

A Model-Based Flood Hazard Mapping on the Southern Slope of Himalaya

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Abstract: Originating from the southern slope of Himalaya, the Karnali River poses a high flood risk at downstream regions during the monsoon season (June to September). This paper presents comprehensive hazard mapping and risk assessments in the downstream region of the Karnali River basin for different return-period floods, with the aid of the HEC-RAS (Hydrologic Engineering Center's River Analysis System). The assessment was conducted on a ~38 km segment of the Karnali River from Chisapani to the Nepal–India border. To perform hydrodynamic simulations, a long-term time series of instantaneous peak discharge records from the Chisapani gauging station was collected. Flooding conditions representing 2-, 5-, 10-, 50-, 100-, 200-, and 1000-year return periods (YRPs) were determined using Gumbel's distribution. With an estimated peak discharge of up to 29,910 m³/s and the flood depths up to 23 m in the 1000-YRP, the area vulnerable to flooding in the study domain extends into regions on both the east and west banks of the Karnali River. Such flooding in agricultural land poses a high risk to food security, which directly impacts on residents' livelihoods. Furthermore, the simulated flood in 2014 (equivalent to a 100-YRP) showed a high level of impact on physical infrastructure, affecting 51 schools, 14 health facilities, 2 bus-stops, and an airport. A total of 132 km of rural–urban roads and 22 km of highways were inundated during the flood. In summary, this study can support in future planning and decision-making for improved water resources management and development of flood control plans on the southern slope of Himalaya.

Keywords: flood frequency; hydrodynamic simulation; hazard mapping; risk assessment; Himalaya

1. Introduction

Extreme weather conditions (e.g., intense precipitation events) increase the probability of disasters that may cause unusual and unexpected events such as flooding and flood-related hazards [1–6]. Continuous but varying precipitation ultimately causes the flow of a river to exceed a threshold, such that it breaches the river bank or previous flood restoration work, resulting in

flooding [7]. Furthermore, a lack of any proper development plan, land-use changes [8], the random building of infrastructures in floodplains, and the blocking of rivers, all tend to increase the likelihood of flooding.

Therefore, floods are considered as one of the most severe and most frequent water-induced natural disasters, causing major damage to habitat, infrastructures, and properties worldwide—regardless of geographical or hydrological locations—and having direct economic impacts [9–13].

Recent floods at the southern slope of Himalaya (e.g., Pakistan, Bangladesh, India, as well as other South Asian Nations) have caused thousands of fatalities, the displacement of millions of people and billions of dollars of damage [14,15]. Other transboundary flood events from 1985 to 2018 have caused the deaths of more than 6000 people and displaced millions in China, Nepal, and India (Table 1). Nepal experiences devastating floods each year that cause 29% of the annual deaths and 43% of the total loss of property [16–18]. Developing countries such as Nepal, Bangladesh and Myanmar are still struggling to minimize the adverse effect of flooding, while developed countries manage flood risk with increasingly sophisticated flood forecasting models and methods to protect the larger floodplains [19,20]. Therefore, long-term planning and flood control mechanisms are needed in Nepal to reduce the impact of flooding.

Table 1. Classification of the total number of flood events causing deaths and displacement of people in Nepal from 1985 to 2018. The intervals of 1990–1995 and 2005–2010 are trans-boundary floods which included China, India, and Bhutan as well as Nepal (Source: Dartmouth Flood Observatory).

Year	1985–1990	1990–1995	1995–2000	2000–2005	2005–2010	2010–2015	2015–2020
Deaths	243	3369	426	920	990	417	165
Displaced (log ₁₀)	4	7	4	6	7	5	4
No. of Events	6	4	6	10	12	7	5

Many studies have focused on identifying floodplains and flood hazards since 1990 in different parts of the world [21–25]. The Hydrologic Engineering Center’s River Analysis System (HEC-RAS) model [26] developed by the U.S. Army Corps of Engineers (USACE) is generally used for investigating flooding and flood-related hazards, and for identifying floodplains globally [21,23,27–30]. For instance, [31] integrated this model into ArcGIS, in 2D and 3D, in the South Nation River system of Ottawa, Canada. Similarly, [32] applied this model in conjunction with an extension in ArcGIS (HEC-GeoRAS) in Los Alamos, New Mexico, USA, for floodplain delineation. [33] identified the risk area for constructing flood control structures in the Barsa river, Bhutan, using the hybrid ArcGIS and HEC-RAS approach. Mapping and risk classification were carried out to determine the location, velocity and depth of floods in Morocco [34]. This model was also used in simulating flood flows and inundation levels for the downstream floodplain in the Huong River Basin, Vietnam [35]. In Nepal, based on the HEC-RAS and its ArcGIS extension (HEC-GeoRAS), previous studies have mapped the flood hazard in the Bishnumati and Balkhu rivers of Kathmandu [36,37]. Moreover, there are other freely accessible tools (e.g., RiverGIS plug-in for QGIS, commercial HEC-GeoRAS, RAS Mapper in HEC-RAS) that can be used in model preparation because HEC is not further developing GeoRAS. These studies in Nepal have also emphasized the importance of geo-informatics in urban river management during flooding.

Several flood modeling programs and software have benefited the scientific community, regardless of the nature of the flooding. To alleviate the negative consequences of flooding, both structural and non-structural measures are key factors that help in minimizing the flood hazard. Here the structural measures such as culverts, dams, and dykes are determined to be hard measures that may be sometimes harmful for both the environment and mankind. Hard measures can be costly and time-consuming, yet soft measures are equally important for saving lives and property. However, studies addressing these measures should be concentrated and categorized to identify the hard and soft approaches to flood control mechanisms. Therefore, flood risk can be minimized by hazard mapping, risk zonation and enhancement of the flood forecasting and early warning systems determined as soft techniques. Limited studies of soft measures have been conducted as initial steps

to establish warning systems, dangers and rough inundation mapping [38,39] in the Karnali River basin (KRB). However, these studies remain far from sufficient to assess inundation extent and water depths for flood control measures in the KRB. The KRB in western Nepal lacks a network of climatic stations with which to assess changes in climatic conditions throughout the region [40] and is one of the most topographically challenging river basins. The two major rivers (Karnali and Bheri) converge in the KRB before passing through several gorges lying across Nepal–India border; flooding in this region is a major problem for the downstream population. Floods have occurred on the Karnali River in 1963, 1983, 2008, 2013, and 2014; these have caused numerous fatalities and widespread damage to infrastructure. The 2014 flood was one of the most severe in the history of the Karnali River, even reaching relatively safe areas; the water level on 15 August 2014 crossed the danger level mark around midnight and floodwaters inundated all the villages downstream, killing 220 people and having a severe impact on 120,000 others [41]. Despite global efforts to improve technology and flood mapping, developing countries like Nepal still face annual struggles to cope with flooding. However, we note that the Karnali Chisapani Multipurpose Project, in the Chisapani area, is planned with the aim of storing about 16.2 billion cubic meters of water; this will have benefits for irrigation, flood control and navigation, as well as producing 10,800 MW of hydropower [42].

The objective of this study is to prepare flood inundation maps and delineate flood hazard zones at a typical region on the southern slope of Himalaya. It can be a preliminary step in determining risk zonation for different spatial inundation scenarios that can aid preparation of early flood warning systems and proper communication mechanisms in downstream communities. The paper firstly discusses the study domain and the flow modeling. Next, model calibration and validation, with the help of observed water levels, are presented. After generating the inundation map, different land-use types, settlements, and infrastructures with their associated vulnerabilities are identified, which will be the initial step towards a comprehensive risk mapping. Evacuation maps and safe shelters can thus be planned with reference to such inundation/hazard and risk maps. Finally, the paper suggests effective land-use planning strategies which will ultimately benefit 175,782 people along the Karnali River.

2. Materials and Methods

2.1. Study Area

The three trans-Himalayan rivers in Nepal are the Karnali, Narayani, and Koshi (Figure 1). Each has numerous tributaries and flows towards the Indo Gangetic Plain (IGP) [43]. The geomorphological configuration of mountains, hills and plains in Nepal promotes the development of severe weather conditions such as localized precipitation and thunderstorms with hail [44,45]. Due to the very steep topographic gradient between the lowlands and high mountains of the Himalaya, downstream regions commonly suffer from severe flooding throughout the monsoon season. Due to high variability in the distribution of rainfall [46,47] and its topographic controls, about 80% of the total rainfall is contributed in the monsoon season June to September, [48] with the remaining 20% in other seasons [47]. The average annual precipitation in this region reaches 1479 mm and average maximum and a minimum temperatures range between 25 °C and 13 °C, respectively [49].

The Karnali River lies between the mountain ranges of Dhaulagiri and Nanda Devi, in the western part of Nepal. The basin extends from 28.2°–30.4° N and 80.6°–83.7° E, covering a total area of 45,269 km² [50] and yielding an average annual discharge of 1441 m³/s [51]. However, the average of observed instantaneous discharge from the years 1962 to 2015 was found to be 9672 m³/s, which seems to be highly fluctuating, whereas the maximum discharge is 21,700 m³/s and minimum is 4300 m³/s. The river is fed by 57 tributaries from six major watersheds (West Seti, Karnali, Humla-Karnali, Mugu Karnali, Tila, and Bheri), all of which originate in Nepal except for the Humla-Karnali, which originates on the Tibetan Plateau in China. The Karnali and Bheri are two major rivers in the KRB, which converge and flow through several gorges across the Nepal–India border and finally join the Ganges in northern India. The study domain selected here is approximately 38 km downstream from Chisapani (Figure 1) in a region suffering from destructive flooding that causes significant loss of

human life and extensive damage to agriculture, human settlements, and other physical infrastructures.

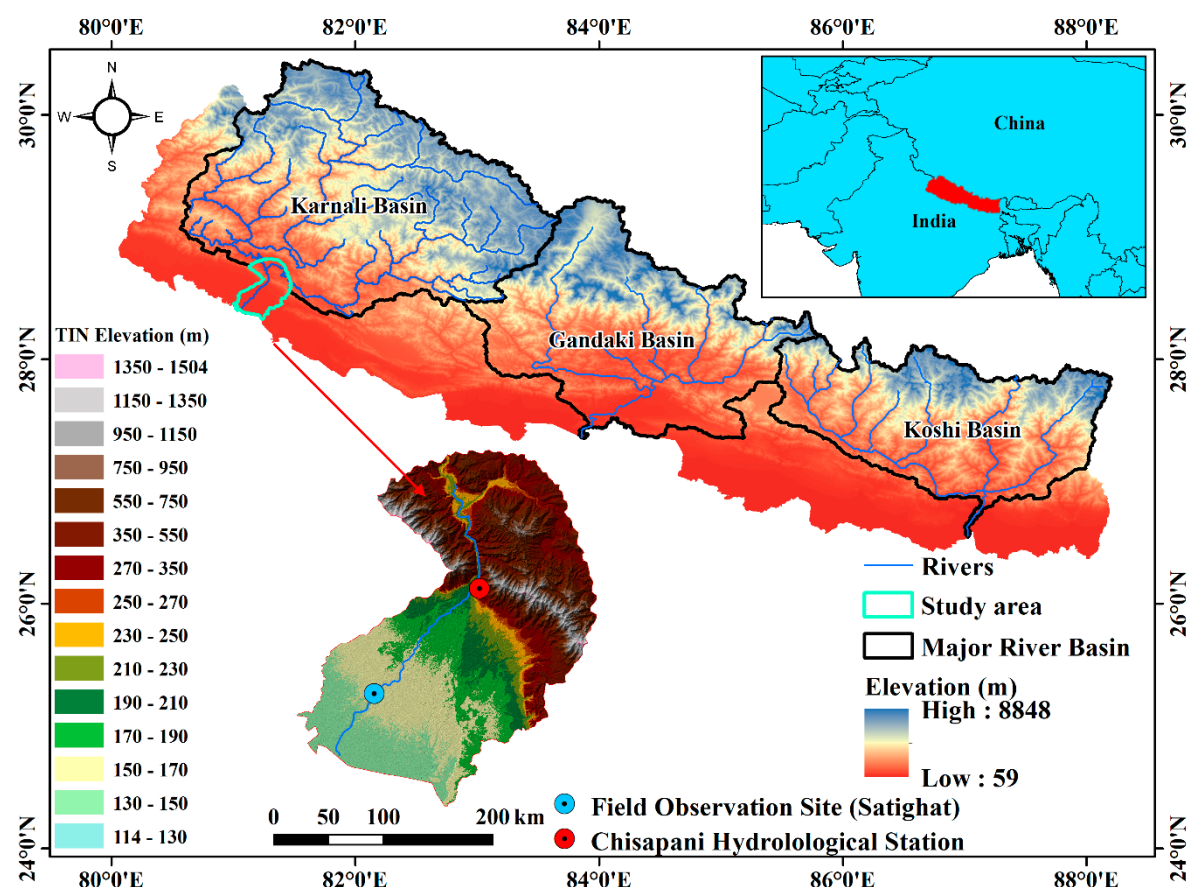


Figure 1. The study area and its elevation in Triangulated Irregular Network (TIN) form. The location of the study area in Nepal and the three major river basins is also provided for reference.

2.2. Data Sets

In this study the water level in the 38 km reach downstream of Chisapani station in the Karnali River Basin (KRB) was simulated to determine the floodplain extent of different year return periods (YRPs) by using HEC-RAS 1D model. The location was chosen based on its vulnerability. Data sets used in the study are summarized as follows.

The Shuttle Radar Topographic Mission (SRTM) digital elevation model (DEM), with a ground resolution of 30 m, is available from the United States Geological Survey's (USGS) web portal [52]. The land-use map (Figure 2) was obtained from the International Centre for Integrated Mountain Development (ICIMOD) website [53]. Instantaneous peak discharge (Figure 3) recorded at Chisapani gauging station from 1962 to 2015, totaling 54 years, was obtained from the Department of Hydrology and Meteorology (DHM), Nepal. River geometry (left bank, right bank, channel, flow paths and cross section cut lines) was generated in HEC-GeoRAS 10.1 (Hydrologic Engineering Center, Davis, CA, USA) with the visual help of Google Earth Pro 7.3.2.5776 (Google, Menlo Park, CA, USA) and the ArcGIS 10.1 (Esri, Redlands, CA, USA) online platform's world imagery and served to verify the accuracy of the modeled terrain. The locations of settlements, number of households, physical infrastructures and their boundaries were adopted from the open street map supported by Geofabrik Denmark [54]. Demographic data (Figure 4) were obtained from Central Bureau of Statistics, Nepal [55] and were supplemented with field work to analyze the social impacts. Field work was carried out to collect water surface elevation, GPS location and land-use characteristics of the floodplain.

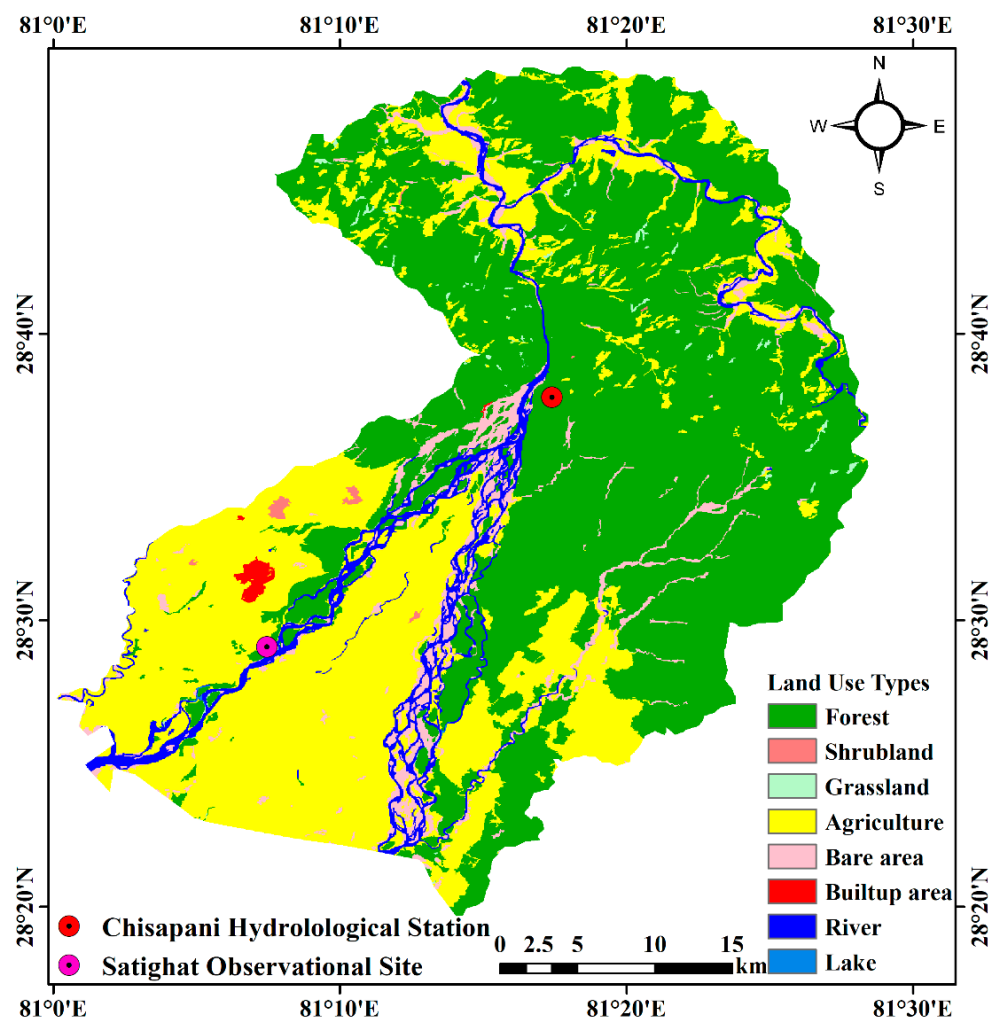


Figure 2. Land-use classification map of the study area.

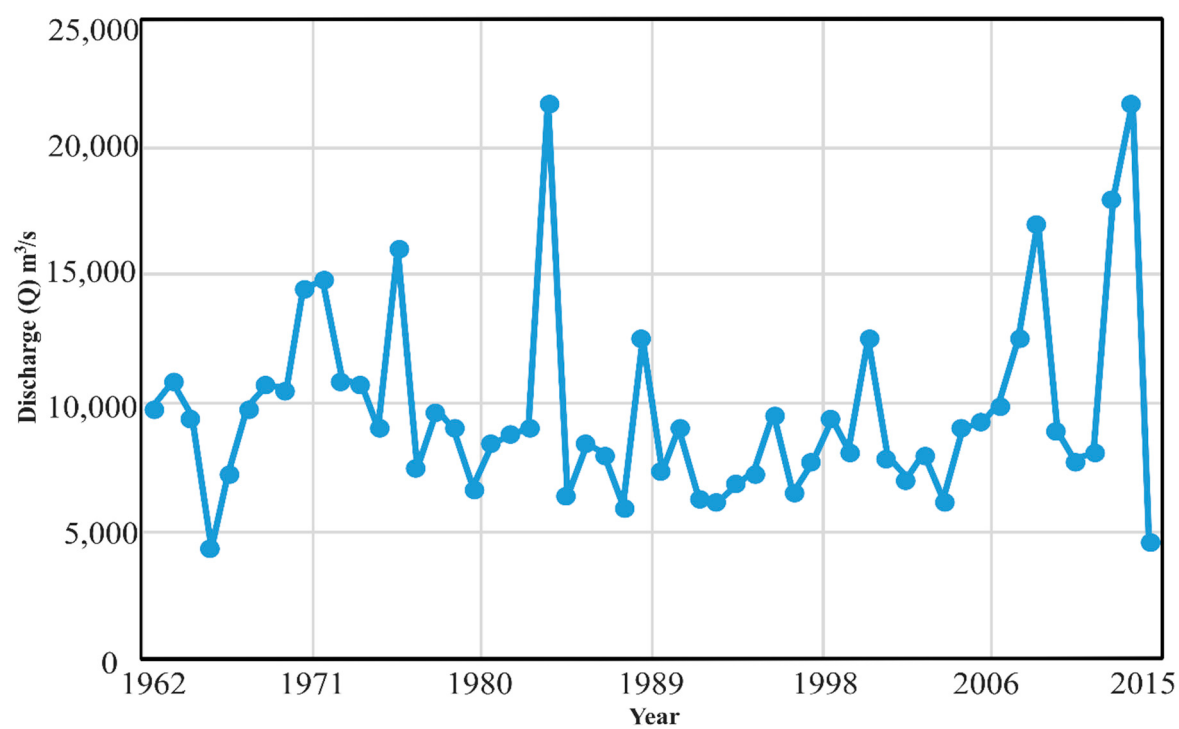


Figure 3. Instantaneous record of Karnali–Chisapani station from 1962 to 2015.

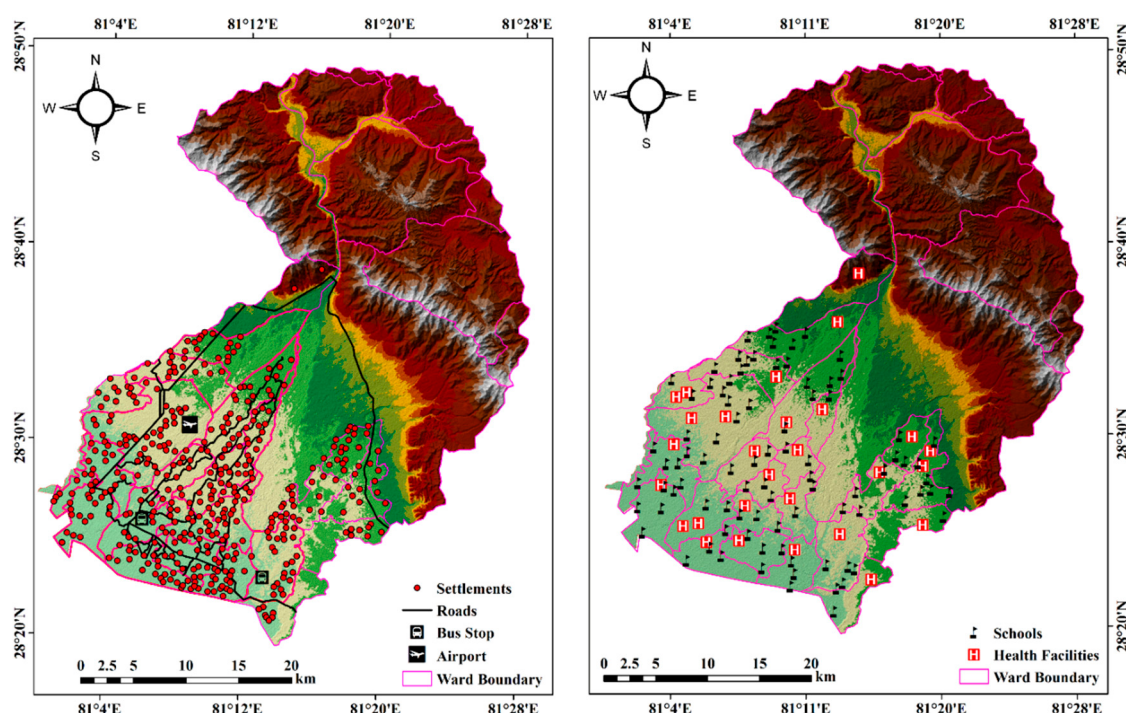


Figure 4. Spatial distribution of physical infrastructures such as roads, airport, bus-terminals and settlements (**left**) and health facilities, schools (**right**) in the study area.

2.3. Methodology

We used the HEC-RAS hydraulic model [26], developed by USACE, to simulate 1D steady flow based on calculated river hydraulics. Floods are generally unsteady; therefore, as an initial step for risk zonation of the inundation area, steady-state conditions were used in this study for different Year Return Period (YRP) floods. The steady-state approach calculates water levels at discrete cross-sections using the flows assigned in the model. Routing is based on the dynamic wave theory of the Saint-Venant equations, as well as the continuity and momentum equations [26]. Similarly, the energy balance equation (Equation 1 below) is determined as the basis of calculation of water surface profile:

$$Z_2 + Y_2 + \frac{a_2 V_1^2}{2g} = Z_1 + Y_1 + \frac{a_1 V_1^2}{2g} + h_e \quad (1)$$

where, Z_1, Z_2 = elevation of the main channel inverts, Y_1, Y_2 = depth of water at cross sections, V_1, V_2 = average velocities, a_1, a_2 = velocity weighing coefficients, g = gravitational acceleration and h_e energy head loss [26]. Here, HEC-RAS uses a semi-implicit solution algorithm, which is a combination of implicit and explicit finite difference schemes [56]. Figure 5 shows the overall framework used in this study. Firstly, flood frequency analysis was performed for different return periods (2-, 5-, 10-, 50-, 100-, 200-, 1000-YRPs) using Gumbel's distribution [57–59]. To determine the best frequency, we used the standard normal distribution G ($\alpha = 1.96$) for the goodness of fit with a 95% confidence limit (Equation 2):

$$S_e = b \frac{S_x}{\sqrt{n}} \quad (2)$$

where, $b = (1 + 1.3K_T + 1.1K_T^2)^{0.5}$.

In Equation 2, S_e is the probable error, S_x is the standard deviation and n is the sample size. K_T is the frequency factor, which depends upon the type of distribution and return period.

The frequencies of both the maximum and minimum discharge were determined and then the calculated frequencies of flow rates within the outliers were applied in the model (Table 2). The extreme values calculated using Gumbel's distribution were applied together with the maximum

instantaneous peak discharge recorded during the historical peak flood as flow inputs in the model. In the second step, a SRTM-DEM [60] was used to create a Triangular Irregular Network (TIN) file containing geometric data to verify the height approximations in ArcGIS. The HEC-GeoRAS pre-processing was then completed and the final output from the ArcGIS and HEC-GeoRAS was processed in the HEC-RAS 1D steady flow simulation. Manning's roughness coefficients ($n = 0.04$ or 0.02) were selected based on visual inspection of the river channel both upstream and downstream as suggested by [58,61] and were adjusted slightly to calibrate the model [56,62]. Similarly, Manning's roughness coefficients were specified for forest (0.08), agriculture (0.035), bare ground (0.03), shrubland (0.035), and grassland (0.032) according to visual inspection of the floodplain characteristics.

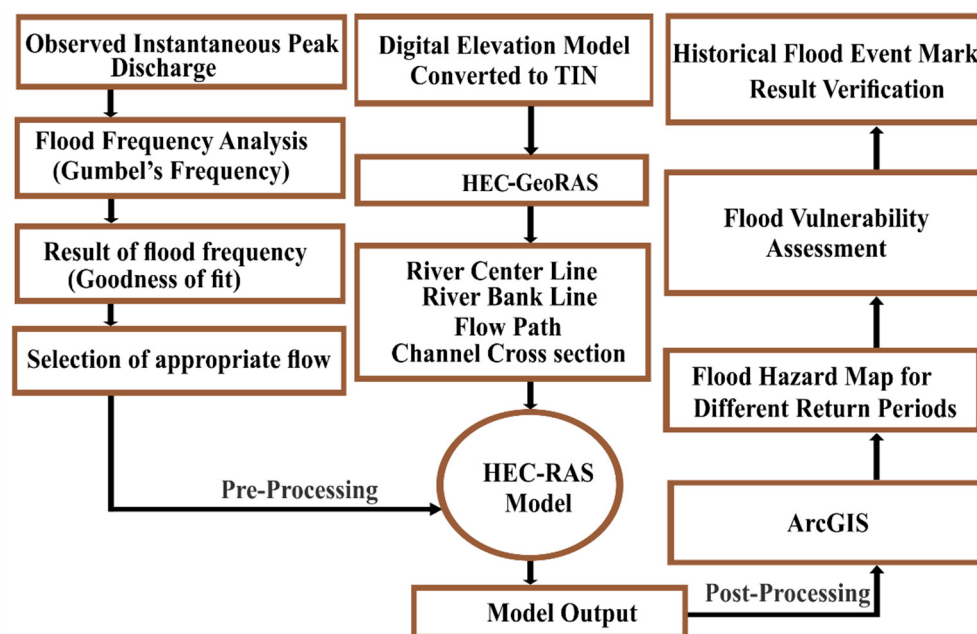


Figure 5. Flowchart of the flood inundation modeling in this study.

The model selected here is considered viable for flood inundation mapping due to the similar geographical and streamflow conditions in the present application to those described in previous studies [63]. The river's transition to lower plains, with significant slope change, can be the determinant factor in the HEC-RAS model. Since the cross-section is extracted from the DEM, the terrain slope is determined as (left = 0.091 and right = 0.678), with bed slopes = 0.641 in the investigated region. Floodplain maps represent key planning documents by providing a visual interpretation of the spatial variability of flood extents and future flood hazards [64,65].

2.4. Model Configuration

Hydrodynamic modeling in HEC-RAS involved several steps in the pre- and post-processing stages. In pre-processing, the geometric data and other required themes were prepared in an ArcGIS environment with HEC-GeoRAS and exported to .sdf format in HEC-RAS. The themes included generation of the river centerline, bank line and flow path from the DEM and World Imagery in ArcGIS; these data were imported to HEC-GeoRAS layers. The TIN and cross-section cut lines in the study domain were constructed for the river using the DEM alone. Geometric data prepared in the pre-processing phase of HEC-GeoRAS were imported into HEC-RAS for the hydrodynamic modeling. Hydraulic data including flow data and associated boundary conditions were used in the HEC-RAS flow plan, where the calculated flood frequencies for different YRPs (including the maximum peak recorded flood in the Chisapani gauging station) were applied to the river cross-section. The steady-state flow simulation was then carried out to calculate the water surface profile under a mixed flow regime. Calculated water surface profiles were exported to GIS format for post-

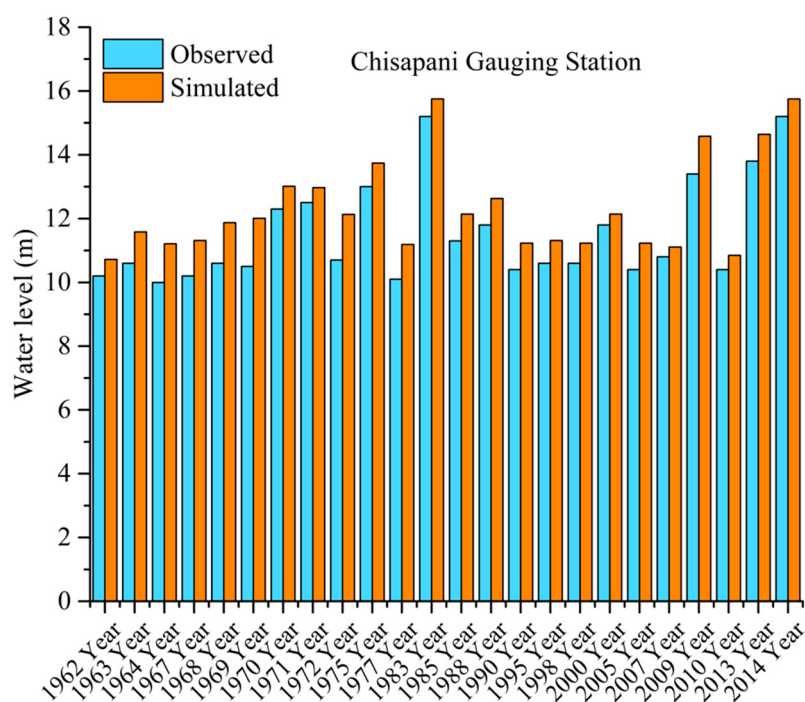
processing. In the post-processing phase, results from HEC-RAS were imported into the HEC-GeoRAS platform after layer configuration with terrain input. The water surfaces for different flow plans were generated for each return period along with the corresponding flood frequency analysis of the maximum peak discharge. The flood inundation map and floodplain boundary were then generated for each water surface profile, using the TIN.

2.5. Model Calibration and Validation

Model calibration and validation is an essential aspect of the hydraulic simulations. Two different stations were used to verify the model's satisfactory performance for further simulations. The model was calibrated using observed instantaneous peak discharge gauge heights recorded over a long period between 1962 and 2014 in the Chisapani hydrological station; the model was then validated with field observations at Satighat. In the case of calibration, the peak flood events of selected years (i.e., 1962, 1963, 1968, 1970, 1971, 1973, 1975, 1983) were taken, whereas validation was based on major flooding's of 2009, 2013 and 2014. After performing the repeated simulations and re-adjusting the river channel water level to the datum height, the difference between observed and simulated water levels was found to be negligible. The Hicks and Peacock equation [66], in Equation 3 below, was adopted to assess simulation performance based on the percentage difference between simulated and observed water levels during historical peak flood events in the downstream region of the Karnali River. A lower percentage error between the simulated (S_{wl}) and observed (O_{wl}) water level indicates a better performance of the model.

$$\% \text{ error} = \frac{(S_{wl} - O_{wl})}{(O_{wl})} * 100. \quad (3)$$

Thus, the simulated 2014 flood water level, with a difference of only 3.61% between the observed (15.2 m) and simulated (15.75 m) water levels, as well as the obtained R^2 value in both the calibration = 0.95 and validation = 0.98, seems to be highly significant and demonstrated the good model performance. A detailed comparison of the calibration and validation processes is illustrated in Figure 6.



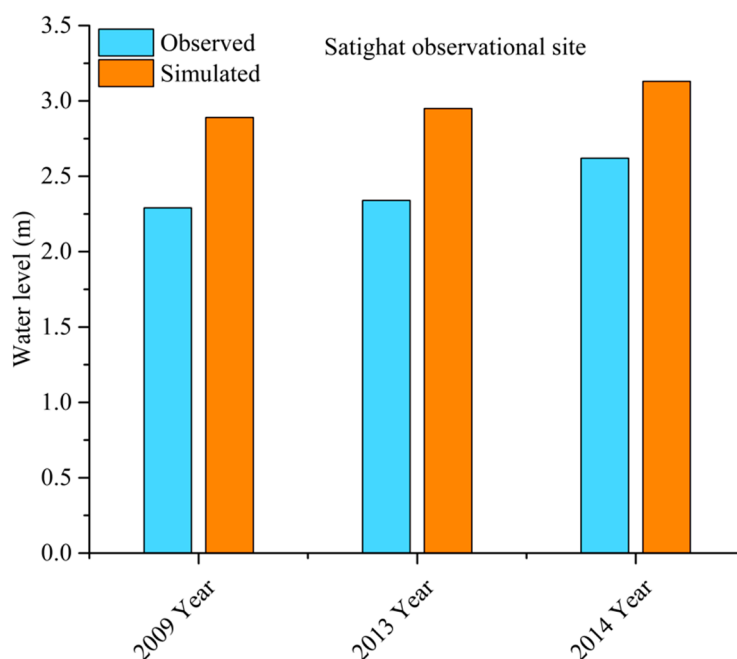


Figure 6. Comparison between observed and simulated water levels at Chisapani gauge (**upper**) and the field observation site Satighat; (**lower**) in the river channel during major historical flood events between 1962 and 2014, as used for model performance evaluation.

3. Results

The simulated floods in all the YRPs showed significant flooding conditions in both river banks of the Karnali river; as a result, the HEC-RAS simulation model was used to prepare flood inundation maps with changes in depth for different YRP flood frequencies. The inundation maps showed the variation in flood depth over the floodplain with increase in discharge. The inundation maps provided a qualitative picture of the depth and its extent during inundation.

3.1. Flood Frequency Analysis

Flood frequencies obtained using Gumbel's distribution for different YRPs are presented in Table 2 and Figure 7 using the log chart along with the recorded historical peak discharge for the different years. Of the three types of extreme value theory, the straight line of Type I was determined as being the most appropriate. The discharges predicted by Gumbel's distribution were 9088, 12,696, 15,085, 20,343, 22,565, 24,780, and 29,910 m³/s for the 2-, 5-, 10-, 50-, 100-, 200-, and 1000-YRPs, respectively (Table 2; Figure 7).

Table 2. Classification of instantaneous discharges (m³/s) at Karnali Chisapani obtained using the Gumbel's distribution for different return periods with maximum and minimum 95% confidence limits.

Return Period (T _r)	2	5	10	50	100	200	1000
Minimum	6748	8389	9185	10,754	11,389	13,442	13,442
Gumbel's	9088	12,696	15,085	20,343	22,565	24,780	29,910
Maximum	11,428	17,004	20,986	29,931	33,742	46,377	46,377

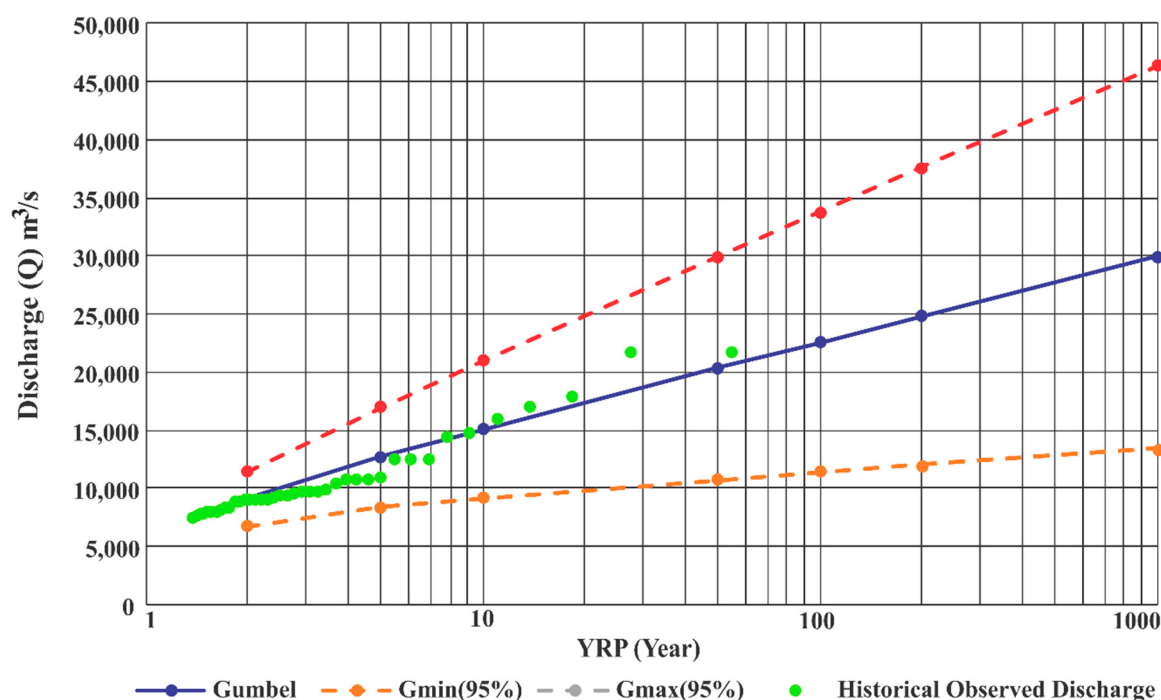


Figure 7. Frequency analysis of flood discharge at Chisapani gauge, showing the Gumbel's distribution and its 95% confidence limits of extreme values (calculated using the standard normal distribution). The year return period (YRP) is plotted on a logarithmic scale for clarity. Historically observed discharge is also given here for reference.

3.2. Comparison and Analysis of Water Surface Profile and Water Surface Elevation

We used two river stations for comparison of water levels and water surface elevations in the model simulation: an upstream station at Chisapani bridge and a downstream station at the Satighat observation station. The upstream station at Chisapani bridge was used for calibration, whereas Satighat was used for validation. Modeled water surface elevations at Chisapani station under 10-, 100-, and 1000-YRP floods and the 2014 peak flood reached 212 m above sea level (a.s.l.) (Figure 8). Under these same YRPs, the river level downstream at Satighat reached 145 m a.s.l. Due to the strongly heterogeneous river bed and slope, it is very difficult to estimate water flow rates during flood and non-flood periods, as illustrated by Figure 8. The river flow varies according to the weather conditions in the KRB and the small river joining the Karnali River. Thus, the water surface profile obtained by the model reproduces the natural characteristics of the river as observed during the site visit.

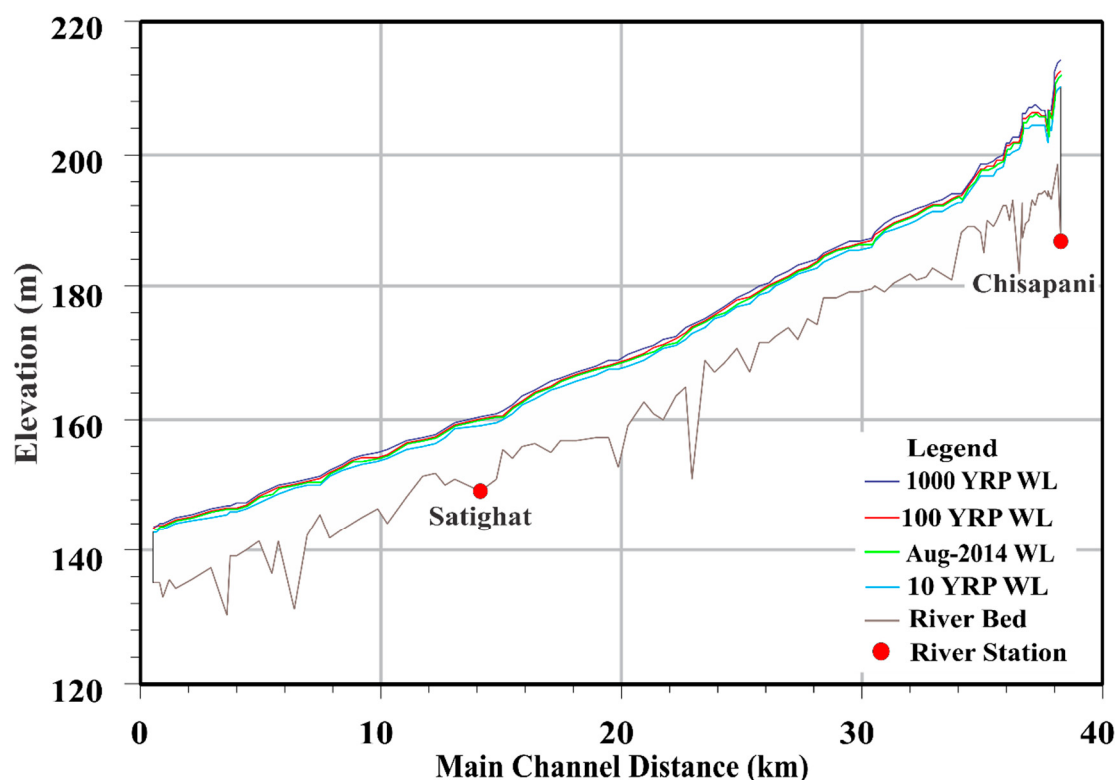


Figure 8. Water surface profile of different YRP floods in the river segment from Chisapani to the Nepal-India border. The Chisapani gauge and Satighat observation station were used for model performance evaluation.

Simulated water levels in the two modeled cross sections at Chisapani and Satighat showed higher overflows from the riverbank during the 10-, 100-, and 1000-YRPs and the 2014 flood, as illustrated in Figure 9. The output cross-sectional plots generated by the model (Figure 9) showed that water levels exceeded river bank heights even during the 10- and 100-YRPs, indicating a situation of critical concern in the downstream area. As expected, in all cross sections of the upper reach and lower reach, the water surface elevation under the 2014 flood was higher than that under the 100-YRP flood. Since we have assumed the flood magnitude in 2014 was approximately that of the 100-YRP, then according to the calculated and observed discharge, the water levels of the 2014 flood in the upper reach (Chisapani) and lower reach (Satighat) would have resembled those illustrated in Figure 9. In addition, the maximum instantaneous discharges in 1983 and 2014 at Chisapani station were both around $21,700 \text{ m}^3/\text{s}$, whereas peak discharge in 1975 was $16,000 \text{ m}^3/\text{s}$ and about $17,000 \text{ m}^3/\text{s}$ in 2009. Such a variable discharge of the Karnali River indicates that future floods could occur at any time.

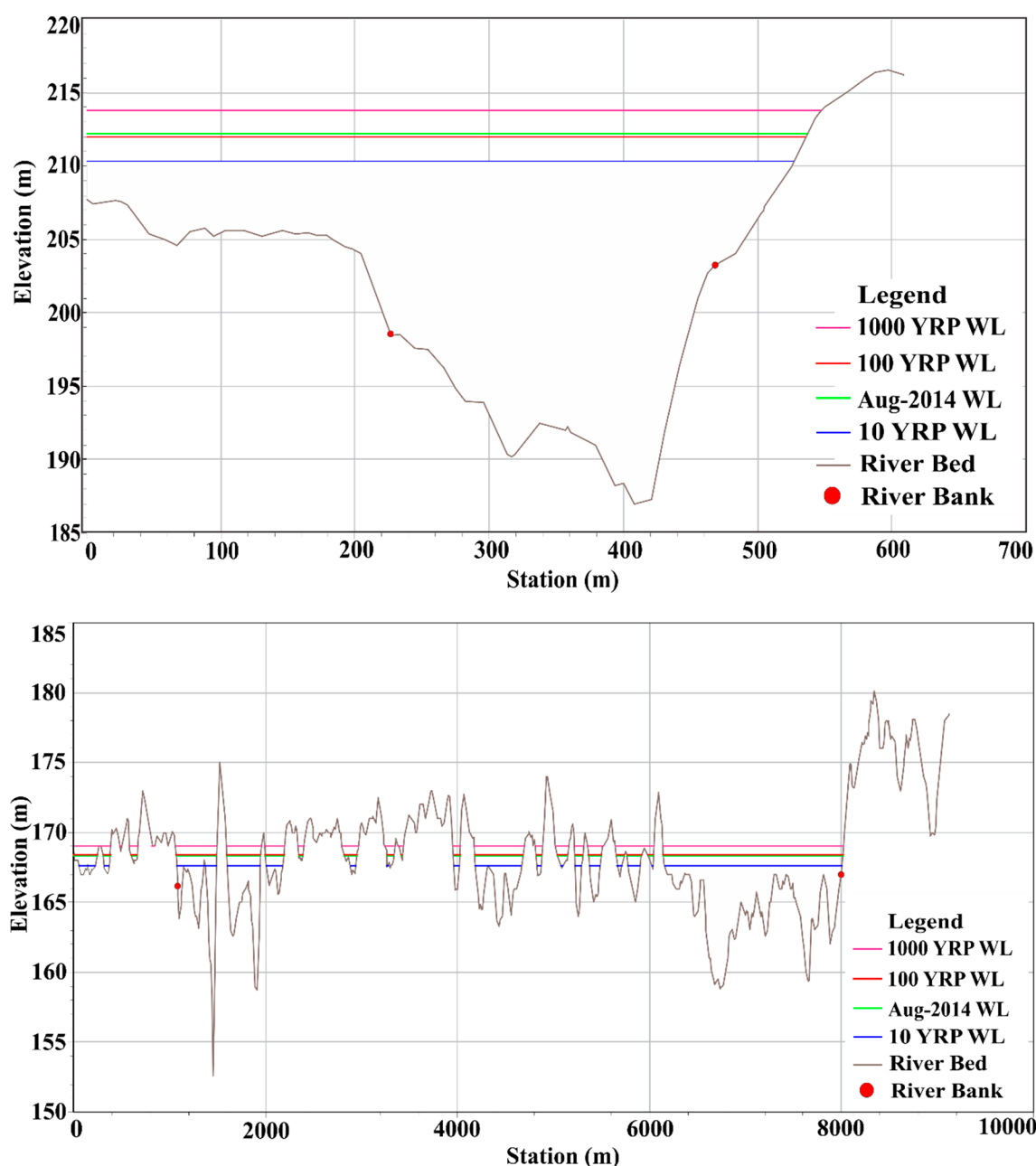


Figure 9. Water surface elevation (WL) in cross sections at Chisapani under different YRP floods, including the 2014 flood (around the 100-YRP) (**upper**), and WL at the Satighat cross section (**lower**).

3.3. Simulation of the 2014 Flood Event

The 2014 flood simulation for the Karnali River was executed in HEC-RAS using steady flow methods. Boundary conditions were established for entire river nodes with normal depths after visual inspection of the study domain. Similarly, an initial condition was imposed by populating the model with the observed water discharge during the flood. The simulated and observed water surface elevation and inundation area corresponded to a 100-YRP; however, [41] reported that this flood event was equivalent to a 1000-YRP and argued that the water level was as high as 16.1 m. In the absence of verified data for different flood events, the Karnali River flood in 2014 can be considered as a historical flood, but its exact magnitude cannot be constrained as a 100- or 1000-YRP. The observed discharge can be compared with the discharge calculated using Gumbel's distribution at both river stations (Figure 9). Moreover, the estimated discharge during flooding is greater than that of the normal flow, as shown in the simulation of the 2014 Karnali floods. The Karnali River has many tributaries fed by snow melt, drops in altitude by approximately 7000 m, and passes through

the deep gorges of the Himalayas; therefore, its discharge varies considerably and leads to the high flood risk simulated by the model. The left bank of the river was found to be more vulnerable than the right, as the surrounding terrain is slightly lower near the left bank. The simulated water surface elevations in the 2014 flood showed that the greatest inundation of the study domain was due to the overflow of the river in the lower reach. Therefore, further riverbank restoration is required in this part of the river.

The DHM has established threshold water level gauge heights of 10 m and 10.8 m for warning and danger levels, corresponding to 201.64 m and 202.44 m a.s.l., respectively [67] (Table 3). The discharge recorded on 15 August 2014, was 21,700 m³/s, with an observed water level of 15.2 m at Chisapani gauging station; this illustrates the severity of flooding in the downstream reach of the river area, which leads on the river overflow from both its banks.

Table 3. Classification of threshold discharge (m³/s), water level gauge height (m) and mean above sea level (a.s.l.) reference height categorized according to the warning and danger levels for flood forecasting in Karnali used by the DHM, Nepal [67].

River Name	Station	Threshold by DHM			Remarks
		Runoff (m ³ /s)	Water Level (m)	Reference to MSL	
Karnali	Chisapani	8200	10.0	201.64	Warning Level
		10,000	10.80	202.44	Danger Level

3.4. Flood Hazard Mapping

The flood hazard is directly linked to the hydraulic and hydrological parameters. Here, a hazard can be defined as a threatening natural event with a specified probability of occurrence [15]. Quantifying flood hazard level and mapping its potential damage can be achieved using water depths reached during flooding. Here, flood hazard was mapped after reclassifying the flood depths into five classes: <1 m, 1–2 m, 2–4 m, 4–6 m, and >6 m. This classification was a crucial step in quantifying flood hazard and its potential damage in the future. The areas bounded by each flood polygon were calculated to assess the hazard level. Therefore, effective land-use planning and its recommendations can be implemented in the downstream region of the KRB with the help of soft measures used in this study.

The flood inundation and hazard mapping in this study show that the existing warning and danger levels correspond well with observations, as demonstrated by the simulated water surface elevation at Chisapani and Satighat. The flood depth classification shows that most of the inundated area has a water depth less than 1 m (Figure 10), but the area with water depths greater than 2 m increases considerably as flood intensity increases. Also, the area with higher flood depth increases and the area with lower depths decreases as flooding intensity increases (Figure 10). Some areas become inundated even in a “normal” flood scenario of the 2-YRP, demonstrating a critical situation in the downstream reaches of these rivers. Flood depths exceeding 6 m in the 1000-YRP flood affect a slightly greater area than that in the 100-YRP flood.

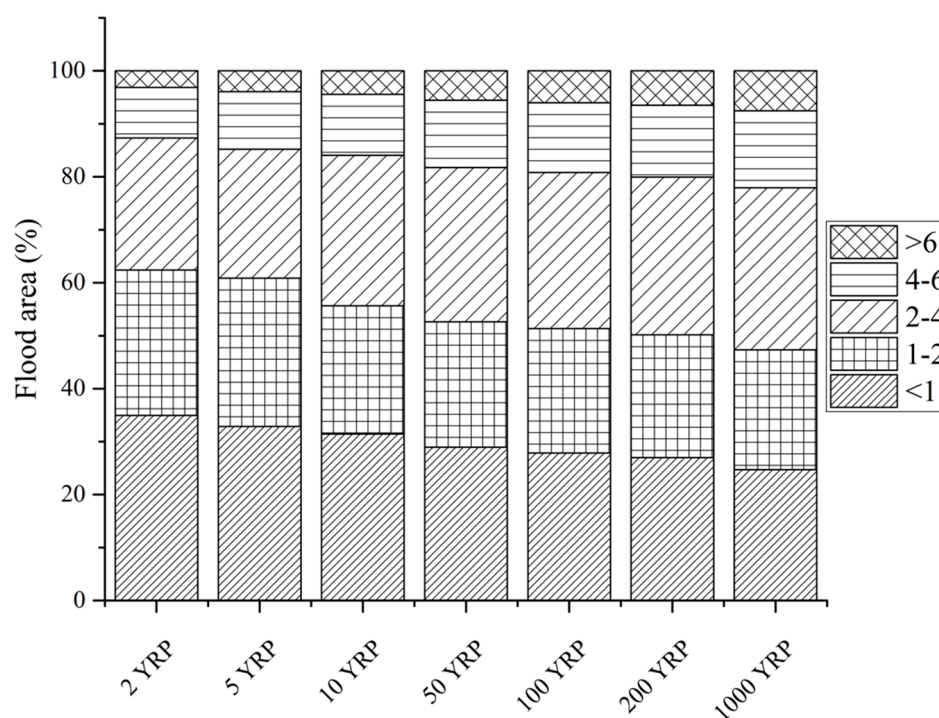


Figure 10. Flooding area percentages according to the classification scheme for inundation water depth (unit: meter), for different YRPs in the study area.

Comparing the simulated floodwater depths of the 100-YRP flood and the 2014 flood showed strong similarity between both scenarios (Figure 11): the river channel is very deep, presenting a significant hazard. Both the 100-YRP and 2014 simulated flood depths presented similar levels of flood hazard in the KRB floodplains. The 2–4 m flood depth class inundated a greater area than the other classes, Figure 11.

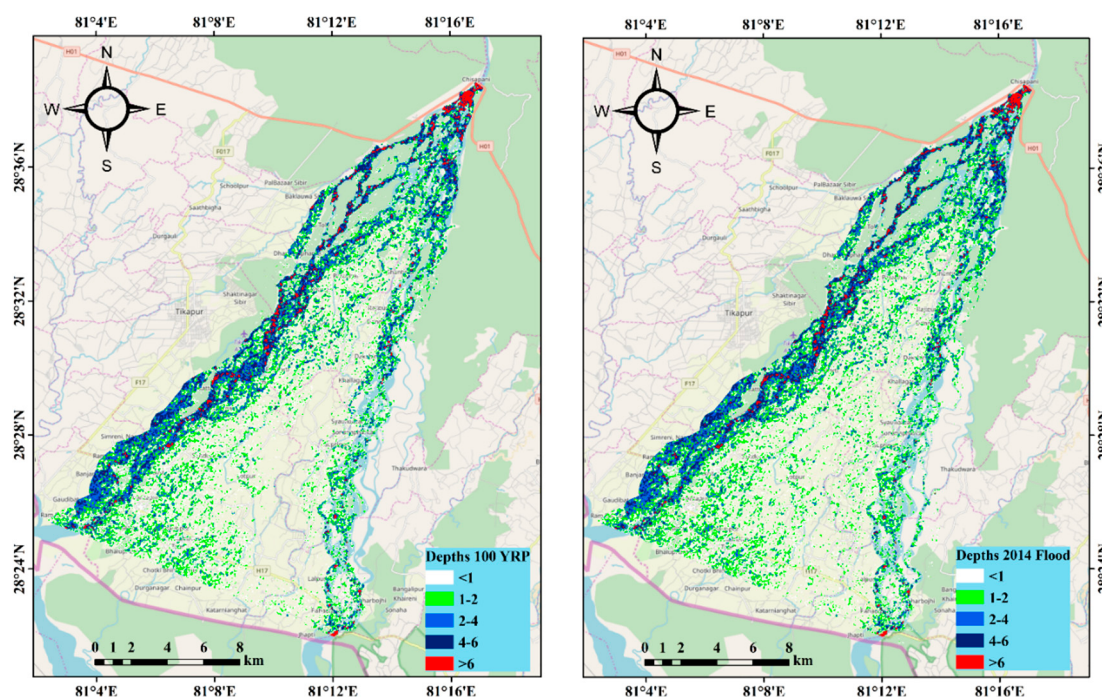


Figure 11. Flood water depths simulated by the Hydrologic Engineering Center's River Analysis System (HEC-RAS) in the study area for the 100-YRP (left) and the 2014 flood (around the 100-YRP) (right).

There is a relationship between intensity and loss. During the early 1990s, a smaller number of flood events were relatively more dangerous to people downstream than at present, due to the lack of a flood forecasting system. As technology has developed, the number of flooding casualties has decreased, but flooding still displaces millions of people. Classifying the data recorded up to 2018 (Table 1) [68] shows that the transboundary floods are more severe, causing many fatalities and forcing displacement of inhabitants that leaves them homeless. Hence, the study reveals the link between flood depth and flood hazard. During extreme flooding events in the monsoon season, the discharge of snow-fed rivers becomes high due to the combination of snow melt and rain, leading to flooding and landslides. The downstream region of the study domain comprises the flat plains of Terai and is more vulnerable to the flood water, as it can more easily inundate settlements. Figure 11 shows that the flood water level is significantly higher than normal in the river channel, and that the river banks can also reach depths of 4–6 m. Similarly, the simulated 2014 floods also yielded high water levels. Although the depth of the Karnali River can be very high due to its stream characteristics, the area of inundation after bank overflows used to be greater. Therefore, it is important to deliver early warning messages via the mass transit system and to communicate with the regional local government offices to minimize losses. To assist with this objective, we classified the flood depths in different locations based on the occurrence and severity of the flood hazard level faced by local communities. This complements the flood mapping used by the DHM in which we tried to investigate the flooding extent in detail for different locations and flood depths.

3.5. Flood Vulnerability Assessment

Nepal is a mountainous country with a high risk of flooding, landslides and soil erosion—especially during the monsoon season [69]. The flat plains of Nepal promote monsoon season flooding and inundation across a large area, mostly on the IGP along the southern flank of the Siwalik Zone [67,70]. The main causes of inundation are ineffective land-use planning, negligent floodplain management and insufficient research prior to the implementation of further development programs. Another major problem which aggravates flooding downstream of the Siwalik Zone near the Nepal–India border is the illegal construction of infrastructure without proper research into land settings, and a lack of cross-drainage passages and embankments on the IGP [71]. The different land-cover types and their vulnerabilities are illustrated in Figure 12. The floodplain assessment demonstrated the highest percentage of vulnerability in the downstream region of the KRB (up to 75%), which was in the cultivated area (53,338 ha), followed by 14,658 ha of barren land. Although only a negligible area of built-up land was inundated, this small area comprises a densely populated county situated close to the river. Counties located along the bank of the Karnali River (Janaki, Tikapur, Geruwa, Madhuwan, Thakurbaba, Rajapur) in the study area are at high risk of flooding during the monsoon. Following the February–March 2018 survey, this study suggests that the population in the KRB is more vulnerable than those near the edges of the floodplain. Tikapur, Rajapur and Geruwa are densely populated counties where 68,917 residents live in 13,214 households designated as high flood risk. The simulated water level at the Chisapani gauging station can show a high level of inundation in downstream regions, depending on the YRP (Figure 13). As the flood discharge increases in the upstream region, the water level reaches around 16 m in the river channel and the inundation area affects more than 10,000 households.

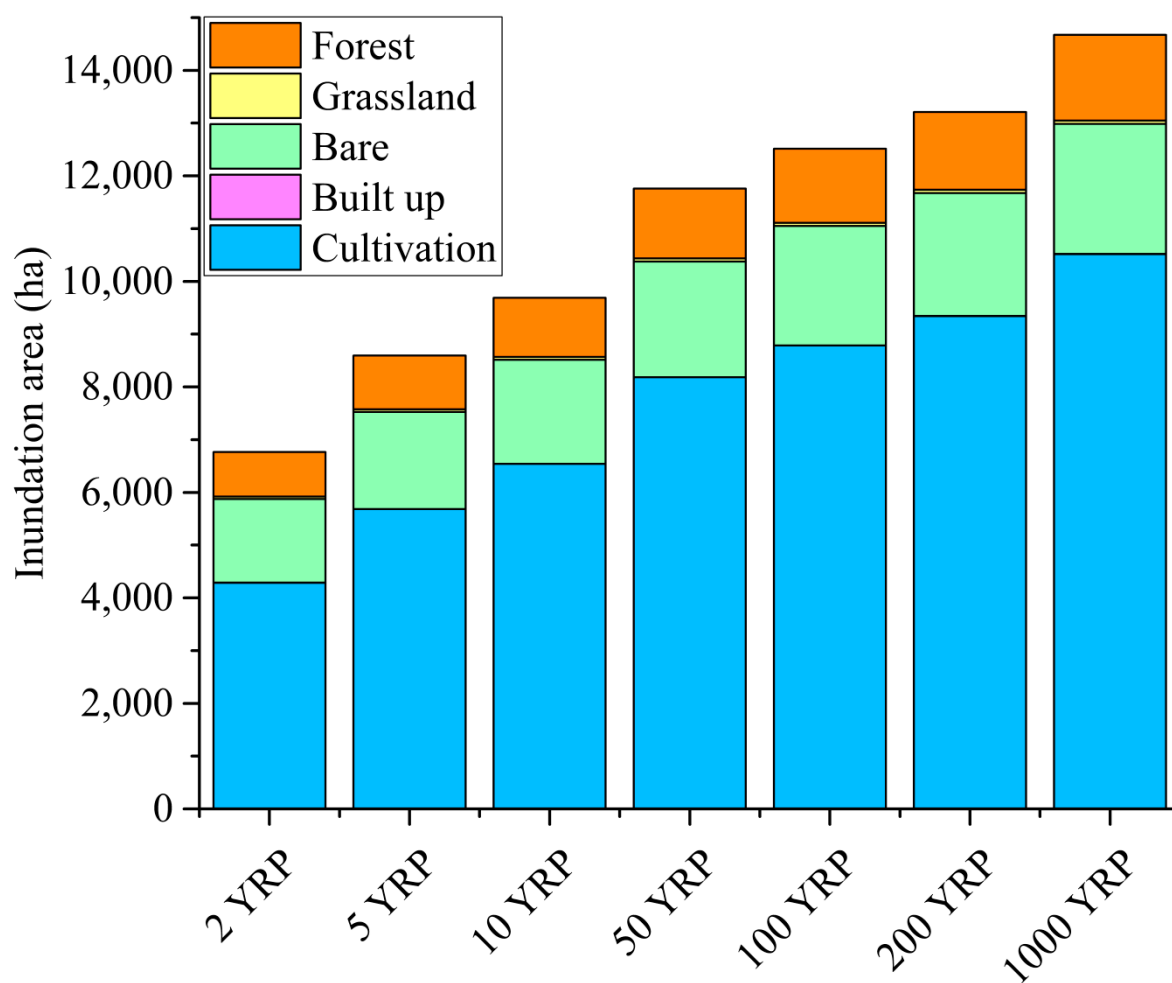


Figure 12. Impacts of different YRP floods on various land cover types in the downstream region (unit: hectares).

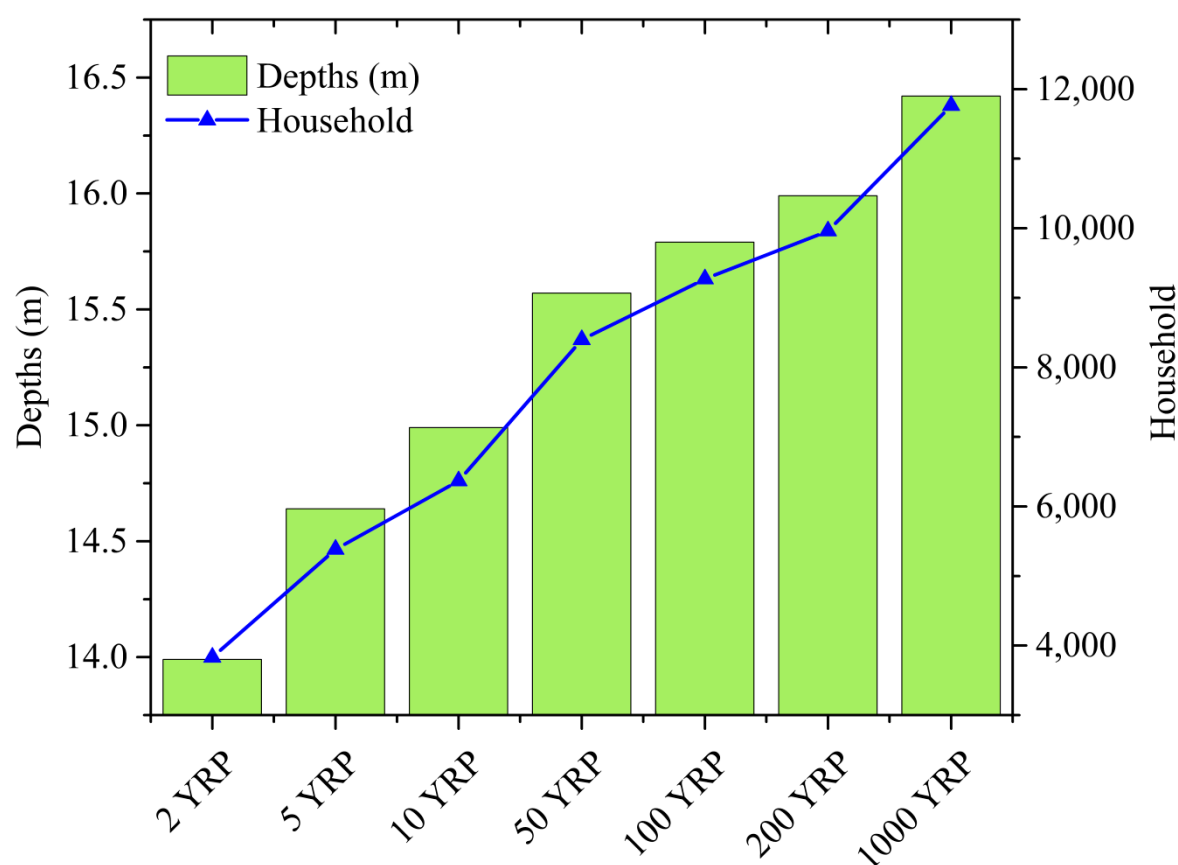


Figure 13. Relationship between the water level depths at Chisapani station (in the river channel) and the number of inundated households downstream (Chisapani station to the Nepal–India border) with different YRP floods.

However, our study suggests that key facilities could be affected during future floods in the Karnali River corridor, including floods such as that in 2014. The major transportation routes (one airport and two major bus terminals), as well as local trade routes and link roads (including 164 km of highways) (Figure 14), are at risk of inundation and resulting collapse of infrastructure. As seen in the inundation scenario of the 2014 floods, many schools, hospitals and settlements were heavily inundated and remain at a high risk of future inundation. The extent of major inundation events and their effect on settlements is presented in Figure 15. The simulated flood of 2014 roughly corresponded to a 100-YRP flood that inundates 8784 ha of agricultural land and 2267 ha of barren ground.

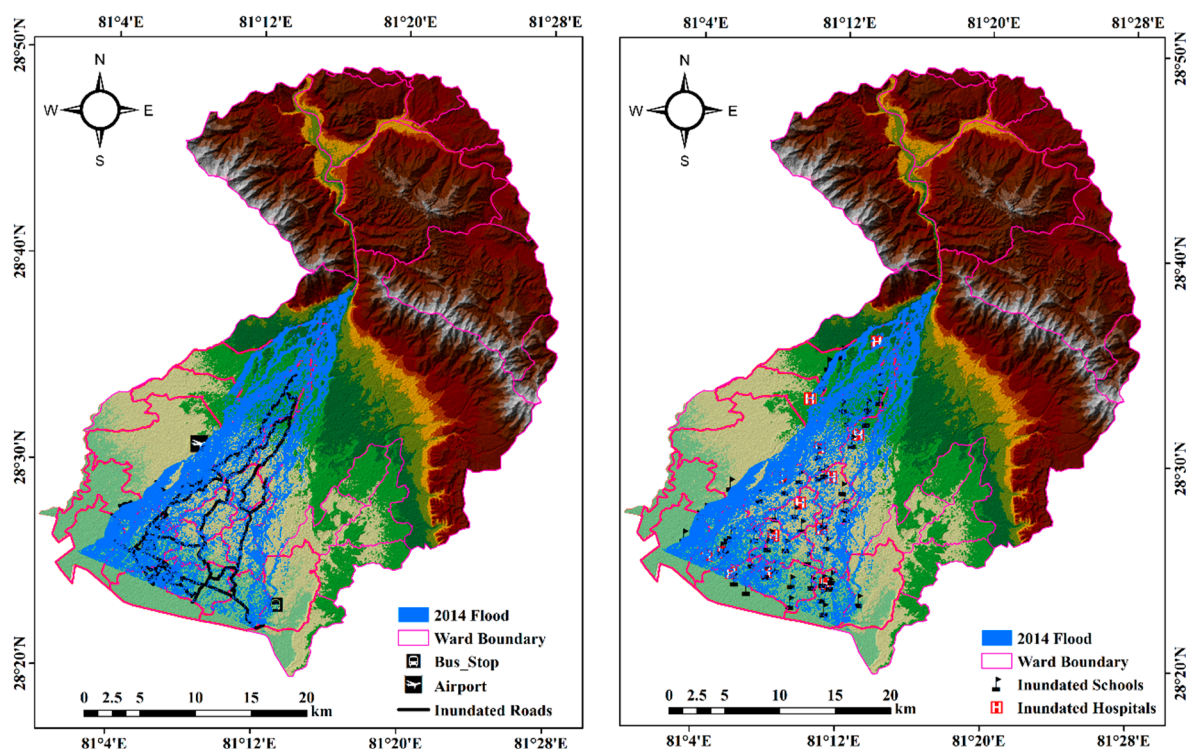


Figure 14. Spatial distribution of major transportation routes (airport and bus stops) (**left**) as well as the health centers and schools (**right**), which were inundated by the simulated 2014 floods between Chisapani station and the Nepal–India border.

During the post-monsoon season, central Nepal and some western parts of Nepal received record-breaking rainfall, reaching 493.8 mm/24 hr at Karnali Chisapani station, which is upstream of the study area. This rainfall was one of the key factors contributing to the 2014 floods with impacts as described above [41,72]. Modeled peak discharge levels observed during the historical floods of 1970, 1971, 1975, 2000, 2009 and 2013 were used for the calibration, yielding gauge height discrepancies below 23%; the historical flood of 2014 was used for the validation and yielded an error of 3.61%. Therefore, the model results agree closely with observed water surface elevation and demonstrate the model's suitability for mapping the floodplains of other rivers with similar characteristics.

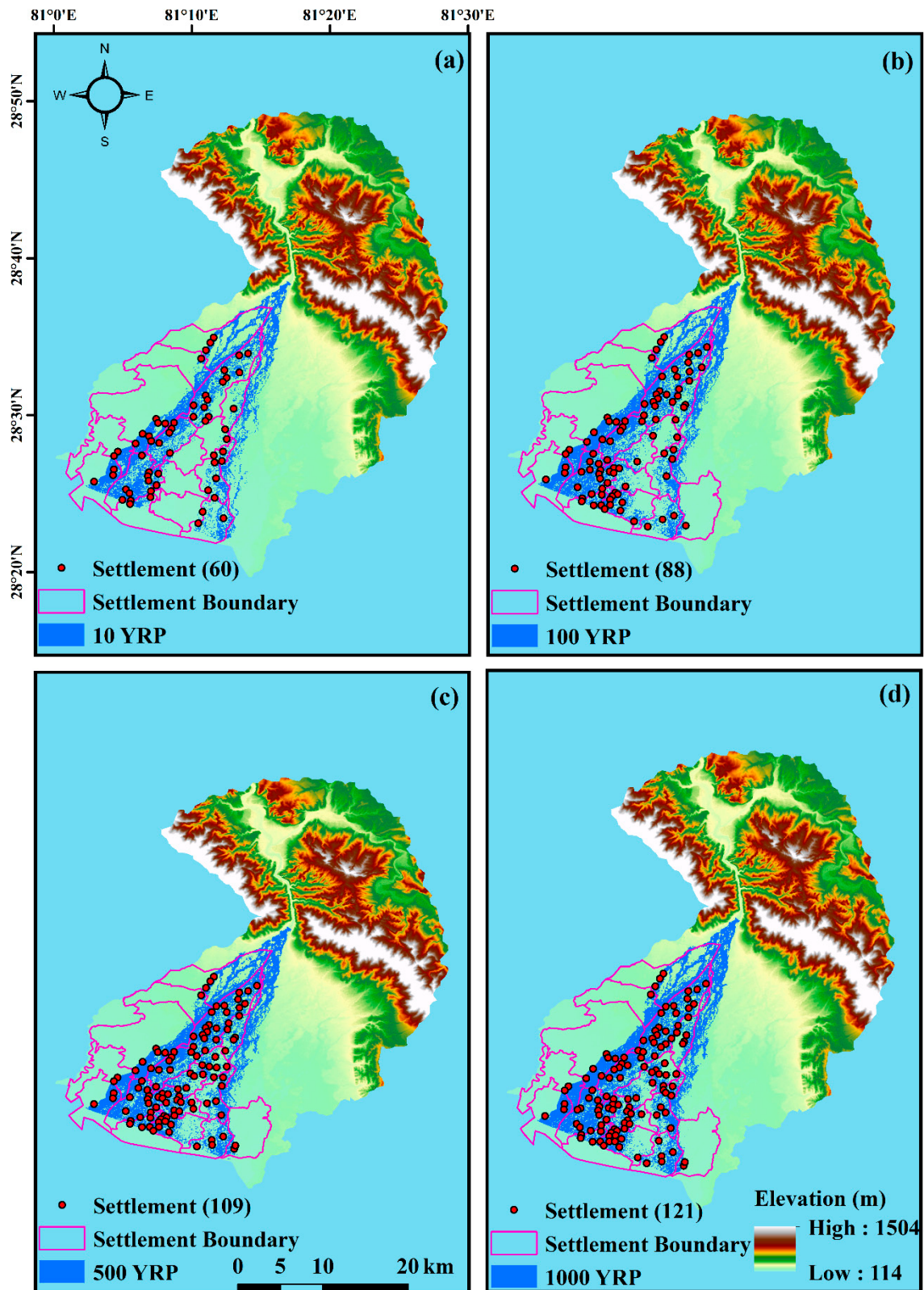


Figure 15. Simulated flood impacts on the number of local settlements given in brackets, with the corresponding boundaries of multiple locations obtained by different YRP floods ((a) 10 YRP, (b) 100 YRP, (c) 500 YRP, and (d) 1000 YRP).

4. Discussion

Disasters such as floods and landslides are very common in the southern part of Nepal bordering India, with different transboundary floods with high number of fatalities (Table 1). They affect the livelihood of the people and cause enormous damage to the physical properties, e.g., destroy houses, infrastructure, agricultural land, and crops. Therefore, it is very important to identify probable future floods and their inundation extent with available tools.

In this study as per the recommendation of the World Meteorological Organization (WMO), Type I (Gumbel) distribution was used to determine the flood frequency [73]. After the calibration and validation (Figure 6) of the model, further simulation was carried out to observe probable scenarios of flood in the KRB. The calculated flood frequency of Type I seemed to be the most applicable and appropriate, as summarized in Table 2 and illustrated in Figure 7. The water surface profile obtained after the simulation by the model reproduces the natural characteristics of the river as observed during the site visit. Also, due to high variability in the velocity of the river from Chisapani to Satighat, greater overflow of the river occurs along the lower reach than along the upper reach, causing an extensive inundation of the region around Satighat (Figure 8). After the simulation, flood extent in all the YRPs showed significant flooding conditions in both river banks of the Karnali River (Figure 9). Based on the flood frequency analysis, inundation areas were determined and compared under different YRP floods. The scenario depicted that high-elevation settlements in the upper reach were not greatly affected by flooding, but the river in the lower reach destroyed settlements during excessive flooding. While it is normal for the river to affect trade routes when it is in flood during the monsoon season, the river still presents the risk of dangerous conditions during high floods. A recent study analyzing two decades of maximum instantaneous discharge of the Karnali River showed very high discharges during the summer monsoon season, reaching 21,700 m³/s, thus presenting a serious threat to the KRB [41]. Moreover, the observed peak discharge of the 2014 flood was broadly consistent with that of the 100-YRP (22,565 m³/s). Thus, we could evaluate the capacity of the HEC-RAS model in generating water surface profiles and elevations. This will help in the further planning of river restoration to mitigate the loss and damage during flooding. Overall, the simulated water surface profile in the HEC-RAS model showed good performance in the KRB. A similar study in Pakistan by [74] compared the water surface elevation and profile of different YRPs for the Kabul River, further illustrating the requirement for policies to mitigate likely future inundation events. Since the model applied to the Karnali River was calibrated with observed historical gauge heights, we can assume that calculated flood levels in the vicinity of both stations are reasonably accurate.

Similarly, in this study the flood depth obtained after simulation helps in mapping flood hazard. Most of the flooded area is within or shallower than the depth class 2–4 m, as evident in Figure 10; however, even floods with depths of 1 m can cause severe damage and are therefore considered of high risk in the downstream region (Figure 11). Higher flood depths generally cause more fatalities and pose serious threats to the settlement along the river and coastal cities [75]. [37] studied the Balkhu River in Nepal to assess the hazard level in illegal squatter settlements along the riverbank and suggested their relocation. They also discussed the details of a plan implemented by the local government whereby construction activities were restricted by regulations requiring a 20 m distance between development and the river bank. A similar approach can be very fruitful in the downstream region of the KRB, which will help in reducing the future impact of flooding. Although a flood projection and water level threshold was established by the DHM in the KRB [67] (Table 3), uncertainty remains regarding the timing of flooding, as it is sometimes caused by anomalous flooding events.

The vulnerability assessment was conducted by identifying the key facilities with the help of field surveys and open street maps (Figures 12–15). Urban, suburban and rural areas generally require greater utility of natural resources such as rivers and watershed areas, and greater construction of river embankments, levees, and dikes, resulting in the bumping of sediments. These factors cause high vulnerability of the human settlements and aquatic habitat in the study area, which must be properly managed to minimize loss. Various land cover types (e.g., bare area, cultivable land,

built-up area, grassland and forest) in the downstream region are at high risk (Figure 12). More than 4000 hectares (ha) are inundated under normal floods, representing a large area around the river banks and urban settlements. Despite severe flooding in almost every year since 1970, Nepal still lacks the proper measures needed to tackle regular flooding of the IGP during the monsoon season [71]. [41] showed that weather conditions were responsible for the Karnali River floods in 2014, which caused over 220 fatalities and was assumed to be a 100-YRP event. Likewise, in Figure 14, the impact assessments for different types of infrastructure were carried out to identify likely future inundation scenarios. Here, the settlements, hospitals, schools, roadways, airports and bus stops were identified as crucial elements of public infrastructure or facilities [4].

Generally, the potential impact of a disaster on a territory is estimated from the potential vulnerability of its critical facilities in a hazardous situation. The potential impact on these key facilities plays an important role in the operation of the governing body and proper functionality of the region. Therefore, effective land-use planning and its recommendations can be implemented in the downstream region of the KRB with the help of the soft measures used in this study. The urgent need for maximum flood forecasting units, the latest early warning technology, and door-to-door awareness campaigns in riverbank settlements and nearby communities are all important objectives that can help in reducing the flood-related loss of life and property [76]. In the context of Nepal, the application of a numerical model and ArcGIS for floodplain analysis was limited by the availability of river geometry, topographical data, and hydrological data. Here, the adequacy of the available topographical information was a major concern; the data used in this study were based on a TIN with high accuracy. In particular, the model was able to accurately determine the severity of the 2014 flood. Therefore, we can assure that the model is valid for flood hazard mapping in the study region.

The accuracy of topographical data significantly plays an important role in delineation of likely inundation. In our study we limited the topographical data to space-borne DEMs, which is not normally recommended. Better topographical data provide clear information of the areas with high susceptible flow velocity and direction. We therefore recommend carrying out river bathymetry, Lidar surveys, and Differential Global Positioning System (DGPS) surveys across the study area. For the spatial extent of inundation our study provides more or less acceptable scenarios. The likely inundation across the study area and the simulated result of this study are almost congruous, which is confirmed by our field level observations and published literatures. We believe this study can provide a baseline for flood risk management in the downstream of the KRB, as well as in the context of similar catchments.

5. Conclusions

In this study, we presented a systematic approach to identifying flood frequency and its future risk based on a spatial extent of inundation in the downstream region of the Karnali River at southern Himalaya. Although a major objective was to focus on flood inundation scenarios, this study had the limitation of not precisely focusing on flow velocity, direction, timing, propagation and its hydraulics during peak flood. Thus, the YRP hazard maps were established based on a hybrid approach using ArcGIS and the HEC-RAS model. By analyzing past hydrological events on the Karnali River and by assessing its present condition, a number of conclusions were drawn. Natural disasters such as floods, landslides, riverbank erosion, debris flow, soil erosion, etc., have posed socio-economic risks leading to considerable loss of life as well as agricultural land, food production, private and public properties. Hence, reducing the impact of natural disasters aggravated by human activities is a critical task in preparing the river management plan for the Karnali River. Executing this plan is essential to reducing the threat of flooding. The extent of the flood hazard in the downstream region of the KRB for the various return periods shows that the total hazard area increases as the YRP increases. High-intensity rainfall across the basin leads to flooding associated with high discharge of the KRB. Hydraulic simulations performed for different YRPs show that a rapidly increasing area of fertile land will be inundated as the YRP increases, thereby threatening the food security of the river basin. The downstream community can prepare well by implementing a timely and well-communicated plan with the help of the spatial inundation scenarios simulated by this study.

Regarding the methodology, the HEC-GeoRAS proved to be capable of flood inundation mapping and was very effective for assessing the magnitude of future flood risk in river basins, as demonstrated in the case of the Karnali River in Nepal. After generating the inundation map, the vulnerabilities of different land-use types, settlements and infrastructures were identified, representing the first step towards comprehensive risk mapping. The evacuation maps and safe shelters can be identified and planned by using such inundation/hazard and risk maps. This work has tried to classify the depths of the floods in different locations during the occurrence and severity of its flood hazard presented to the local communities. This research complements the flood mapping approach used by the DHM, and we have tried to investigate in detail the flooding extent at different locations for varying river depths. This study will also help in the resettlement of communities near the river, since we can take advantage of this study to identify the modeled floodplains and vulnerability, which can be disseminated to the local authorities for effective land-use planning.

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Conflicts of Interest: The authors declare no conflict of interest.

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