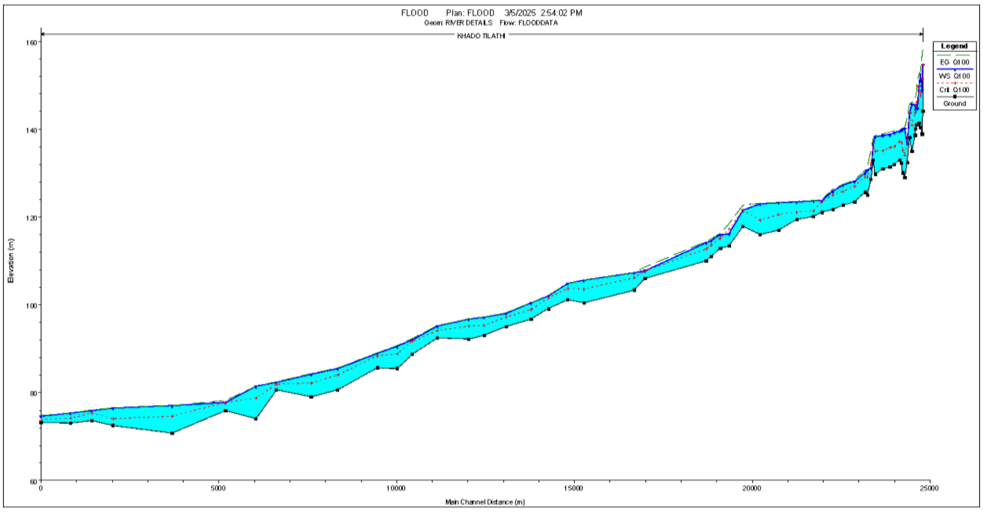

Figure 5. Hydraulic Simulation

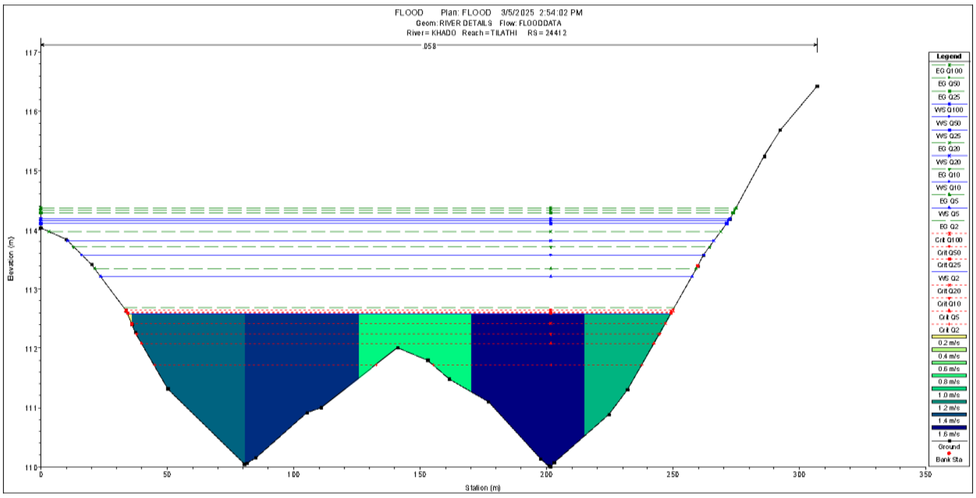

Figure 6. Hydraulic Simulation

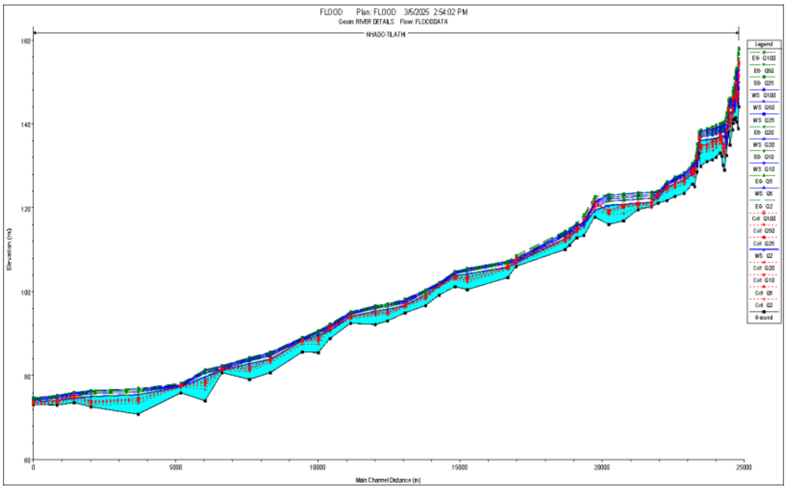

Figure 7. Hydraulic Simulation

4.3 Inundation Analysis

Inundation analysis using HEC-GeoRAS, based on the results derived from the HEC-RAS simulation, was carried out to delineate flood zones. The Figure below illustrates maps corresponding to the 2 years, 5 years, 25 years and 100-year return periods, respectively. The more such images are presented in the annexes.

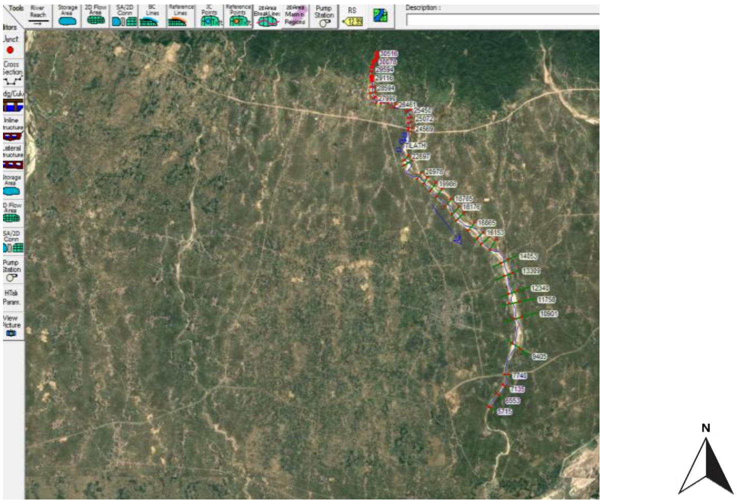

Figure 8. Inundation Analysis

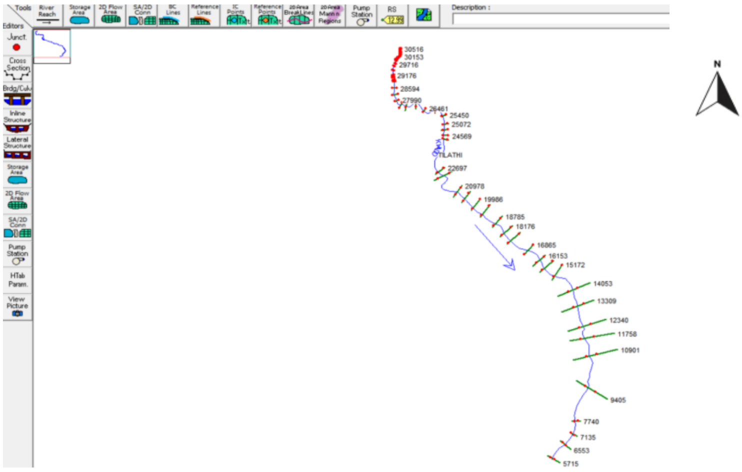

Figure 9. Inundation Analysis in cross-section

4.4 Analysis of flood frequency

The Gumbel method analyzes flood potential using annual maximum rainfall data by calculating mean, standard deviation, and Gumbel parameters. Rainfall estimates for return periods (2–100 years) show higher intensity with more extended periods. The Rational Formula estimates flood discharge using the Khando River's 117.3 km² catchment and elevation range (67–419 m). Analysis of rainfall data from 1986 to 2015 indicates that the average annual precipitation in the area is approximately 1,800 mm. Predicted peak discharges range from 348.22 m³/s (2-year) to 805.02 m³/s (100-year), highlighting the need for flood control.

4.5 Flood Hazard Mapping

Using HEC-RAS with HEC-GeoRAS, maximum discharge depths and flood hazard maps were created in accordance with Nepal's river training manual. Return periods (2–100 years) showed depths rising from 0.00125 to 3 m, with greater depths increasing risk. The GIS model classified zones as high, medium, or low risk, with high-risk areas shaped by topography.

5. Conclusion

The Khando River flood hazard mapping identifies flood-prone areas, confirmed by historical data and surveys. The implementation of improved risk mitigation and sustainable river basin management. Based on historical and recent data of the Khando River, the study examines flood and rainfall frequency patterns and develops flood hazards maps, revealing that areas face greater risk as the return period increases. Hazardous areas in the Khando River basin include Rayapur, Bhataniya Toll, Basbiti, Paunwa, Hariharpur, Pakari, Maleth, Rajbiraj, Topa, Musharniya, Tilathi, Launiya, Beylahi, Koilari, Rampur Bajar, and Kunauli Bajar (India), along with several schools, temples, and public places. The study recommends the implementation of real-time Early Warning Systems, the reinforcement of levees and drainage infrastructure, and the adoption of land-use planning measures to limit development within flood-prone zones.

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