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FLOOD INUNDATION MAPPING OF BAGMATI RIVER AND IMPACT ASSESSMENT ON BUILDING INFRASTRUCTURES ON TERAI PLAINS OF NEPAL

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Abstract

Starting from the northern hills of Kathmandu Valley, the Bagmati River flows through the Mahabharat and Siwalik ranges and discharges at Padherodovan into the Terai region of Nepal. The river poses a flood hazard in the downstream areas, especially during the monsoon season. This study is about mapping flood inundation in a 2D unsteady flow simulation model using HEC RAS. The study was conducted on ~16 km stretches of the Bagmati River in Bagmati Municipality of Sarlahi district. River discharge values for various return intervals were calculated using instantaneous discharges, and probable floods of 2, 5, 10, 25, 50, and 100-year return periods were simulated for developing flood inundation maps. Flood inundation maps depict varying depths during different return periods, offering insights into the fluctuation of flood depth across the floodplain with increasing discharge. During a 100-year return period flood, which was almost equivalent to the flood of 1993, around 5061 buildings were affected, while during a 5-year return period flood, around 2511 buildings were affected. This study provides essential data for understanding flood patterns, aiding in land use zoning and flood risk mitigation for risk-informed development along the Bagmati River.

***Keywords**: Bagmati river, flood inundation mapping, HEC-RAS, flood depth, flood impact, flood risk assessment, flood management*

1. Introduction

Nepal falls in 11th position on disaster vulnerability worldwide and second highest country at risk of floods in South Asia [1], [2]. Especially during monsoon season, flooding causes loss of lives, property, and livelihood [3]. In Nepal, due to floods alone, 3,329 fatalities have occurred, affecting 3.9 million people and causing an estimated loss of US $5.8 billion between 1971 and 2011 [2]. As half of the population is exposed to four significant hazards, one of them being flood, most (26.47%) of flood incidents have impacted Madhesh Province, causing about 45.14% of national flood-related losses and damages [3]. In Madhesh province, Rautahat and Sarlahi districts have been categorized as high flood hazard districts [4]. In 2017 and 2018, among 16 types of disasters, 15 types of disasters were officially recorded with a total incident count of 6381, the first one being fire (3973), followed by landslide (483), lightning (432), flood (418) and others [5]. In 2023 alone, 156 flood incidents were reported in Nepal, causing 16 fatalities [6]. The flood of 1993 all over Nepal was one of the catastrophic flood disasters that affected 28000 people in mountainous regions and around 42000 people in low-lying areas. Over Nepal, the flood caused 1168 fatalities, 15164 houses were destroyed, 18726 houses were damaged, and 67 irrigation schemes were washed away [7]. In the Sarlahi district alone, there were 497 fatalities, 1363 houses fully damaged, and 1530 houses partially damaged, and the Bagmati irrigation project and its infrastructures were washed away [8].

The problem of floods and their impact are chronic, and the front-liners of climate-induced disasters like floods are those living on the floodplain and having low socioeconomic status. The expansion of urban & semi-urban areas and unplanned developmental activities on flood plains are increasing the vulnerability of people and infrastructure, thereby putting more population and economic investments at risk [9]. The high sediment load of rivers from the hilly and Himalayan region gets deposited or causes siltation in low-lying areas, driving changes in natural slope, river morphology, drainage system, and land-use/land cover, which increases the variability of flood occurrence and cascading effects of flood damage [10]. Although open data related to flood hazards in the region is available, the practice of hazard mapping, evaluation of the impacts, and capability of using the available data are limited and have not been explored by government and non-government bodies in carrying out development activities in the flood plains [11].

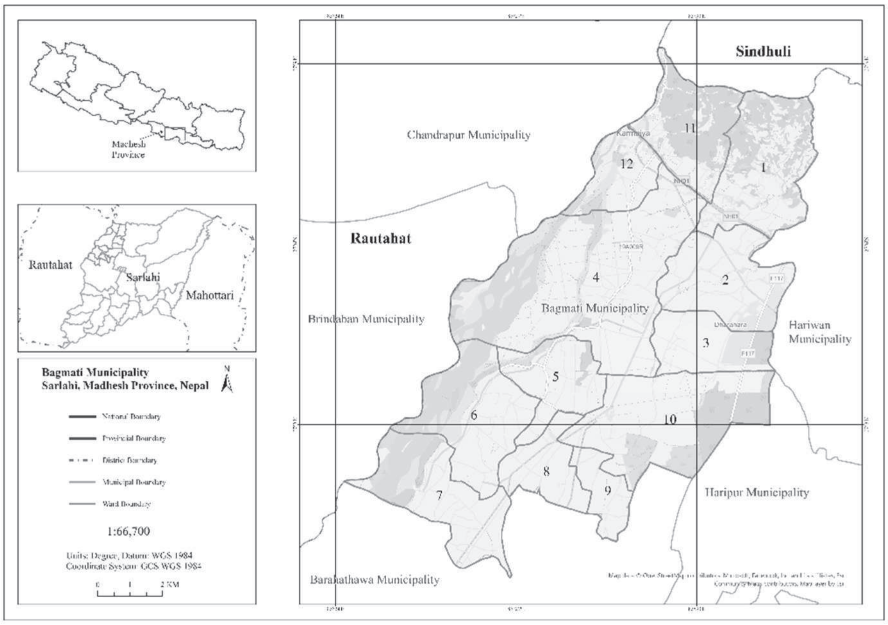


Figure 1: Map showing Bagmati River and ward-wise boundary of Bagmati Municipality

This study is focused on Bagmati Municipality, which lies in the floodplain of the Bagmati River in Nepal. The Bagmati River lies in the central part of the country; it originates at Shivapuri Mountain (Mahabharat Range) in the northern hills of Kathmandu Valley, flows through the Siwalik ranges, and discharges into the Terai plains. The river flows between Sarlahi district and Rautahat district, starting from Padherodovan, near DHM river station 589, until it crosses the Nepal-India border and enters Bihar in India. The altitude of the origin of the Bagmati River is about 2677 meters and is about 93 meters on the Indo-Nepal border [12]. The catchment area of this river at Padherodovan is 2804 sq. km, and at the Nepal-India border is 3750 sq. km [13], [14]. Bagmati Municipality lies on the left bank of the Bagmati River for a stretch of approximately 16 km. Notably, the western segments of wards 11, 12, 4, 5, 6, and 7 are positioned along the banks of the Bagmati River. Regarding topography, certain wards 1 and 11 are located at elevated hill elevations, while the remaining are in the plains.

This study aims to prepare flood inundation maps of Bagmati River using the Hydrologic Engineering Center's River Analysis System (HEC-RAS) simulation and thereby assess the impacts of the flood on land area and building infrastructures identified in Openstreet Map (OSM) in the municipality area. This study can help other researchers and governing bodies understand the extent and impact of floods and propose flood-resilient infrastructures and development practices in the floodplain.

2. Methodology

The methodology of this study is as given below:

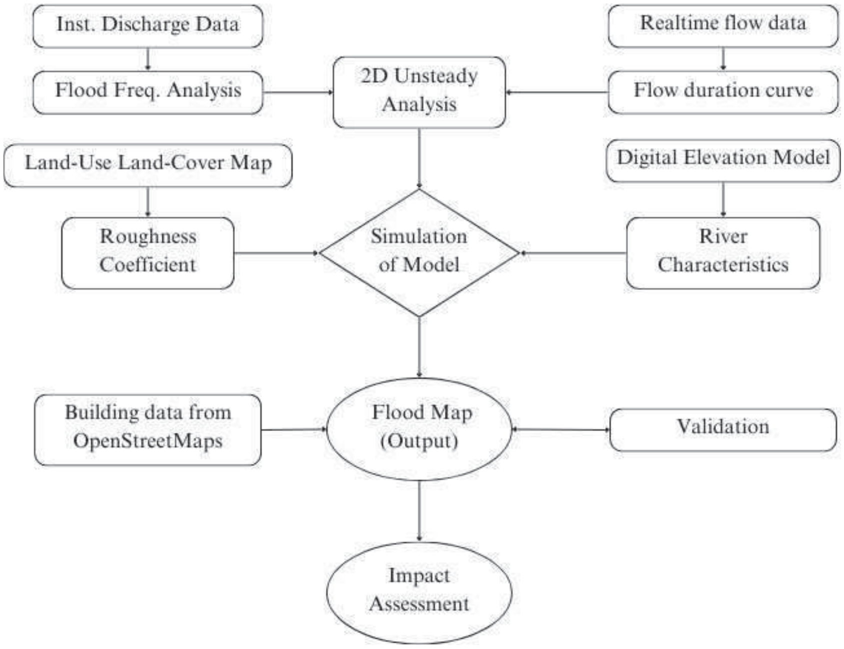


Figure 2: Flowchart of flood inundation mapping for the study

2.1 Flood Frequency Analysis

Among the commonly used distribution techniques for flood frequency analysis, in the case of the Bagmati River, Gumbel distribution was found to be best suited [15]. Hence, Gumbel distribution using instantaneous discharge values (1979-2013) was used to calculate the flood discharge values of different YRPs.

Table 1: Discharge values for different return periods

Flood Return Period (years)	2	5	10	25	50	100
Flood Discharge (m^3/s)	4267.22	6983.08	8781.22	11053.17	12738.64	14411.66

2.2 Flow duration curve

The development methods of flow duration curves include using historical streamflow records, hydrological (rainfall-runoff) models, and flow records from nearby gauging stations [16]. In this study, as the other methods of developing a flow duration curve were not feasible, assuming that the nature of rising and recession limbs for other hydrographs are similar, the real-time flow data of the 1993 flood was converted and used as a flow duration curve for different return periods [17].

2.3 Roughness coefficient

The land use land cover (LULC) indicated the presence of different categories of land use; therefore, the roughness coefficient (Manning's n) was used as mentioned in the flood control and management manual [18]. In case of no data or other categories of land use, the default value of 0.035 was taken as the default, considering them as floodplains with high grass pastures, and was linked with a geometry file [19].

2.4 River Characteristics

This study used digital elevation model (DEM) data of grid size (~5m, ~5m) for flood simulation. The flood plain (potential inundation area) of Sarlahi and Rautahat districts was taken as the 2D flow area with a grid size of 10m by 10m. Boundary conditions are the flow conditions within which the flow channel is defined: Upstream BC and Downstream BC. An upstream boundary condition line was created at Padherodovan River station (station number 589) with flow hydrograph data as input for upstream BC. Regarding downstream boundary conditions, the rating curve at the Dheng Bridge of India was considered [20].

2.5 Model simulation and developing flood map

To properly simulate the unsteady flow (complex and dynamic) situation where flow conditions vary significantly over time, unsteady flow analysis was employed to simulate the inundation mapping [21]. Unsteady flow conditions were set up to represent the flow characteristics of flooding events, and the simulation was carried out in a 2D model. To carry out flood mapping using unsteady flow data, unsteady flow analysis was the next step of the study, which included geometry pre-processor, unsteady flow simulation, post-processor, and flood plain mapping. The simulation was carried out for 24 hours with a computation interval of 1 second & hydrograph output interval of 1 second, and thereby, the max profile of mapping output and detailed outputs were obtained for 2, 5, 10, 25, 50, and 100 years return period [22].

The lack of universally accepted standards for categorizing hazard levels has been observed in flood hazard mapping. The variability in flood hazard classification across different geographic regions often depends on local criteria or expert judgment rather than standardized thresholds [23]. A similar study on the Karnali river basin has categorized flood depth into different hazard levels, and a similar approach has been considered in this study [10].

Table 2: Flood hazard classification based on inundation depth

S. No.	Flood Hazard Type	Depth (m)	Hazard
1.	H0	<1	Very Low
2.	H1	1.0-2.0	Low
3.	H2	2.0-4.0	Moderate
4.	H3	40-6.0	High
5.	H4	>6.0	Very High

2.6 Validation of flood map

Validation of flood inundation maps ensures the accuracy of modeling results by comparing simulated maps with pre-existing data, satellite imagery, historical records, and community-based information. Several studies include comparing historical flood data with simulations in the Philippines and validating community-based flood hazard maps with satellite data in India [24], [25]. In New Zealand, community involvement in flood mapping enhanced resilience and improved map accuracy [26].

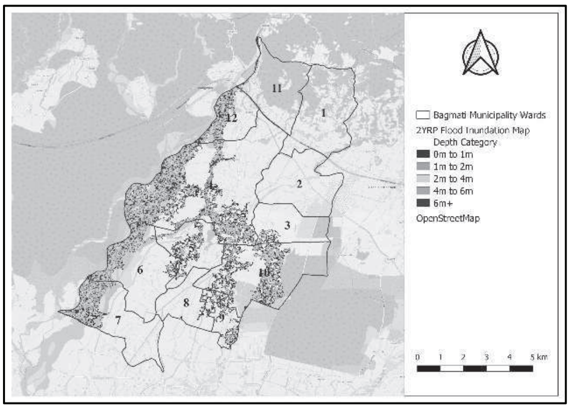
Due to the lack of aerial imagery, documentation, or historical datasets for validation, this study involved comparing simulated flood inundation maps with field data. The 1993 flood (equivalent to a 100-year return period) was used for validation, comparing simulated and observed water levels at several locations along the Bagmati River. Field assessments were conducted at 104 key locations, with 45 affirmative responses on actual flood occurrence in 1993. Among them, 29 matched the simulated inundation map, resulting in a model accuracy of 64.4%.

2.7 Extraction of building data from OSM using QGIS

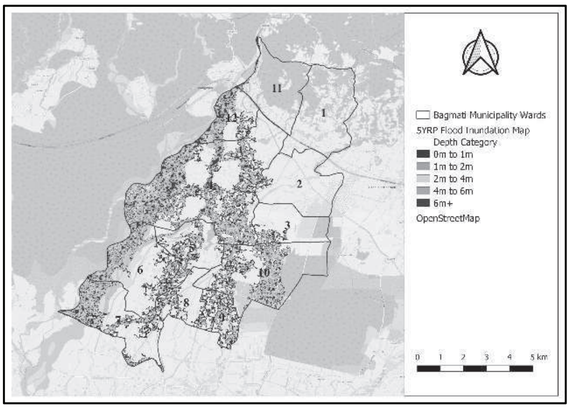
To extract building data from OSM using Quantum Geographic Information System (QGIS), the QuickOSM plugin was used, the 'building' tag was used to specify the data, and the Bagmati Municipality was chosen as the geographic area of interest. After running the query, each data was retrieved from OSM on 2023 July 29. The results were displayed as a new layer in QGIS and then exported as a shape file. The shape files were then converted to point data by extracting the centroid location of building polygons. QGIS plugins were used to review the simulation output from flood mapping and identify the extent of impacted building infrastructures & land area. As depth is considered the significant parameter in defining flood hazard, the impact was assessed based on the inundation depth caused by simulated flood [27].

3. Result and discussion

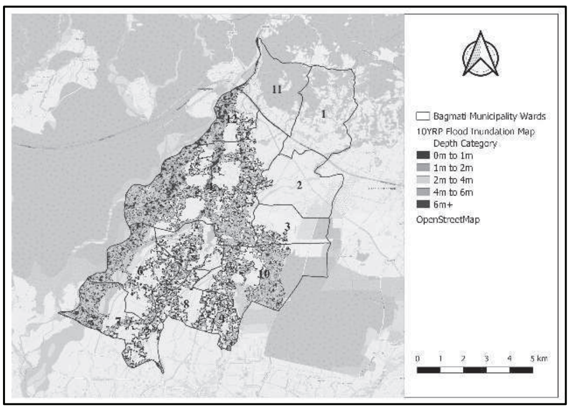
The flood frequency analysis of river discharge using the Gumbel distribution for different return intervals and the HEC-RAS simulation model generated flood inundation maps showing varying depths for 2, 5, 10, 25, 50, and 100 years. Consequently, flood inundation maps were developed for each period. For proper representation of flood hazards, the maps were categorized into different hazard levels and the area inundated under each category was calculated.



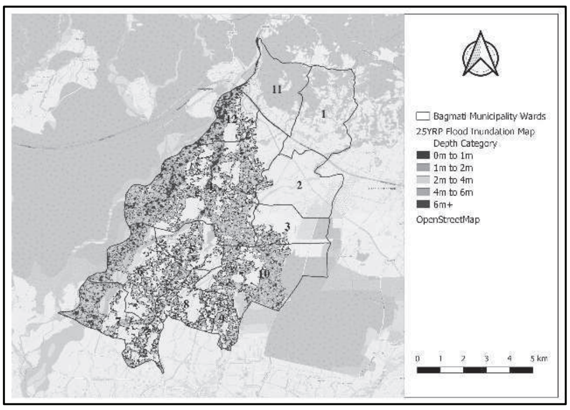
(a) 2 YRP



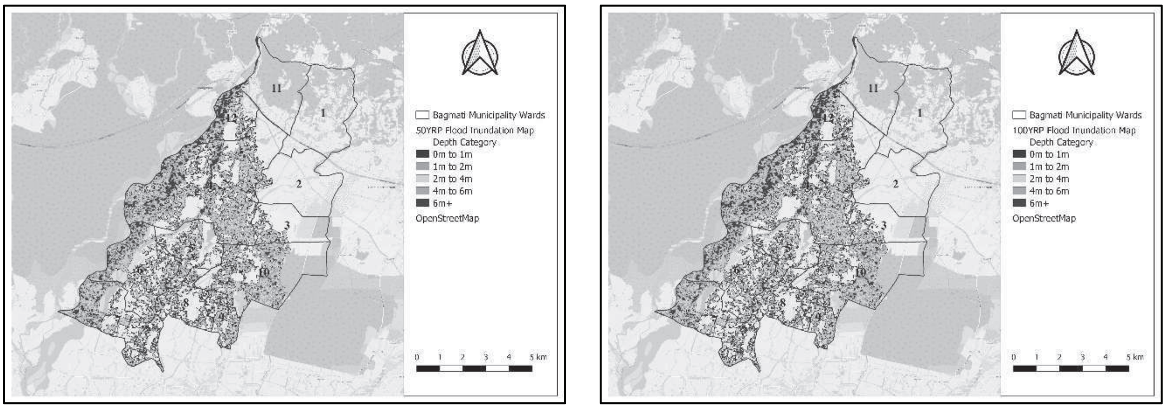
(b) 5 YRP



(c) 10 YRP



(d) 25 YRP



(e) 50 YRP (f) 100 YRP

Figure 3: Flood inundation map of different return periods

The simulation results indicated a significant increase in the area affected by flooding as the flood intensity increased, expanding from 21.42 sq. km. (2 YRP) to 42.22 sq. km. (100 YRP). This trend is consistent with other studies on flood hazard mapping, including the lower Karnali basin [10], flood hazard mapping of the Bagmati river in Kathmandu valley using GIS [28] and the Nepal flood hazard assessment [29]. Inundated areas increased due to higher discharge of water flowing into low-lying regions, particularly in flat terrains that offer minimal resistance to water spread, which poses more significant risks to infrastructure and human safety. Moreover, extreme flood events like that of 1993, which occur less frequently but with higher intensity, encroach on areas previously considered low-risk. The increase in flooding areas, even during more frequent floods, might be the deposition of sediments in the river bed or the construction of new waterways within the region. Although the embankment along the river has been constructed, the area and community on the other side of the embankment are under constant threat.

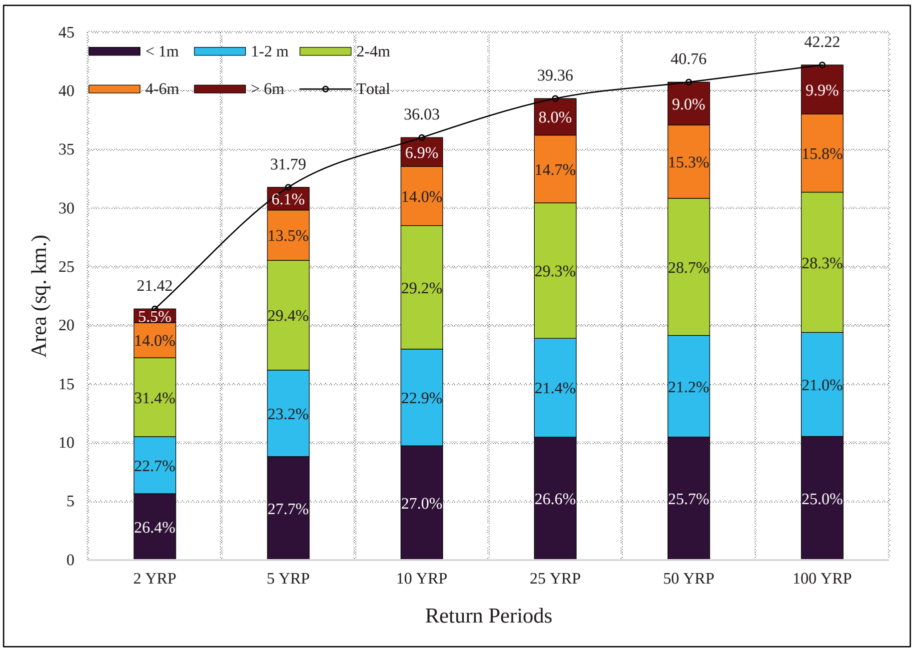


Figure 4: Flooding area according to the classification scheme for inundation water depth for different YRPs

The river channel is filled with floodwaters even during frequent nominal discharges, and the increase in flow within the waterbody is not substantial in this category, confirming that the water flow is mainly confined within the river channel. Specifically, the area of inundation less than 1m (H0) remained relatively stable, increasing slightly from 5.66 sq. km (2 YRP) to 10.54 sq. km (100 YRP), accounting for about 26% of the total inundated area across all return periods. The mapping data also show that lower-depth inundation zones 1 to 2m (H1) maintain a relatively stable area even as flood intensity increases, suggesting that the coverage of new inundation occurs in higher-depth zones. This coverage of new inundation has direct implications for floodplain management, as policies should increasingly focus on protecting or relocating assets in zones that are prone to deeper and more frequent flooding.

The study revealed that most of the flooded areas fall within the 2 to 4m (H2) depth category, as evident in the figure, expanded notably from 6.73 sq. km (2 YRP) to 11.96 sq. km (100 YRP), comprising nearly 28-31% of the total inundated area indicating a trend towards deeper flooding as the intensity increases. Additionally, areas inundated by 4 to 6m (H3) of flood depth increased significantly, from 2.99 sq. km (2 YRP) to 6.66 sq. km (100 YRP), growing from 14% to 15.8% of the total flood-impacted area. Finally, the most severe flooding, exceeding 6 meters in depth (H4), expanded from 1.18 sq. km (2 YRP) to 4.19 sq. km (100 YRP), with its proportion of the total area affected rising from 5.5% to 9.9%.

It has been considered that flood depth is the most critical factor contributing to flood hazards associated with any location, with depths over 2m leading to substantial economic losses and infrastructural damage [30], [31]. The increase in area with >6m flood depth category for a 100-year return period underscores the long-term threat posed by extreme flooding events. However, even floods with depths of 1m can cause severe damage and, therefore, are considered high-risk in the downstream region. Some wards 4, 10, and 12 areas were inundated even during the 2 YRP flood, which is a "nominal" flood scenario, indicating a critical situation in those areas. The extreme flood 1993 was similar to the 100 YRP flood simulation, not just in terms of discharge but also in terms of damage and loss, aligning with the damage incurred in the mentioned wards.

Table 3: Number of buildings in different hazard categories for different YRP floods

Flood depth category	2 YRP	5 YRP	10 YRP	25 YRP	50 YRP	100 YRP
H0 (less than 1m)	716	1314	1705	2038	2176	2295
H1 (1m to 2m)	378	750	1015	1266	1429	1546
H2 (2m to 4m)	153	391	543	758	940	1063
H3 (4m to 6m)	18	53	57	88	113	132
H4 (more than 6m)	0	3	10	14	16	25
Total	1265	2511	3330	4164	4674	5061

The study area is predominantly occupied by residential buildings, with a sparse distribution of approximately 90 households per square kilometer [32]. The area of inundation of residential land and the number of affected households increased progressively from 2 YRP to 100 YRP. Of 16,167 building structures within the study area, 31.30% were in flood hazard locations in 100 YRP flood scenarios.

On the assumption that the building structures have been constructed with a nominal plinth level of 0.45 meters [33], the analysis shows that the population located on the banks of the Bagmati River and in low-lying areas is in hazardous conditions during probable floods. The floodwaters flow through wards 11, 12, 4, 6, 7, and 10, even during a 5 YRP flood, which are densely populated areas and are therefore designated as high flood hazard areas. As the flood discharge increases in the upstream region, the water level reaches approximately 14 meters in the river channel, affecting around 2,800 households and 12,500 people.

4. Conclusions

The study utilized the HEC-RAS 2D model to simulate flood scenarios in the Bagmati River, explicitly focusing on Bagmati Municipality in Sarlahi district. Flood inundation maps were developed for various return periods (2 to 100 years), emphasizing flood depth as the primary hazard factor. The results show significant risks to both agricultural and residential areas, with even a 25-year return period flood affecting around 40% of the area and 26% of building structures. These findings underscore the region's vulnerability to potential floods, especially in densely populated areas.

This research highlights the urgent need for long-term flood risk management strategies, particularly for safeguarding agricultural production and residential infrastructure. Integrating scientific modelling and strategic planning is essential to enhance community resilience. The study provides a foundation for informed decision-making in flood risk management while recommending further research and flood adaptation measures to mitigate the escalating flood risks in the area.

5. Suggestions and recommendations

The overview of flood mapping and its impact on building infrastructures suggests the increasing extent of inundation, particularly in agricultural and residential land-use categories, highlighting the urgency for implementation of land-use zoning/planning for mitigating the impacts of flood following flood control and management manual developed by Water and Energy Commission Secretariat. Flood plain zoning, one of the basic non-structural measures for flood plain management, prevails over other methods like installation of EWS, risk communication, risk insurance, and other structural measures. By discouraging settlement in high-risk zones, preventing inappropriate development of public and private infrastructures, and managing land use to minimize overall risk, floodplain zoning aims to curtail the potential devastation caused by floods, followed by developing land use planning policy.

The suitable locations of safe shelters and emergency evacuation routes in case of flood can be identified and planned with the help of these kinds of inundation maps and combining the vulnerability of those locations. This study aims to categorize the flood hazard level based on inundation depth and presents the need for risk-informed decision-making in development practices in the locality. This study also complements the flood mapping and validation approach by combining the scientific results and field observation used in similar research and studies by governmental and non-governmental development agencies. Household-level data collection is necessary to assess the vulnerability to floods and disasters. Further studies on risk assessment for flood or even multi-hazard scenarios can be carried out based on this study.

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