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RESEARCH ARTICLE

Flood inundation mapping of the Mahakali river segment, Kanchanpur district, Nepal, using the HEC-RAS model

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ABSTRACT

Floods are among the most frequent and destructive natural hazards worldwide. Nepal is highly vulnerable to water-induced disasters, particularly floods and landslides during the monsoon season. The Mahakali River Basin, one of Nepal's major river systems, experiences annual monsoon-induced floods that cause severe damage to livelihoods and settlements in the Dodhara Chandani and Bheemdatta Municipality of Kanchanpur District. This study aims to analyze rainfall trends, estimate peak flood discharges for multiple return periods, and develop flood hazard maps using HEC-RAS to support flood risk management and sustainable planning in the Mahakali River basin. Primary field observations were combined with rainfall, discharge, topographic, and DEM data obtained from the DHM, Department of Survey, USGS, and Google Earth to support flood hazard assessment and hydraulic modelling. Flood inundation was simulated using HEC-RAS 6.3.1 with SRTM 30 m DEM, design discharges for multiple return periods, and Manning's roughness coefficients to generate flood hazard maps. The Peak flood discharges for 2, 10, 50, 100, and 200 return periods were estimated using Gumbel's distribution and the WECS/DHM method. The estimated peak discharges ranged from 6,642.45 to 19,086.75 m^3/s using the WECS/DHM method and from 2,835.81 to 26,264.31 m^3/s using the Gumbel distribution. Flood inundation mapping was performed using the one-dimensional steady flow HEC-RAS model, which revealed maximum water depths of 13.56 m, 14.39 m, 14.79 m, 14.96 m, and 15.12 m for the respective return periods. Rainfall trend analysis of 2000 to 2023 indicated an increasing pattern at Mahendranagar Station (slope = 40.97, R^2 = 0.2649) and a slightly decreasing trend at Dodhara Station (slope = –5.65, R^2 = 0.0124) over 23 years. Land use analysis from 2013 to 2022 indicates a decline in agricultural and built-up areas due to flood-induced erosion and inundation. This study integrates rainfall trend analysis, flood frequency analysis, hydraulic modelling, and land-use change assessment to identify flood-prone areas and support flood risk management. The generated flood hazard maps provide a practical tool for municipal planning, flood zoning, and disaster risk reduction in the Mahakali River basin and other ungauged river basins.

Keywords: ***Mahakali river, flood frequency, hazard mapping, inundation, HEC-RAS***

1. INTRODUCTION

Flood is the most destructive natural hazards, primarily caused by intense rainfall or rapid snowmelt, resulting in significant social, economic, and environmental impacts. (Ogras & Onen, 2020). Flood hazard is the likelihood and intensity of flooding caused by factors such as heavy rainfall, river overflow, and land-use change. In Nepal, steep terrain, monsoon rainfall, and climate change make flood hazards more frequent and severe (Dhakal, 2013; Gaire et al., 2015). In Nepal's mountain river systems, upstream–downstream interactions are particularly important because high-gradient catchments rapidly transfer floodwaters and sediment to densely populated lowlands (Delalay et al., 2018; Dhakal, 2013).

Flood hazard assessment is therefore essential for quantifying flood probability and associated impacts over time (World Bank, 2016), and forms a critical basis for land-use planning, flood risk management, and disaster mitigation. Floods affect nearly all geographic regions (Das, 2018) and impose long-term socioeconomic consequences, including population displacement and the spread of waterborne diseases such as malaria and cholera (WHO, 2005).

Nepal is highly vulnerable to water-induced disasters, particularly floods and landslides during the monsoon season (June–September), when approximately 80% of annual rainfall occurs (Uprety et al., 2020). According to the United Nations Development Programme (UNDP, 2004), Nepal ranks 20th globally in multi-hazard vulnerability, 4th in climate change–induced hazard vulnerability, and 30th in flood susceptibility. Recent studies also confirm Nepal's high vulnerability to floods and climate-related hazards (MoHA, 2023; IPCC, 2022). Monsoon-driven floods frequently result in loss of life, infrastructure damage, and destruction of agricultural land (Shakya, 1998; Ghimire et al., 2018). Intense short-duration rainfall causes rapid changes in river flow, leading to channel shifting, bank erosion, and sediment deposition, which are further intensified by activities such as sand mining, unplanned riverbank development, deforestation, and poor land-use practices (Khatakho et al., 2021). Misinterpretation of flood return periods can result in underestimation of risk if probabilistic concepts are not properly understood (World Bank, 2016). Land use and land cover changes significantly affect natural resources by influencing soil and water quality, biodiversity, and climate systems (Awasthi et al., 2002). Human land management practices aimed at addressing climate change can have ecological impacts, and future land use changes may also influence climate projections beyond the effects of atmospheric greenhouse gas concentrations alone (Feddema et al., 2005).

Floods represent the most catastrophic natural hazard in Nepal in terms of both mortality and economic loss, with the Terai region being particularly susceptible due to its proximity to major river systems and the degraded Siwalik Hills (Subedi et al., 2021). Nepal ranks 30th among 198 countries in global flood risk assessments (Maharjan & Paudyal, 2016). According to the Ministry of Home Affairs (MOHA, 2019), floods were the fourth most frequent disaster in 2017–2018 but caused the highest fatalities (183 deaths), affecting 16,196 families and causing an estimated NPR 60.9 million in losses. Dodhara Chandani Municipality in Kanchanpur District is particularly vulnerable to flooding due to its location along the Mahakali River. Between 1993 and 2019, floods affected 2,938 families, causing fatalities, injuries, missing persons, and widespread housing damage (MOHA, 2019). In 2021, flooding inundated approximately 15 ha of agricultural land in the Kutiyakabhar area, affecting 24 families.

Persistent flooding has caused substantial damage to agriculture, livestock, settlements, and critical infrastructure. Comprehensive flood hazard mapping for the Dodhara Chandani Municipality remains limited. Although flood studies have been conducted in different rivers of Nepal but detailed hydraulic flood inundation mapping for the Mahakali River segment in Kanchanpur District remains limited.

This study was therefore undertaken to generate flood inundation maps using the HEC-RAS model, providing scientific information to support flood risk assessment, land-use planning, and disaster management in this highly flood-prone region.

The main objective of the study is to develop a comprehensive flood hazard map for Dodhara Chandani Municipality within the Mahakali River watershed. And the specific objectives are to analyze long-term rainfall trends, Peak flood discharges for multiple return periods using hydrological models, and delineate flood hazard zones through HEC-RAS hydraulic modeling. The results are expected to support evidence-based flood risk management, enhance disaster preparedness, and contribute to sustainable development planning in flood-prone regions of western Nepal.

2. MATERIALS AND METHODS

2.1 Study area

The study area is located in Kanchanpur District of Sudurpaschim Province, Nepal, on the border of Bheemdatta Municipality and Dodhara Chandani Municipality (Fig.1). It comprises 56.84 square kilometers and ranges from 80° 4' E to 80° 6' 30" W longitude and 28° 49' N to 28° 59' N latitude. The area is surrounded by India to the north, west, and south, with Bheemdatta Municipality and Shuklaphanta National Park to the east. Elevations range from 174 m to 225 m, and temperatures range from 6.9°C to 37.5°C. The Mahakali River, a 233-kilometer-long transboundary river that originates in the Api Himal, runs through this region. The river, which has a catchment area of 15,446 km² (35% in Nepal), frequently floods, leading to riverbank erosion, agricultural damage, and loss of lives, livestock, and infrastructure in Dodhara Chandani and adjacent communities. The Mahakali River flows through the Siwalik (Churia), Bhabar, and Terai regions. The Siwalik area is dominated by sandstone, mudstone, siltstone, and conglomerate, whereas the Bhabar and Terai consist mainly of Quaternary alluvial deposits. These formations support fertile soils but are also susceptible to flooding and riverbank erosion (Dhital, 2015; Joshi, 2018).

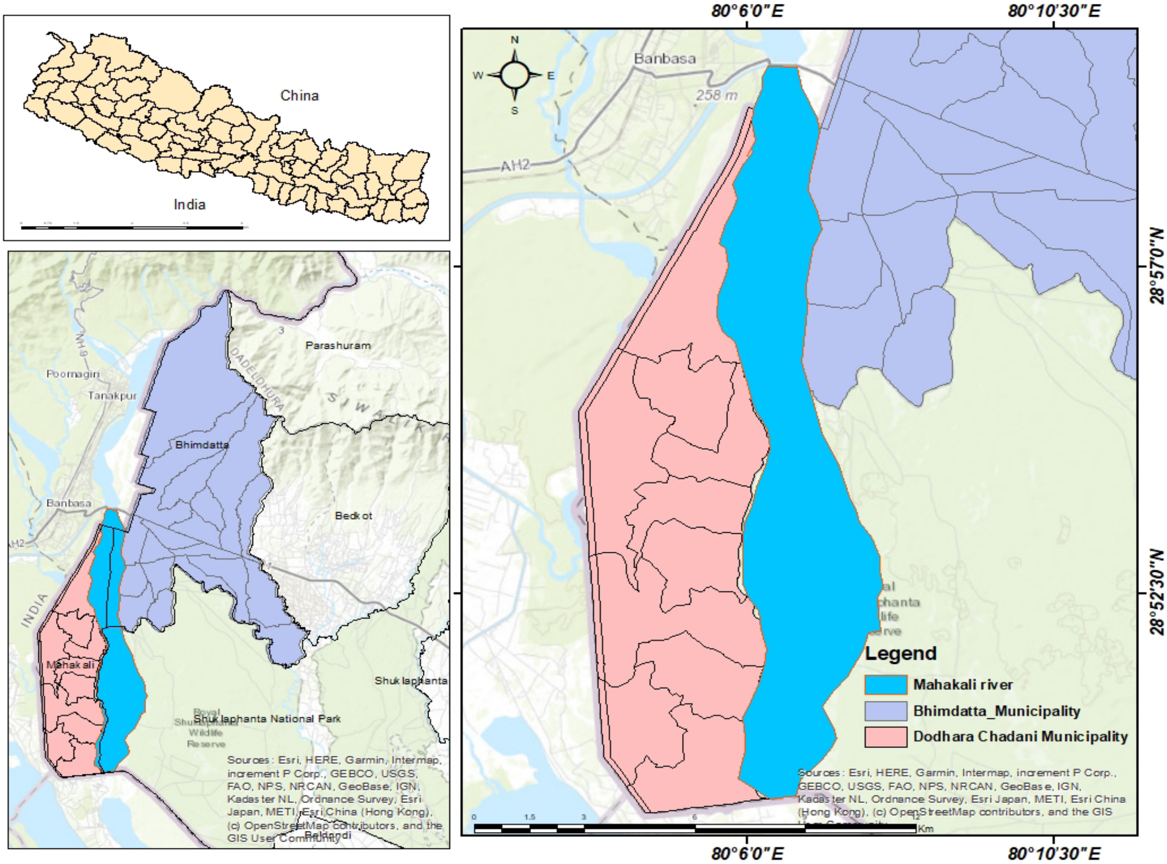


Fig. 1: Location map of the study area

2.2 METHODS

Data collection

Primary data were collected mainly through field observations, which included assessing flood impacts, land use/land cover conditions, and past disaster events during multiple visits to the study area. Photographs were taken for visual interpretation, and GPS devices along with checklists were used to record additional information. Meteorological data, such as rainfall, discharge and temperature, were collected from the Mahendranagar and Dodhara Station, with data sourced from the Department of Hydrology and Meteorology (DHM). A digital topographic map of the study area was also obtained from the Department of Survey. Secondary data were sourced from Google Earth image analysis, The USGS SRTM 30m DEM were used in flood hazard mapping, and GIS-based information value assessments. Additional topographic and geological maps and DEM data were obtained from USGS and Google Earth. Relevant literature, including reports, books, and publications, was reviewed from libraries, CBS, DoS,DoWIDPC, and online resources. The methodological flow diagram is shown in Fig. 2.

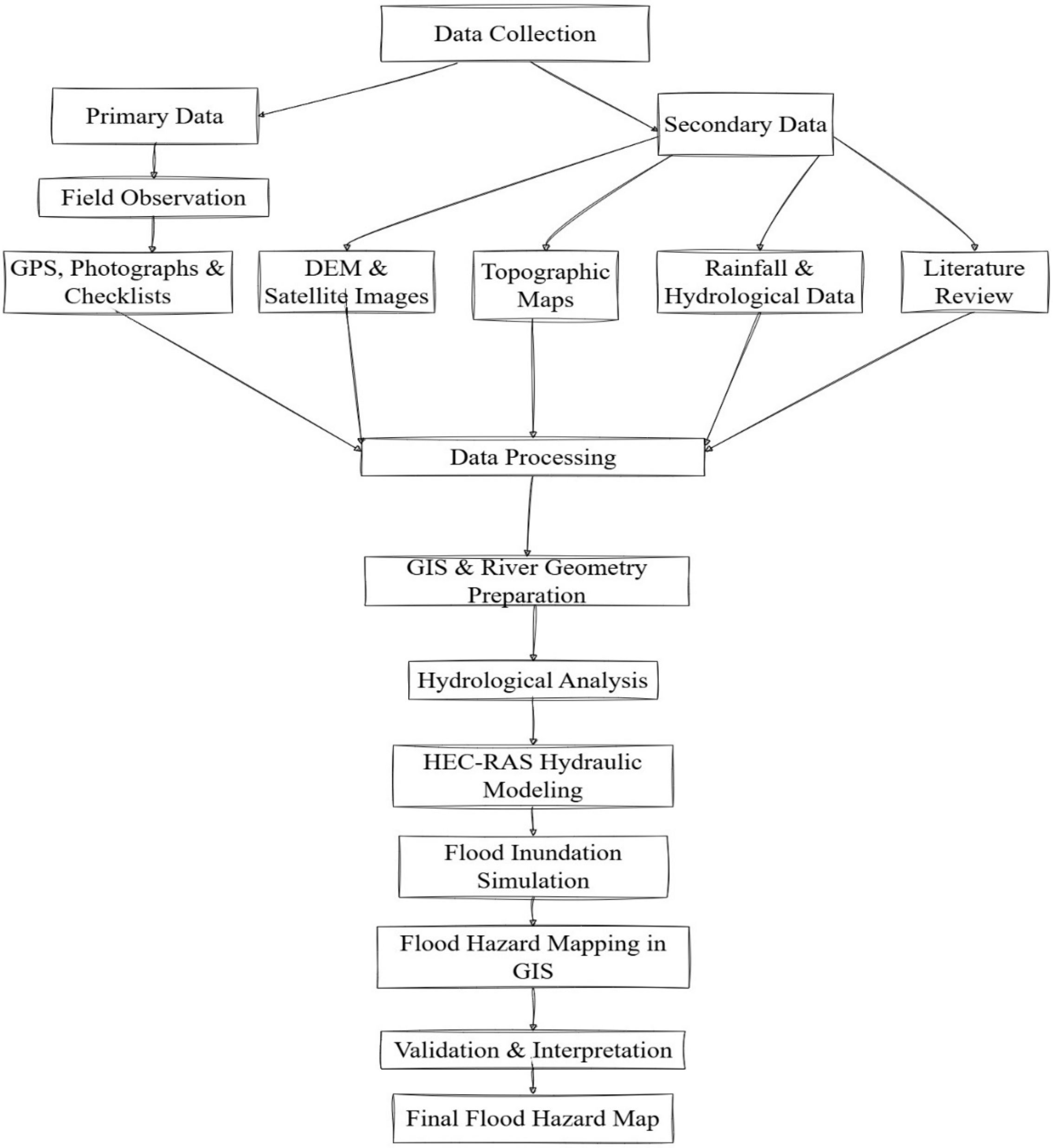


Fig. 2: Methodological flow diagram

River line

The river line was created and digitized by using the RAS mapper toolbox in HEC-RAS. The RAS mapper's satellite image (DEM) was used as a basic map to direct the digitization procedure. The river centerline was digitized to follow the river's center and was oriented upstream to downstream.

Bank line

To distinguish the main channel from the floodplain area, bank lines were created. By considering the elevation of the entire bank's terrain, bank lines were digitized. Starting at the upstream limit and moving downstream, digitization was done. First, the right bank was digitalized, then the left bank.

Flow line

The overall flood area that might be affected under high flood conditions was considered when digitizing the flow lines. In both the main channel and the floodplain regions, reach lengths between cross sections were calculated using flow path lines. Inside the flood plains, the left and right flow lines were digitalized.

Cross-section

From upstream to downstream, the cross sections were drawn and digitized from left to right. RAS Mapper's aerial imagery was used as a guide to ensure that no two cross-sections intersected. The cross sections were drawn in the stream to capture all of the variability of the area in the modeling.

Land use/Land cover

Land use/ land cover landsat-8 data was download from USGS. And classify the land use from supervised classification by using Arc GIS. This classification is classifying the National Land Use Project (NLUP) of the Government of Nepal.

Model set up and run

The hydraulic model was developed using HEC-RAS version HEC-RAS 6.3.1 to simulate flood inundation under steady-state, subcritical flow conditions (Brunner, 2023). Geometric data, including the river centerline, flow paths, bank lines, and cross-sections, were extracted from the SRTM 30m resolution DEM and imported into HEC-RAS. Cross-sections were generated at an average spacing of 100–200 m, with additional sections in areas of complex channel geometry (Brunner, 2023).The upstream boundary condition was defined using design discharges for the 2-, 10-, 50-, 100-, and 200-year return periods derived from annual maximum discharge records obtained from the Department of Hydrology and Meteorology (DHM), while a normal depth boundary condition was applied at the downstream end using the channel bed slope (Brunner, 2023). Manning's roughness coefficients (**n**) were assigned based on channel and floodplain characteristics following standard hydraulic modeling guidelines (Chow, 1959). Water surface profiles were computed using the standard-step method, and flood inundation maps were generated using HEC-RAS Mapper (Brunner, 2023).

2.3 DATA ANALYSIS

Trend analysis

Rainfall data for the Dodhara and Mahendranagar stations in Kanchanpur District were obtained from the Department of Hydrology and Meteorology (DHM). The relationship between rainfall recorded at the two stations was evaluated using simple linear regression, with the coefficient of determination (R^2) used to assess the strength of the relationship. The least squares method was employed to estimate the regression slope and examine the trend. Descriptive statistics, including mean rainfall, standard deviation, and coefficient of variation, were calculated using Microsoft Excel, and the results were presented graphically using charts

Digital elevation model preparation

This study used Shuttle Radar Topography Mission (SRTM) 1 arc-second global elevation data, which enables free access to this high-resolution global data set and provides worldwide coverage of void-filled data at a resolution of 1 arc-second. The Georeferenced Tagged Image File Format (GeoTIFF), a standard image format for GIS applications, is available for the Digital Elevation

Model (DEM) data (Farr *et al*. 2007). The absolute vertical error was found to be substantially reduced according to SRTM-30m accuracy assessments, with the most accurate predictions being around 5 m. SRTM 30m DEM is appropriate for use in mapping flood hazards at the watershed level given its free availability and output scale of almost 1:50,000 (Kellndorfer *et al*. 2004). The United States Geological Survey provided tiles of SRTM 30m covering the Mahakali River basins for this study (USGS). Sinks were filled using tools from ArcGIS's Spatial Analyst Toolbox once the DEM had been generated.

Flood frequency analysis

The maximum instantaneous discharge data was fitted with Gumbel distributions to find out the best probability distribution representing the peak flows. Frequency analysis was done on the peak yearly discharge data at the upstream as well as the downstream gauge station, and streamlines were created from the ASTER DEM using HEC-HMS and provided as one of the inputs to the model HEC-RAS.The hydraulic parameter for input to HEC-RAS was selected using the values derived from the Gumbel distribution. The Gumbel distribution was used for estimating peak discharge at several return periods. Gumbel method was used for statistical flood frequency analysis, while the WECS/DHM method was applied as the standard empirical approach for Nepal. Using both methods allowed comparison and validation of the estimated design floods.

Gumbel method

The Gumbel distribution is one of the most frequently adopted distribution types for modeling hydrological extreme events such as floods and storms widely used throughout the world. (Gumbel 2004) presented the methodology of flood hazard mapping.

The return period T is the reciprocal of the probability of exceedance. Therefore,

$$\frac{1}{T} = 1 - e^{-e^{-y}} \quad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$y = ln.ln\frac{T}{T-1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

In the Gumbel method, the value of flood discharge is obtained from the frequency formula,

$$x = \bar{x} + Ks \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

The frequency factor K is evaluated with the frequency formula:

$$y = \bar{y}_n + K\sigma_n \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

In which *y* Gumbel (reduced variate, a function of return period and $\bar{y}_n$ and σ_n are the mean and standard deviation of the Gumbel variate, respectively. These values are a function of record length *n*.

From above the equations (3) and (4);

$$x = \bar{x} + \frac{y-\bar{y}_n}{\sigma_n} s \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Combining equations (2) and (5)

$$x = \bar{x} + \frac{ln.ln\frac{T}{T-1} - \bar{y}_n}{\sigma_n} \ldots\ldots\ldots \quad (6)$$

WECS/DHM method

The Water and Energy Commission Secretariat, Department of Hydrology and Meteorology (WECS/DHM) of Nepal created the WECS/DHM technique. For the pre-feasibility study of hydroelectric projects in Nepal, this method is typically used to identify the hydrological characteristics of an ungauged basin. The Excel file for WECS/DHM is accessible, and it requests information such as the total catchment area, the catchment area below 5,000 m elevation, and the monsoon wetness index (Acharya & Joshi 2020).

Calculation of peak flood discharges for return periods of 2 and 100 years are:

$$Q_2 = 1.8767 \times (A_{below\ 5000m} + 1)^{0.8783} \qquad (7)$$

$$Q_{100} = 14.630 \times (A_{below\ 5000m} + 1)^{0.7342} \qquad (8)$$

Peak flood discharge for different return periods:

$$Q_T = e^{(\ln Q2 + S\sigma)} \qquad (9)$$

$$\sigma = \ln (Q_{100}/Q_2)/2.326 \qquad (10)$$

were,

Q_2-2-year flood discharge in m^3/s

Q_{100} – 100-year flood discharge in m^3/s

Q_T – T-year flood discharge in m^3/s

$A_{below\ 5000m}$ – basin area below 5000 m elevation in km^2

σ is a parameter

S is a standard normal variate whose value depends on return periods (Table 1).

Table1. Values of standard variates based on return periods (Acharya & Joshi 2020).

Return Period (T) in year	Standard Variate (s)
2	0
10	1.282
50	2.054
100	2.326
200	2.576

Determination of manning's roughness

Land use/land cover information and satellite images from ESRI, Open Street Map (OSM), and Google Earth were used to determine the variation in Manning's values. Manning's value was calculated using the land use/land cover types in the watershed area. Manning's value estimates for natural channels and flood plains were calculated using Chow's method (Perry 1960)(Table 2).

Table 2. Manning's Roughness Coefficient for Different Land Use

Land use types	Manning's Value (n)
Barren land	0.030
Bush	0.050
Cultivation area	0.035
Cutting area	0.040
Forest	0.100
Grassland	0.035
River	0.040
Sand	0.030

(Source: Chow, 1959)

Hydrological modelling using HEC-RAS

Hydrologic Engineering Center's River Analysis System (HEC-RAS) is freely available software which was developed by the US Army Corps of Engineers to perform steady flow water surface profile computations, one- and two-dimensional unsteady flow simulations, movable boundary sediment transport computations, and water quality analysis. For the one-dimensional steady flow multiple profile analysis in this study, HEC-RAS 6.3 was employed. One-dimensional models solely account for longitudinal flow via the channel and floodplain (HEC-RAS, 1995).

Running the HEC-RAS model

The floodplain area's cross-sectional geometry data were generated using the DEM. The geometric components, such as the river centerline, banks, flow paths, and cross sections, were created and digitalized using the RAS mapper. The satellite image was used as the base map in RAS Mapper to direct the digitization process. The flow and boundary condition data were inserted, and the steady flow option was selected. The HEC-RAS model was used to create flood inundation scenarios with various upstream and downstream discharge magnitudes.

Selection of model/tools for analysis

In this study, flood hazard map and water surface profiles were calculated by using model HEC-RAS version 6.3 Peak flood discharges for different return periods were calculated by rainfall-runoff model HEC-HMS version 4.10, and GIS data processing was done using ArcGIS version 10.4. This study used the software tools HEC-RAS, and HEC-HMS were primarily made possible by the systems' availability for free use. ArcGIS was utilized because it is the most popular and highly suggested GIS data processing software.

Field verification

Although formal model calibration and validation were not performed due to the unavailability of observed water level, flow depth, and flood extent data, the flood hazard maps for different return periods were verified and refined through field observations. Information on historical river courses, flood marks, bank heights, river undercutting, channel shifting, and flood impacts on engineering structures was collected during field surveys (Fig. 3a–f). In addition, interviews with residents of flood-prone communities were conducted to document historical flood events, observed flood levels, channel migration, and the socioeconomic impacts of flooding, thereby supporting the qualitative validation of the model results.

a)

b)

c)

d)

e)

f)

Fig. 3: a) DGPS Router set for taking GPS data at Mahakali River Bank, b) GPS data collection at Agricultural land, c) GPS data collation at Plain land, d) GPS data collection at Water surface, e) River bank cutting by Mahakali River at Kutiyakabhar, f) Embankment for Protecting River bank cutting and stop flood Inundation

3. RESULT AND DISCUSSION

Rainfall trend analysis

Observed trend of yearly rainfall of Dodhara station in 23 years fluctuating between 1274 mm and 2707 mm total rainfall per year (Table 3). The rainfall characteristics of the Dodhara and Mahendranagar stations exhibit notable spatial and statistical variations. Mahendranagar records a slightly higher mean annual rainfall (1943 mm) than Dodhara (1832 mm), but with a much wider range (2086 mm compared to 1433 mm), indicating greater variability and more extreme rainfall events.The higher coefficient of variation (28%) and standard deviation (540 mm) at Mahendranagar compared to Dodhara's 19% and 345 mm further suggest that rainfall at Mahendranagar is less consistent and more variable over time. Skewness and kurtosis values reveal differences in rainfall distribution: Dodhara shows positive skewness (0.35) and moderate kurtosis (0.47), indicating occasional years of unusually high rainfall, whereas Mahendranagar displays negative skewness (−0.58) and lower kurtosis (0.10), suggesting occasional dry years but generally above-average rainfall. Overall, Mahendranagar experiences higher rainfall amounts with greater temporal variability, while Dodhara shows more stable rainfall patterns with fewer extremes, reflecting local climatic and topographic influences on precipitation behavior.

Table 3. The statistical information of Rainfall of Dodhara and Mahendranagar Meteorological Station

Station	Maximum (mm)	Minimum (mm)	Mean	S. D	CV (%)	Skewness	Kurtosis
Dodhara	2707	1274	1832	345	19	0.35	0.47
Mahendranagar	2843	757	1943	540	28	-0.58	0.10

The annual rainfall trend at Dodhara Station from 2000 to 2023 shows considerable inter-annual variability with alternating wet and dry years (Fig. 4). Although the regression line indicates a slight decreasing trend (slope = −5.6591), the coefficient of determination ($R^2 = 0.0124$) suggests that this decline is statistically insignificant, implying no substantial long-term change in rainfall during the study period. Rainfall peaked in the early 2000s and mid-2010s, with several years exceeding 2000 mm, while notably lower rainfall occurred around 2005, 2012, and 2019.The low R^2 values indicate that annual precipitation is highly variable from 2005,1012 and 2019 This reflects the influence of irregular monsoon patterns and localized climatic influences rather than a consistent directional trend.

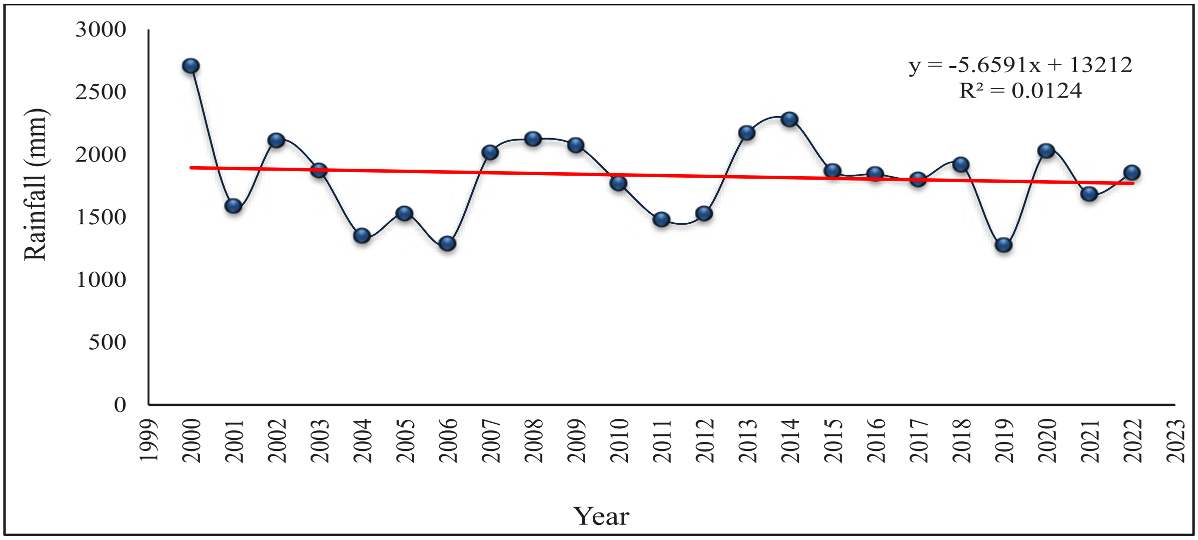


Fig. 4: Total rainfall per year of Dodhara Station from 2000 to 2023

The annual rainfall distribution at Mahendranagar Station from 2000 to 2022 exhibits noticeable inter-annual variability with a general increasing trend over the study period (Fig. 5). The positive regression slope (40.978) and a moderate coefficient of determination ($R^2 = 0.2649$) indicate a gradual rise in rainfall, suggesting that approximately 26% of the variation in annual rainfall can be explained by the upward trend. Rainfall was relatively low in the early 2000s, with a few dry years around 2003–2005, followed by several wet years after 2010, particularly around 2008, 2015, and 2021 when rainfall exceeded 2000 mm. This upward trajectory implies a tendency toward wetter conditions recently, possibly linked to intensified monsoon activity or localized climatic influences.

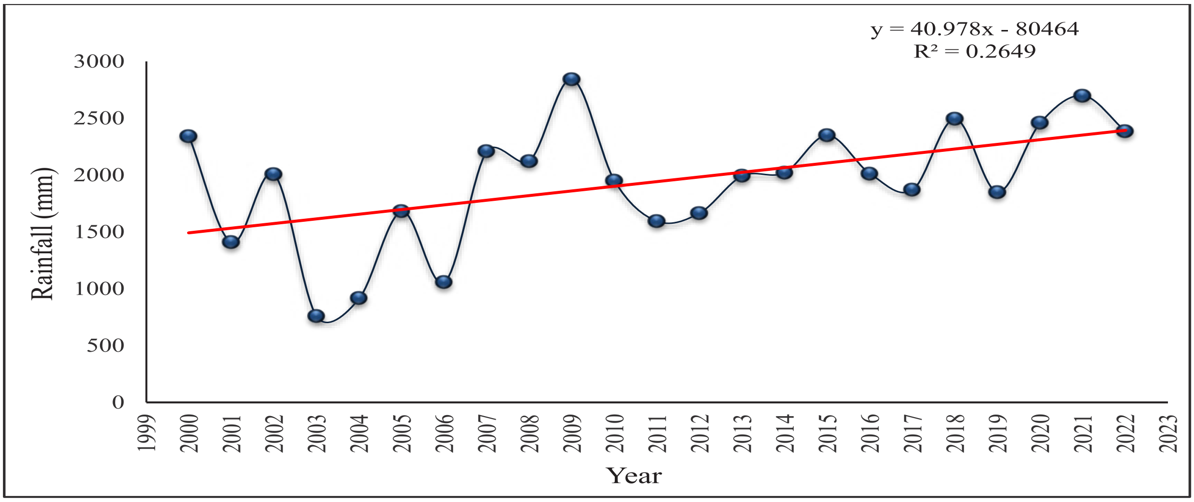


Fig. 5: Total rainfall per Year of Mahendranagar Station from 2000 to 2022

As a comparison between two meteorological stations (Dodhara and Mahendranagar), the total annual rainfall trend was observed from 2000 to 2022. At Mahendranagar station, the trend of total annual rainfall per year accumulates slightly higher than at Dodhara station (Fig. 6). Rainfall is showing a quite significantly increasing trend (slope = 40.97) in Mahendranagar station, and in Dodhara station, rainfall is showing a slightly decreasing trend (slope = -5.65). Comparatively, Dodhara station has low rainfall than Mahendranagar Station because it perhaps lacks of proper data recorded or missing the data of rainfall between 23 years period.

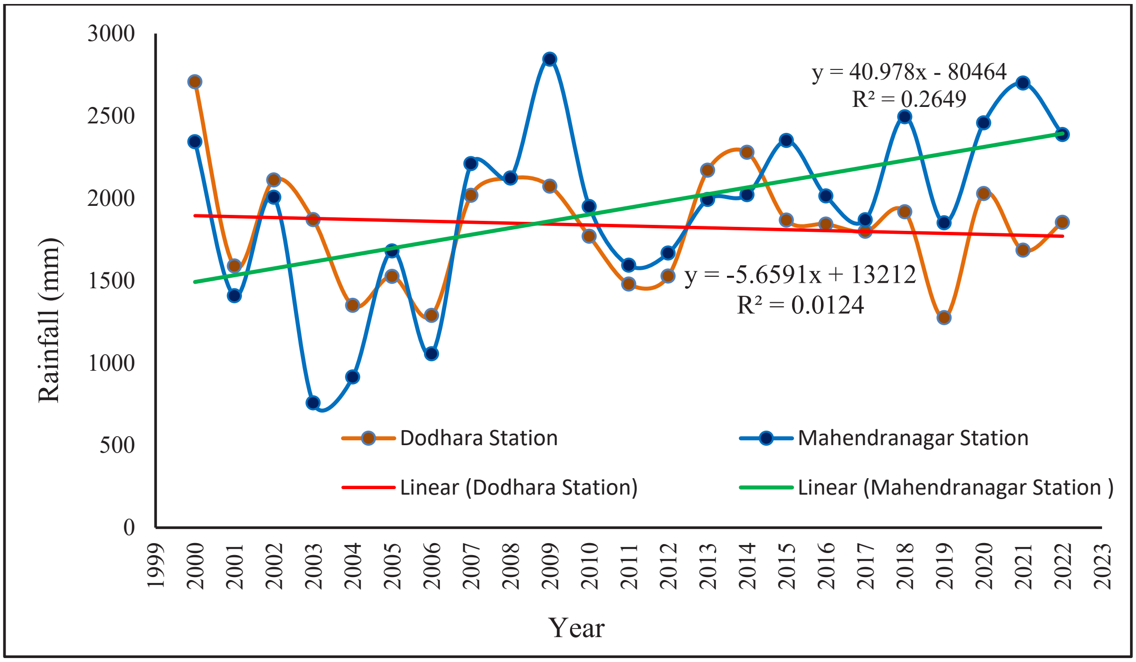


Fig. 6: Trend of Total Annual Rainfall of Dodhara and Mahendranagar Station from 2000 to 2022

Flood Frequency Analysis

The flood frequency is calculated in 2, 10, 50, 100, and 200-year return periods of the Mahakali River basin by using Gumbel's, and WECS/DHM methods are summarized below in Table 4.

Table 4. Discharge of Different Return period

Return Period	WECS-DHM	Gumbel
	Discharge (m^3/s)	Discharge (m^3/s)
2	6642.45	2835.81
10	11221.87	11789.59
50	15415.67	19639.36
100	17262.27	22957.89
200	19086.75	26264.31

The flood frequency analysis observed by Gumbel's method showed discharges of 2 years, 10 years, 50 years, 100 years, and 200 years return periods are 2835.81, 11789.59, 19639.36, 22957.89, and 26264.31 m^3/sec for respectively, which were slightly higher then as compared to the results obtained by WECS/DHM methods because the input data of rainfall and land use vary the discharge of Gumbel's distribution method, which is graphically represented (Fig.7).

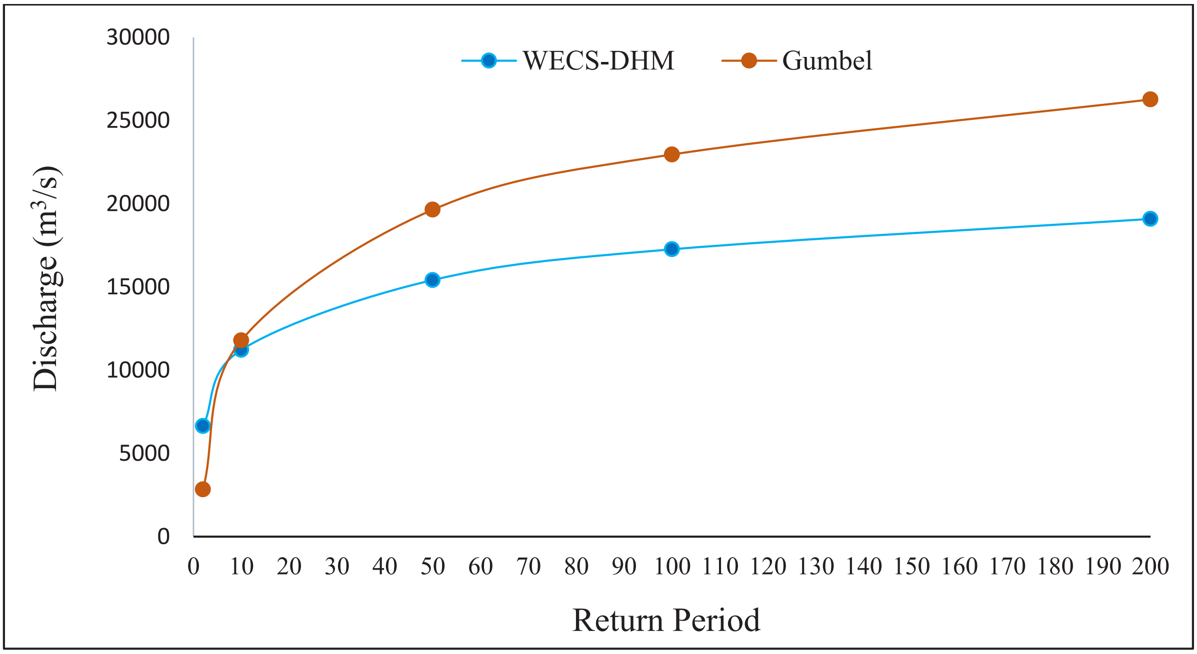
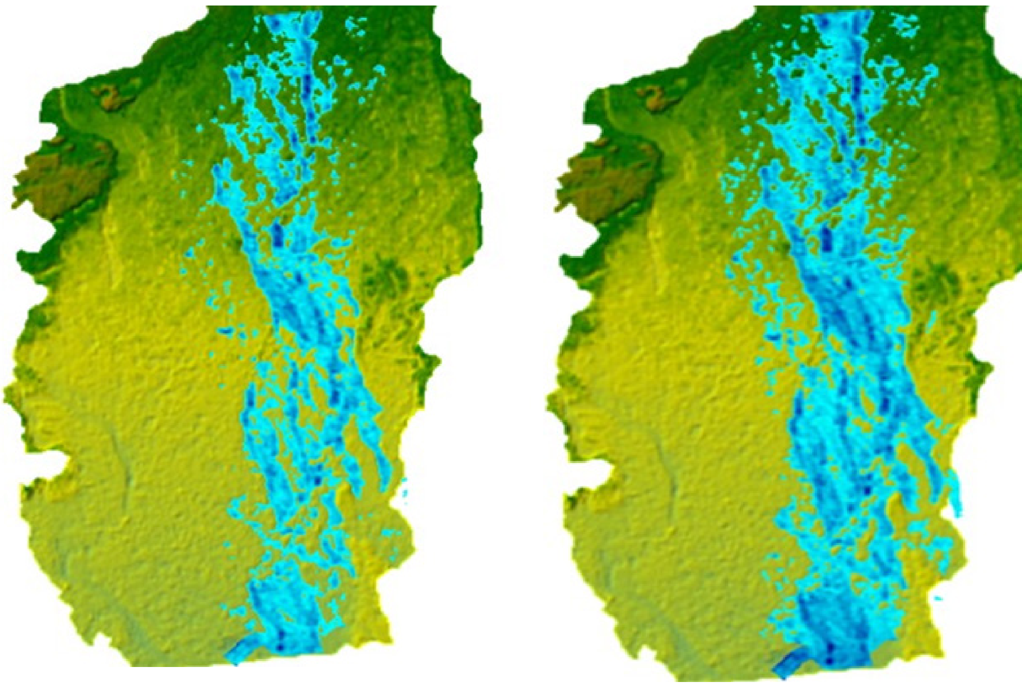


Fig. 7: Relation between return periods and discharge

Flood Hazard Mapping

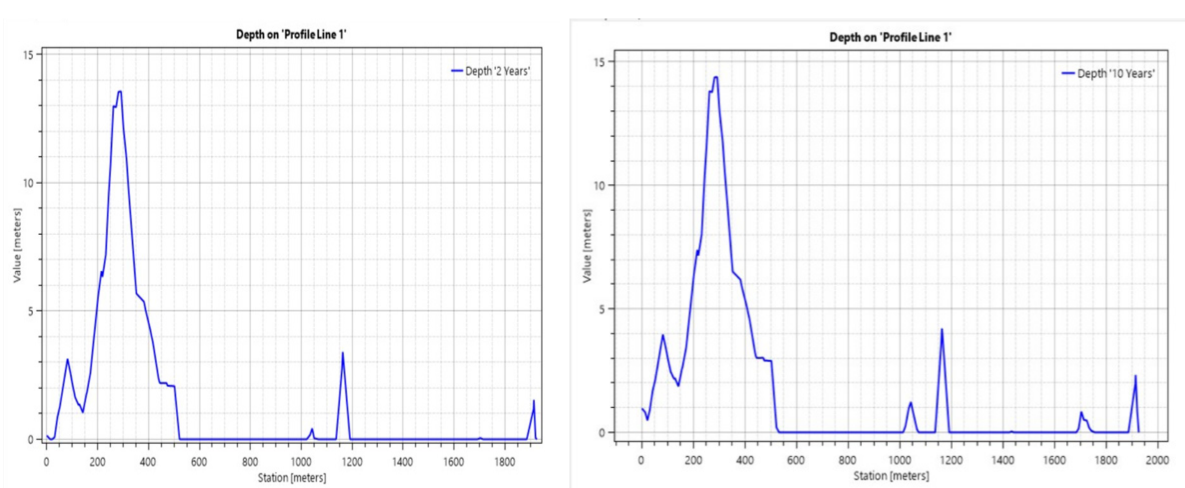
The flood hazard map study revealed a significant expansion of river-inundated regions corresponding to rising discharge levels from floods with a return period ranging from 2 to 200 years. The Manning's roughness coefficient (n) for the main channel is 0.04, while for the floodplains, it is 0.03, applicable to the subcritical flow alteration in the cross-section. The water level profile is calculated along the river for various return times with the HEC-RAS model. Dodhara Chadani municipality comprises 10 wards, of which 8 directly about the Mahakali River. These wards are numbered 1, 2, 4, 5, 6, 7, 9, and 10. The eight wards exhibit a greater potential risk and vulnerability to flooding compared to the remaining two wards. Ward no. 10 is under significant risk of river inundation due to the confluence of the Mahakali and Rangun Rivers. The HEC-RAS simulated flood danger map directly influences the residential zones in wards 1, 2, 4, 5, 6, 7, 9, and 10 (Fig. 8 a, b). Consequently, under both extreme and exceedingly rare river flow situations, the Mahakali riverbank within the municipality experiences flooding, rendering it unsuitable for residential development. The flooding resulted in the loss of agricultural products in the municipality. This municipality annually encounters flooding in all regions throughout the monsoon season from June to September, with occasional post-monsoon flooding resulting from the delayed transition of the monsoon.



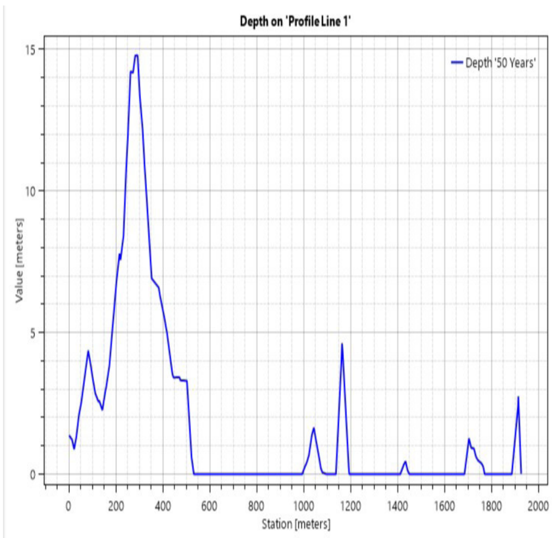
a) b)

Fig. 8: a) 2 years flood inundation map, b) 100 years flood inundation map

The graphical representation of the depth profile indicates that the water levels for the 2, 10, 50, 100, and 200-year return periods are 13.56 m, 14.39 m, 14.79 m, 14.96 m, and 15.12 m, respectively. The maximum water level in this depth profile is 15.12 for a 200-year return period. As river discharge rises, the water level correspondingly ascends. It illustrates the flooding state in a river. The graph (Fig. 9,a-e) illustrates the water depth profile.



a) b)



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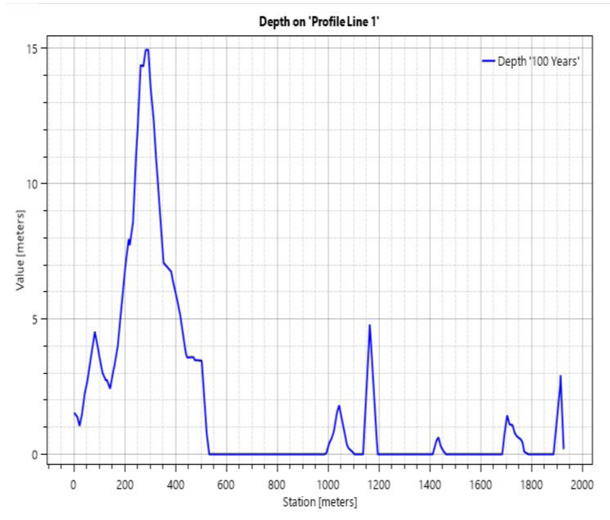

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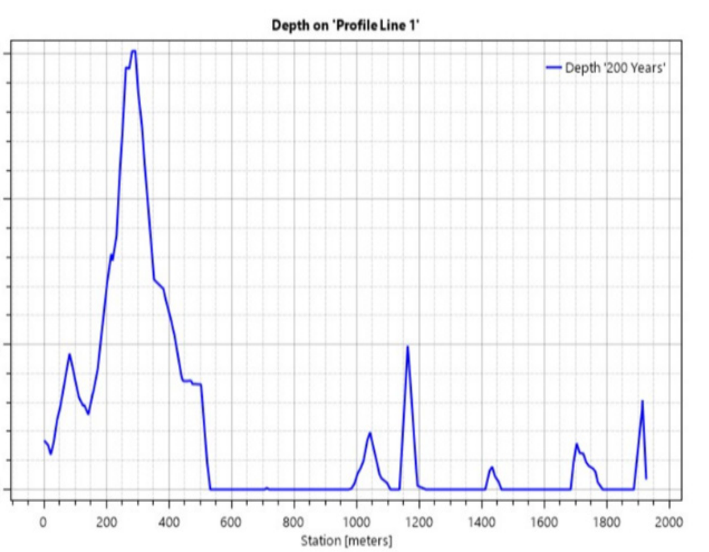
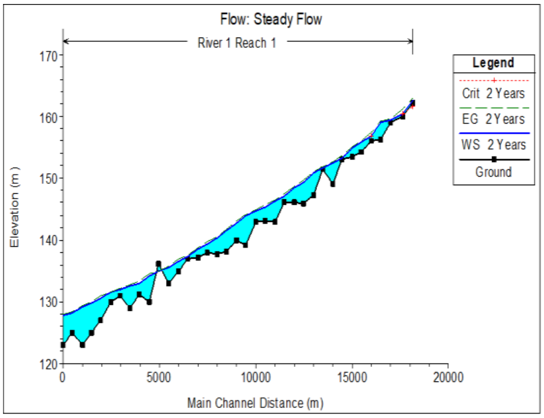


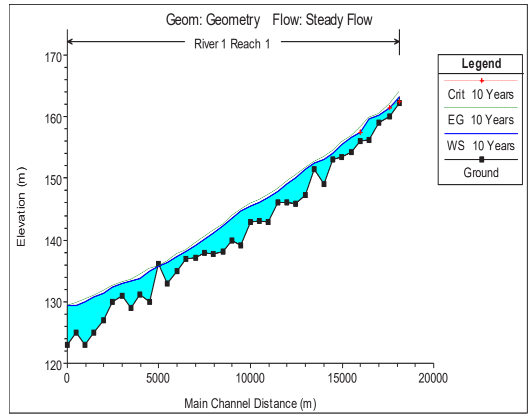
e)

Fig. 9: a) Depth profile of 2-year return period, b) Depth profile of 10-year return period, c) Depth profile of 50-year return period, d) Depth profile of 100-year return period, e) Depth profile of 200-year return period

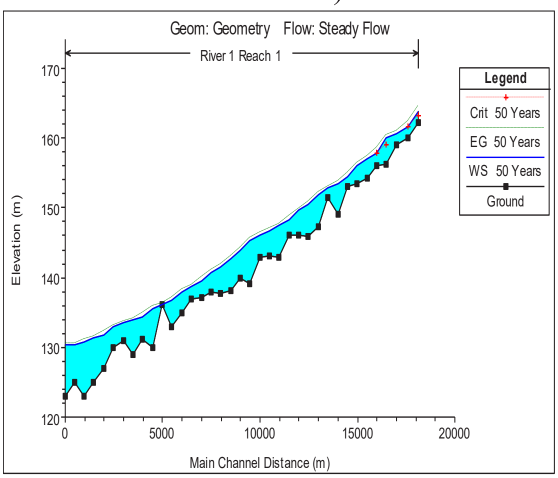
The hydraulic modeling conducted with HEC-RAS established the water surface profile (Fig.10 a-e). The water's surface profile generally mirrored the riverbed profile. The distance of the steady flow main channel is contingent upon elevation to model the water surface profile throughout various return times. The ground level exceeds the water level at a distance of 5000 m along the main channel due to the presence of islets in the Mahakali River, potential sediment deposition, and inferior quality of the DEM data. Islets facilitate the transition from a single river channel to several channels.

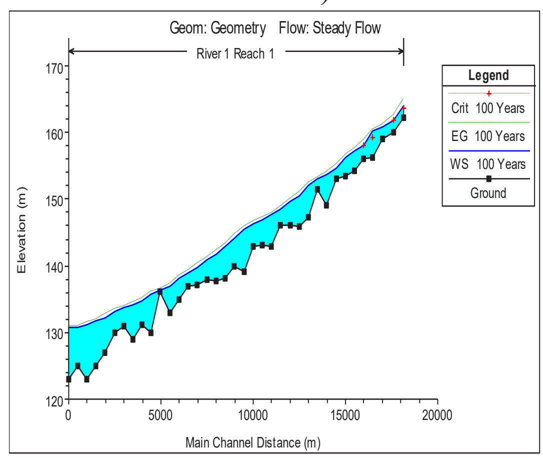


a)



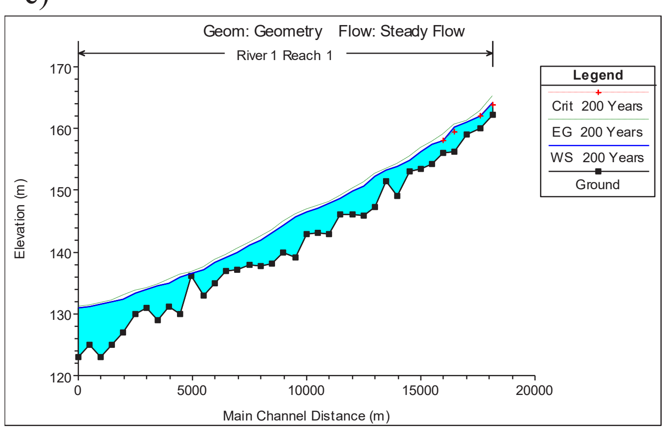
b)





c)

d)



e)

Fig. 10: a) Water surface profile of Mahakali River at 2 years return period, b) Water surface profile of Mahakali River at 10 years return period, c) Water surface profile of Mahakali River at 50 years return period, d) Water surface profile of Mahakali River at 100 years return period, e) Water surface profile of Mahakali River at 200 years return period.

The model was developed for return periods of 2, 10, 50, 100, and 200 years, incorporating various peak flood discharges to create distinct stages of the Mahakali River cross-section. In cross-sectional profiles, the ground elevation exceeds the sea surface at Stations 900 and 1200 due to the presence of islets and potential silt deposition (Figure 11.a). It bifurcates one channel into numerous smaller river channels. The Labels River, Reach, and River Station in the HEC-RAS dataset designate each cross section. When oriented downstream, the cross section is delineated by specifying the station and ascending from left to right. The cross-sectional profiles provide a comparative picture of a river's channel and valley at designated locations along its course. The cross-sectional profile illustrates the valley floor, the valley walls, and the channel. The cross-section maintains adequate depiction of channel hydraulic features (Figure 11. a-e).

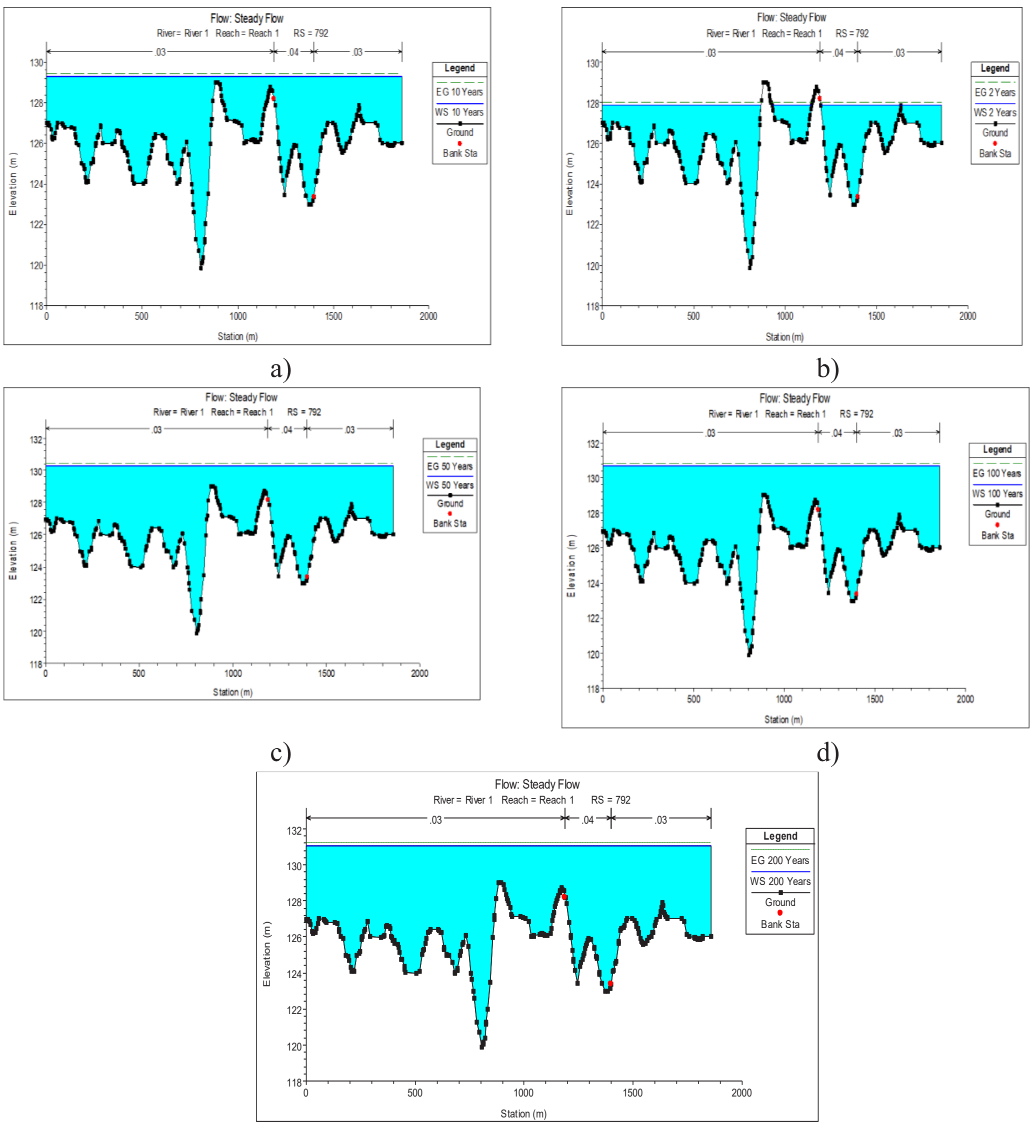


Fig. 11: a) Cross-section of the Mahakali River in 2 Years Return Period, b) Cross-section of the Mahakali River in 10 Years Return Period, c) Cross-section of the Mahakali River in 50 Years Return Period, d) Cross-section of the Mahakali River in 100 Years Return Period, e) Cross-section of the Mahakali River in 200 Years Return Period

The application of HEC-RAS computed the rating curve at the outlet section, illustrating the link between elevation and discharge at that specific location. The rating curve generated using the HEC-RAS model in the section demonstrated a linear relationship (Fig. 12). The rating curve of river discharge and water surface elevation indicates that the river's discharge progressively increases with the elevation of the water surface.

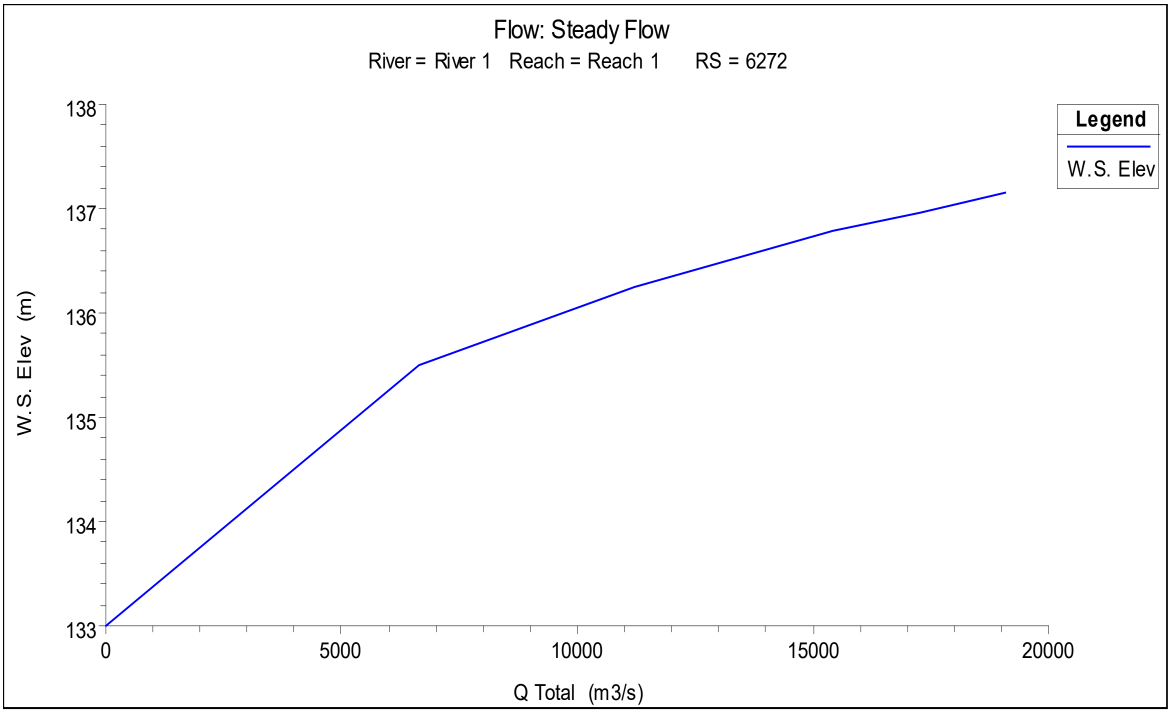


Fig. 12: Rating Curve of Mahakali River, Chandani Dodhara section.

Rainfall is a major factor influencing hydrological processes, water availability, and flood risk. To assess long-term variability, annual rainfall data from Dodhara and Mahendranagar stations (2000-2022) were analyzed. Dodhara showed an increasing annual rainfall trend of 38.81 mm year^{-1}, while Mahendranagar exhibited a slight decreasing trend of 1.95 mm year^{-1}. Monsoon rainfall also showed a marginal decline (1.66 mm year^{-1}), indicating changes in seasonal rainfall patterns.

These results reflect the spatial and temporal variability of rainfall reported in previous studies in Nepal (Shrestha et al., 2000; DHM, 2017; IPCC, 2021) and emphasize the need to incorporate rainfall variability into watershed management, flood risk assessment, and climate adaptation planning. Mahendranagar Station averaged 413.4 mm of monsoon rainfall from 1984 to 2013 (Maharjan & Paudyal, 2016). The Mahakali River watershed receives 165.93 mm of rainfall annually (Weather and Climate, 2023).

Mahendranagar station has a slope of 40.97, indicating an increase in rainfall, while Dodhara station has a slope of -5.65, indicating a decrease in rainfall. A positive slope suggests rising rainfall, while a negative slope indicates falling rainfall. The average and annual rainfall are both decreasing by 10 mm/year (USAID-Nepal, 2017).

In areas with limited water resources, drought frequency and duration increase (Kessabi et al., 2022).

Extreme indexes rise and fall. Although neither statistically significant nor regionally coherent, extreme precipitation indexes are rising. Extreme wet-day precipitation is increasing rapidly in the far west, mountainous regions bordering the Midwest and western Siwalik, and the central and eastern Alps and Himalayas (Awasthi & Owen, 2020).

According to the comparative statistics rainfall trend study, Mahendranagar is slightly growing while Dodhara is falling. Erratic and variable rainfall patterns harm cropping systems and natural water resources and agricultural production (Hussain et al., 2015).

The most prevalent flood prediction approach is rainfall runoff correlation. The country lacks adequate hydrological and topographical databases. Nepal has land use, land cover, soil type, and fine-resolution DEMs for rainfall-runoff data. Nepal often builds flood control infrastructure using inaccurate river basin methods (Rijal, 2014).

An unmeasured station's river discharge can be predicted using Gumbel's distribution (Bhagat, 2017).

The Nepal Water and Energy Commission Secretariat/Department of Hydrology and Meteorology (WECS/DHM) method was used to calculate the instantaneous annual flood flow of the watershed's ungauged streams (Paudel, 2011).

Gumbel's and WECS/DHM methodologies compute Mahakali River basin flood frequency in 2, 10, 50, 100, and 200-year return periods. Using Gumbel's method, discharges for 2-year, 10-year, 50-year, 100-year, and 200-year return periods were 2835.81, 11789.59, 19639.36, 22957.89, and 26264.31 m^3/sec, slightly higher than WECS/DHM methods.

The model data depend on rainfall and land usage, which raises Gumbel's distribution method discharge over WECS/DHM. The Mahakali River has 167 glaciers. Glacier melting diminishes their ability to manage water flow, especially in dry months (USAID-Nepal, 2017).

The findings o (Neupane and Subodh Dhakal,2017) on kamala watershed sindhuli shows that decline in forest and riverbank areas and an increase in agricultural land, settlements, and orchards between 1995 and 2014. They attributed this land use changes primarily to population growth and the conversion of forests into farmland and residential areas.

During the monsoon season of 2013, 2019, and 2021, the Mahakali River near Sarda Barrage had its greatest flow of 15404.36, 368.11, and 15495.65 m^3/s (Republica Nepal, 2021).

Lack of data to simulate the model smoothly causes this study's river discharge to be higher than others. As flood discharge rises, flooded areas proliferate (Dangol & Bormudoi, 2017).

The simulated discharge was higher than reported values because it was estimated based on watershed rainfall and catchment characteristics. In ungauged basins, the absence of observed streamflow data limits model calibration and increases uncertainty in flood prediction, making the selection of a hydrologically similar reference catchment challenging (Acharya & Joshi, 2020).

In most informal settlements of developing cities, hydraulic flood inundation data is unavailable, inconsistent, incorrect, or inaccessible for flood modeling. This trend may contribute to the lack of flood modeling research in developing cities, especially informal settlements (Tom et al., 2022).

A comparison of high-resolution, simulated flood extent with satellite-based data shows that the model reasonably reproduces large inundated areas (Panthi et al., 2015).

HEC-RAS automated floodplain mapping and analysis provide more accurate, consistent, and usable results in less time and money (Manandhar, 2010).

The HEC-HMS hydrological model was built to determine how rainfall impacts peak flows and surface runoff. The flood's characteristics and extent were analyzed using HEC-RAS flood inundation maps (Khadka & Bhaukajee, 2018).

Graphs indicate that the HEC-RAS model in steady flow analysis simulated discharges of 6642.45, 11221.87, 15415.67, 17262.27, and 19087.75 m^3/sec, inundating 13.56, 14.39, 14.79, 14.96, and 15.12 m of water level, respectively. In 2, 10, 50, 100, and 200-year return periods, water depth is 13.56 m, 14.39 m, 14.79 m, 14.96 m, and 15.12 m. Water levels peak at 15.12 m in 200-year return intervals of 2, 10, 50, and 100 years. The Terai region has more rainfall than the hilly region since the terrain slopes and water flows slowly. The simulated water level is higher than the real-time recorded water level. The simulation data showed heavy rain or flooding. Field observations and visualization of historical flood marks and river channel cutting in the research region show a significant danger of flood inundation in Dodhara Chadani municipality wards 1, 2, 4, 5, 6, 7, 9, and 10, with wards 3 and 8 at a reduced risk. Of the 10 wards in Dodhara Chadani, 8 have direct contact with the Mahakali River basin. At the confluence of the Mahakali and Jogbudha rivers, Ward 10 is more likely to flood than the others. With rising water levels in Mahakali and Jogbudha, Dodhara Chandani municipality is at risk of flooding. The settlement remains at risk since 42 houses are regularly flooded during monsoon. The Indian side discharging water from the Sarada barrage puts Kutiyakabhar people at risk of flooding during monsoon and dry seasons (Bhatta, 2023). Mahakali River flooding damaged Dodhara Chadani Road and a four-lane bridge, submerging 12 buildings (Deuba, 2021). Wards 8 and 10 have been flooded, and 25.31 ha of rice fields have been swamped by the Mahakali River (The Kathmandu Post, 2018). Emergency preparedness and evacuation will benefit from a floodplain map that illustrates the extent and depth of flood-prone zones (Khalil & Khan 2017).

Flood risk maps help estimate losses and implement mitigation techniques like land use limitations and emergency measures (Awal & Shakya, 2007).

After the flood, researchers detected environmental consequences. Nepal is vulnerable to climate change due to its agricultural economy, complicated climate, and mountainous topography. The river path expanded as it lost its natural state. Sand deposits were seen in the river's middle and banks. The main environmental effects were these. The flood's sand and silt blanketed agricultural areas' fertile topsoil (Maharjan & Paudyal, 2016).

Between 2013 and 2022, the Mahakali River significantly transformed land use along the northern riverbank of Dodhara Chandani Municipality. Flooding, riverbank erosion, and inundation increased barren land while reducing agricultural land, built-up areas, and forest cover, demonstrating the river's substantial impact on the local landscape (Lillesand et al., 2015; IPCC Sixth Assessment Report, 2022).

Riverbed erosion, which covered 700 meters, displaced ten households at Kutiyakabhar (The Kathmandu Post 2018).

Due to Indian riverbank erosion and deposition, the Mahakali River has been diverted to Nepal (Paudel et al., 2013). Floods have damaged and swamped land utilized for numerous reasons, affecting the area (Subedi et al., 2021).

Substantial bank cutting and large sand deposition on neighboring arable land under development have increased flooding (Khadka & Adhikari, 2014).

4. CONCLUSION AND RECOMMENDATION

This study demonstrates that rainfall and flood dynamics in the Mahakali River basin are characterized by pronounced spatial variability, increasing rainfall extremes, and substantial uncertainty arising from limited hydro-meteorological data. Analysis of long-term rainfall records indicates an overall increasing annual rainfall trend at Dodhara, contrasted by weak and inconsistent trends at Mahendranagar, with evidence of declining monsoon rainfall. These heterogeneous patterns suggest that changes in rainfall intensity and variability, rather than uniform shifts in mean rainfall, are the dominant drivers of hydrological instability in the region. Flood frequency analysis reveals that Gumbel's distribution yields higher discharge estimates than the WECS/DHM approach, reflecting the sensitivity of statistical methods to rainfall inputs and land-use conditions in ungauged basins. Hydraulic modeling using HEC-HMS and HEC-RAS shows increasing inundation depth and extent with higher return periods, with simulated water levels exceeding observed records due to calibration constraints and data scarcity. Flood risk is highest in river-adjacent and confluence zones, where recurrent inundation, riverbank erosion, and upstream flow regulation amplify vulnerability. Land-use and land-cover changes over the past decade confirm the long-term impacts of flooding, including loss of agricultural land, expansion of barren surfaces, channel migration, and displacement of settlements. This study integrates rainfall trend analysis, flood frequency analysis, hydraulic modelling, and land-use change assessment to identify flood-prone areas and support evidence-based flood risk management in the Mahakali River basin under changing climatic conditions. The generated flood hazard maps provide a practical tool for municipal land-use planning, flood zoning, infrastructure development, emergency preparedness, and flood risk management, supporting informed decision-making and climate-resilient development in the Mahakali River basin and other river basin. The findings recommend strengthening hydro-meteorological monitoring, integrating flood hazard maps into municipal land-use planning, improving flood early warning systems and community preparedness, implementing riverbank protection measures, and regularly updating flood hazard maps to support effective flood risk reduction and climate-resilient development.

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AUTHORS' CONTRIBUTION

Anmol Nagarkoti, Priyanka Aidi, and Prakash Bahadur Ayer collected the data, analyzed it, and prepared the draft manuscript. Priyanka Aidi and Pratikshya Bista supported field work and data analysis. Dr. Bharat Prasad Bhandari and Dr. Tirtha Adhikari did supervision and final manuscript preparation. All the authors contributed to the final manuscript preparation.

CONFLICT OF INTEREST

The authors declare no competing interest

DATA AVAILABILITY

Data will be available from the corresponding authors if required.

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