

FLOOD HAZARD MAPPING AND FLOOD VULNERABILITY ANALYSIS OF BUILDING STRUCTURES AT SETTLEMENT - SCALE

Suraj Lamichhane¹, Nirajan Devkota¹*, Hari Prasad Poudel¹, Somnath Luitel¹

¹ Department of Civil Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University

Abstract

This research investigates flood hazards and vulnerabilities in Sauraha region of Nepal, employing a multidisciplinary methodology. Hydrological studies, field surveys, and hydraulic modeling were conducted to assess historical floods, estimate flood discharges, and analyze building vulnerabilities. Findings indicate that major tributaries substantially contribute to flood flow, with the East Rapti River posing a significant risk. Gumbel's distribution and Log Pearson's III distribution provided anticipated flood discharges for various return periods, illuminating the severity of potential inundation. Hydraulic simulations forecasted extensive inundation during a 100-year return flood, especially along the riverbanks, impacting commercial structures and tourist attractions. Vulnerability assessments revealed that 75% of riverside buildings face extreme vulnerability during such events. Urgent flood protection initiatives, including mandating flood-resilient building designs and preserving natural drainage systems, are imperative. The study identifies limitations, suggesting detailed assessments and sophisticated modeling for comprehensive flood mitigation strategies. Overall, this study underscores the immediate need for targeted interventions to address the persistent and complex flood dynamics in Sauraha.

Keywords: Flood hazard mapping, Vulnerability assessment, Hydraulic modeling, Sauraha region, Flood resilience

1. Introduction

Extreme weather conditions, particularly intense precipitation, significantly elevate the likelihood of catastrophic events like floods, leading to substantial risks and repercussions (McPhillips et al., 2018; Zhang et al., 2012; Zhao et al., 2019). These floods occur when rivers exceed critical flow thresholds, breaching banks and overwhelming existing flood control measures due to erratic precipitation patterns (Dulal et al., 2007). The absence of robust development plans, land use changes, poorly planned infrastructure in floodplains, and river obstructions markedly escalate the vulnerability to flooding, leading to significant global loss of lives and property annually.

Nepal, a region profoundly affected by these calamities, has endured recurrent and devastating floods, result-

ing in human fatalities and infrastructure damages over the past decades (Dhakal, 2015; Shrestha et al., 2021). Notable incidents such as the 1993 flood, the 2008 Koshi River flood, and the 2017 water flood underscore the severity of these events, especially in densely populated areas and agricultural lands. Such occurrences consistently reveal the most significant losses along riverbanks, exemplified by events like the 1993 and 2017 floods in Nepal, where extensive damage was concentrated near waterways (Gautam and Dong, 2018; Ministry of Home Affairs and (DPNet-Nepal), 2009).

However, despite various studies documenting these events, there remains a considerable gap in understanding and mitigating the impact of flooding in specific regions, notably in Sauraha. This study endeavors to fill this critical void by focusing specifically on the Sauraha region, where recurrent flooding has inflicted substantial losses and damages. The novelty and significance of this research lie in its focused approach toward mapping flood hazards and analyzing vulnerability uniquely in the context of geographical and socio-economic characteristics of Sauraha.

*Corresponding author: Nirajan Devkota
Affiliation: Department of Civil Engineering, Pulchowk Campus,
Institute of Engineering, Tribhuvan University
Email: 078phce112.nirajan@pcampus.edu.np
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The vulnerability to flooding of Sauraha is multi-faceted, owing to its geographical proximity to river basins, rapid changes in land use within short periods, and the lack of comprehensive studies addressing flood hazard mapping and vulnerability assessment in this specific locale. Therefore, the primary objective of this research is to generate detailed flood hazard maps and conduct a comprehensive analysis of flood vulnerability specific to Sauraha. Understanding the intricacies of flooding in this region is crucial for developing effective mitigation strategies, enhancing emergency response mechanisms, and formulating tailored preventive measures to alleviate the unique challenges faced in Sauraha.

2. Material and Methods

2.1. Study area

Sauraha, situated on the fringes of Chitwan district in Nepal, is a bustling hub adjacent to the renowned Chitwan National Park. This locale, depicted in Figure 1, has garnered widespread acclaim as a favored destination among tourists. Its picturesque setting along the East Rapti river, however, faces recurrent challenges posed by flooding, resulting in considerable property damage. These floods emanate from the East Rapti river, obstructing local drainage systems and submerging the adjacent area, including its tributaries - Dhungre Khola and Budi Rapti.

The climate in Sauraha embodies subtropical traits, characterized by a pronounced summer monsoon from mid-June to late September, succeeded by a comparatively drier winter. Approximately 80 percent of the annual rainfall cascades down during the monsoon, aligning with the defining monsoonal pattern observed across the Indian Subcontinent. This distinctive weather pattern triggers substantial floods and alterations in river pathways. Notably, the influence of the northern mountain ranges imparts an orographic effect on this region, amplifying rainfall compared to other locales in the country. The Department of Hydrology and Meteorology (DHM) has diligently recorded precipitation data, indicating that the average annual rainfall in this study area is 1915 mm. Sauraha experiences warm summer temperatures, peaking at an average of 34°C in May, while winter ushers in a mix of warm and cold spells, with minimum temperatures dropping to 7°C in January. The unique environmental landscape of Sauraha is molded by the various climatic nuances present in the region.

2.2. Methodology

To meet the outlined objectives, a cross-disciplinary approach was adopted, focusing on the designated pilot study area. A survey of approximately 2 km² was conducted to assess the built environment. Additionally, hydraulic modeling encompassing the two key rivers, namely the East

Rapti and Dhungre Khola, was undertaken. The sequential methodology is delineated in Figure 2.

Concurrent with hydraulic modeling, vulnerability assessments of infrastructure and structures were conducted. The Department of Hydrology and Meteorology (DHM) supplied topographic data used to generate a digital elevation model (DEM) through Kriging's interpolation method. Hydraulic simulations were executed using HEC-RAS and HEC-GeoRAS models. Scenario modeling and mapping considered at least four return periods, including a 100-year interval. Zoning procedures involved a continuous interval scale for flood inundation levels to construct flood inundation maps.

Data on individual buildings and infrastructure within the study area were collected, utilizing GPS surveys for spatial information acquisition. Subsequently, vulnerability functions (depth-damage curves) were developed through empirical and analytical formulations. The empirical models, following Gautam and Dong's methodology from 2018, were chosen for their higher accuracy. Calibration of depth-damage models utilized available data and expert opinions to construct representative models aligned with local construction practices. Comparative analysis between hazard maps and vulnerability levels for buildings facilitated delineating performance levels during varying inundation levels.

GIS mapping was instrumental in visualizing flood inundation maps, lifeline vulnerability assessments, and evacuation planning maps.

2.2.1 Inventory of the river and flood plain area

Throughout the field investigation, an extensive on-site inspection was carried out on the eastern side of the East Rapti River and within the center of Sauraha Bazar in order to evaluate the regions affected by the flooding of the river and nearby streams. The survey aimed to identify key areas affected by flooding and evaluate existing structural measures. Detailed documentation of existing structural conditions, including assessments of buildings' structural health and potential restoration needs, was carried out. Utilizing GPS tracking systems facilitated a thorough inventory of the surveyed areas.

Additionally, the research involved a comprehensive analysis of the morphological features of the river. Detailed assessments and reports were conducted on the morphology of river, identifying areas at risk of erosion and potential flood hazards along its course.

2.2.2 Detailed physical survey (DRONE survey)

The entire Sauraha area, along with the East Rapti River and its surrounding tributaries, underwent a thorough topographic survey. Employing Dynamic Remotely Operated

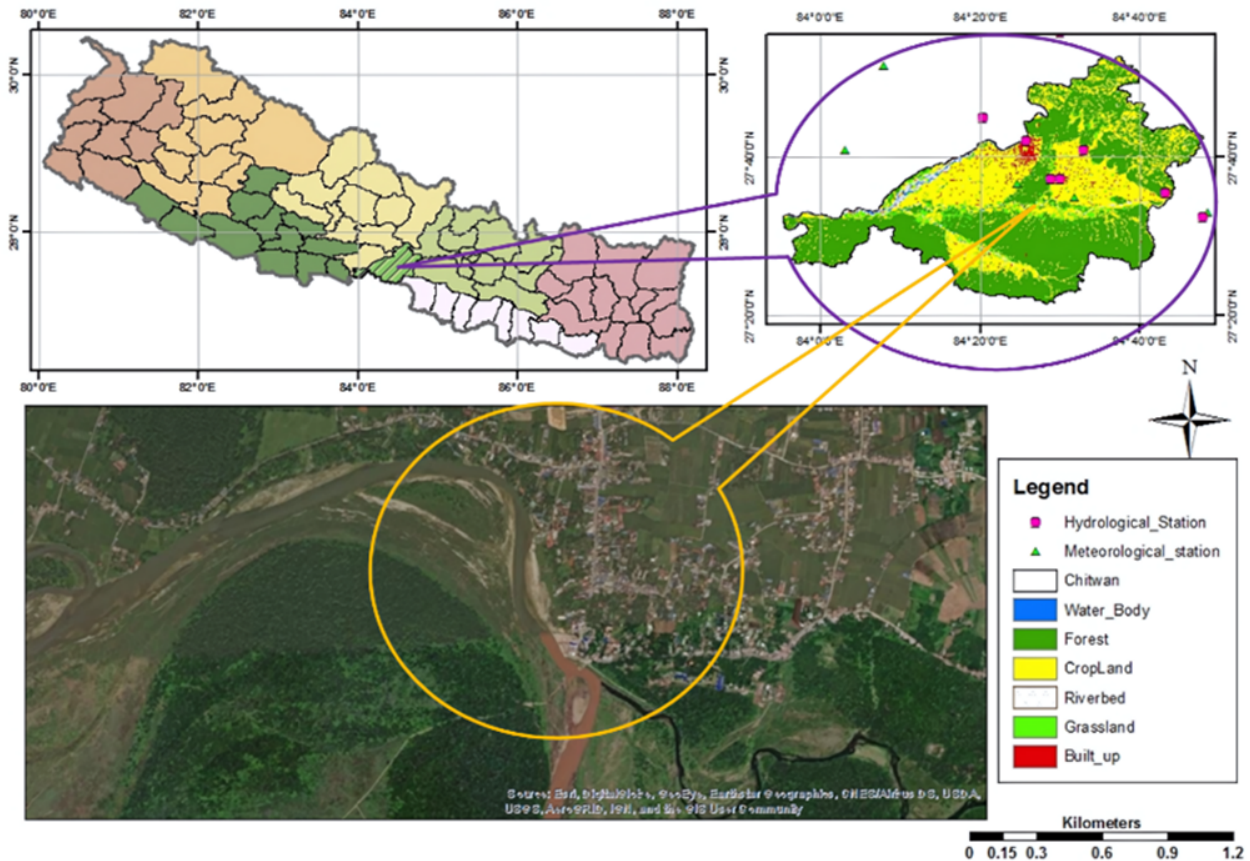


Figure 1. Location map of the study area

Navigation Equipment (DRONE) facilitated the terrain survey, ensuring precise and detailed mapping of the area. The survey coordinates were assigned utilizing benchmarks established from either the DGPS survey within the area or the national trigonometric points established by the survey department, leveraging available data for accurate geospatial referencing. The DRONE survey methodically charted numerous specific characteristics along the river's edge, encompassing private land, current pathways, waterways, and defensive constructions like embankments, spurs, gabion walls, and other relevant structures.

2.2.3 Hydrological study

The primary focus of the hydrological study revolved around estimating the designed flood discharge for the East Rapti River and its principal tributaries within the study area. To facilitate this assessment, hydrological and meteorological data were sourced from the Department of Hydrology and Meteorology (DHM), supplemented by field observations and consultations with the local community. Detailed analysis of the catchment area and its general characteristics for the East Rapti River and its major tributaries upstream of Sauraha Bazar, encompassing Dhungre, Lothar, and Manahari, was conducted using Google Earth images and topographic sheets. These resources provided crucial insights into the catchment's geographical features and enabled a comprehensive understanding of the area's hydrological dynamics.

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2.2.4 Flood frequency analysis

Flood frequency analysis serves as a direct predictor for the peak discharge of a specified frequency by utilizing runoff (streamflow) data. This method proves most effective in estimating flood magnitudes for return periods shorter than the observable record, where interpolation techniques can be applied. When forecasting flood flows for extended return periods necessitates record extrapolation, caution is exercised, limiting extrapolation to a maximum of twice the duration of the available record to ensure accuracy (Zhou et al., 2008). In Nepal, only a handful of locations boast streamflow records spanning 30 years, often containing limited instances of flood occurrences. For estimating flood

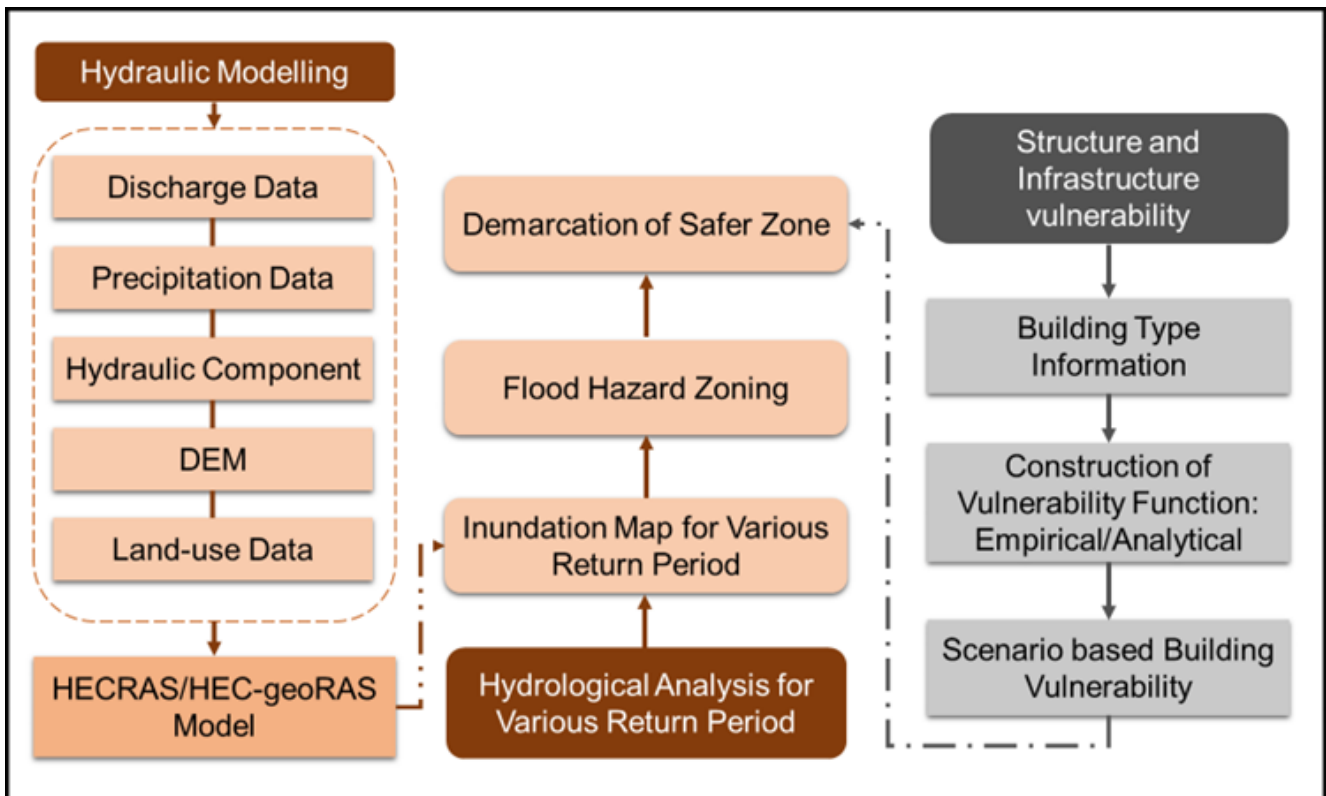


Figure 2. Flowchart of methodology

discharge with higher return year frequencies, preference is given to yearly flood series spanning over 25 years. Notably, the Rajaiya station (East Rapti) stands out with an extensive data series spanning more than 50 years, enabling the application of statistical procedures such as Gumbel's distribution method. This extended record offers a more robust foundation for precise estimations of flood characteristics, enhancing the accuracy of flood frequency assessments.

2.2.5 Flood modeling

The simulation of flood flow utilized the HECRAS (Hydrologic Engineering Centre River Analysis System) software, incorporating two-dimensional steady flow water surface profile computation. HECRAS stands as a widely adopted hydraulic modeling software renowned for its user-friendly interface and robust tools, particularly for one-dimensional hydraulic calculations in various networks of natural and constructed channels. For optimal outcomes, the accuracy and sufficiency of input data are paramount. The model predominantly utilized Geometric Data and Hydraulic Data as its primary inputs. The river network information was carefully geo-referenced, integrating data obtained from field surveys to guarantee accuracy. Notably, the East Rapti River in Sauraha receives substantial water inflow from

Dhungre Khola, which joins from the right bank slightly upstream of the primary village. Further, multiple small drainages merging into the river within Sauraha were identified, their confluence points precisely marked and integrated into the HECRAS river network data.

Table 1 shows the junction assigned to the HECRAS river network. Associated flow data at each junction were assigned.

The selection of the Manning's n value for the hydraulic model is crucial for both model stability and achieving accurate output results. Manning's n values that are too low can result in shallower water depths, elevated velocities, and potentially induce supercritical flows. This concern is particularly pronounced in steep streams where velocities are inherently high. To address this, Manning's n values were thoroughly cross-referenced with both observed surface types and the recommended values proposed by (Marcus et al., 1992) to ensure the assignment of reasonable and appropriate values.

3. Result and Discussion

3.1. Flood flow analysis

The assessment of flood flow along the East Rapti River and its principal tributaries followed standardized method-

Table 1. River network and junction detail

SN	River	Reach	Junction
1	East Rapti	Sauraha	Dhungre Khola
2	East Rapti	Sauraha	Budhi Rapti
3	East Rapti	Local drain	Local drain just d/s of settlement

Table 2. Flood discharge at Rajaiya (East Rapti) for a different return period

Method	Return Period (Yr) (flow in m^3/s)						
	2	5	10	25	50	100	200
Gumbel	1290	1800	2140	2570	2890	3210	3520
Log Pearson III	586	985	1270	1647	1935	2227	2524

ologies. Flow contributions from the Manahari, Lothar, and Dhungre Khola identified as the three major right tributaries significantly influence the overall flood flow within the river at Sauraha. The estimation of flood discharge of Rapti River relied on time series flood data obtained from the Rajaiya gauging station (Station no. 460, Catchment area 579 sq km), spanning a period of fifty-three years since 1963, crucial for the comprehensive flood study. Table 2 presents the anticipated flood discharge for various return periods derived from the analysis using Gumbel's distribution and Log Pearson's III distribution.

Similarly, the flood discharge calculations for the gauged major tributaries (Manohari and Lothar) followed the same methodology. However, for the ungauged tributaries (Dhungre and Budi Rapti), estimations were generated utilizing catchment ratio and various empirical methods.

Table 3 below provides a summary of the estimated flood discharge at several locations for 50 and 100 years return periods. Additionally, Figure 3 depicts a schematic plan illustrating the network of the East Rapti River and its major tributaries, central to this study. Several research investigations carried out on rivers in Nepal, utilizing comprehensive historical data, have demonstrated that the Gumbel method provides more valuable insights in comparison to alternative approaches. (Sharma et al., 2018; B. Thapa and Shrestha, 2020). The Gumbel method's effectiveness in modeling extreme hydrological events, such as floods, by focusing on the distribution of maximum values of datasets, makes it a more reliable approach for providing comprehensive information for such analyses. This reliability is particularly suitable for regions with significant climatic variability (Dahal and Hazarika, 2019; Karmacharya et al., 2016).

3.2. Flood mapping output

A 1D steady flow simulation using HEC-RAS was conducted for the East Rapti River. The gathered geometry data from field surveys encompassed essential elements such as river cross-sections, bank lines, flow paths, and flow directions. Hydraulic input data comprised flood profiles for return periods of 2, 5, 10, 25, 50, and 100 years.

During the 100-year return period, extensive inundation was observed across the area, with settlements experiencing an average depth of 1 meter. The backwater effect stemming from the low-sloping tributary of the river triggered subsequent inundation within the settlement area. Notably, the peripheral indigenous and marginalized settlements surrounding the core market—comprising mud, wattle, and daub houses—were notably more vulnerable than the core commercial area as in Figure 4.

Figure 4a and 4b portray the flood inundation maps corresponding to return periods of 25, and 50 years, providing visual representations of the extent of inundation.

3.3. Flood vulnerability curves for existing building types

The study area predominantly features three primary building types. An inclusive classification method, established through field investigations, delineates the existing structures into three categories: residential buildings, commercial establishments, and wattle and daub houses.

Residential structures predominantly consist of reinforced concrete, while all identified commercial buildings are also constructed using reinforced concrete. Wattle and daub constructions, commonly found in residential areas, small shop outlets, and other non-building structures, were also identified. Vulnerability functions were applied to these three structure types to assess their vulnerability at the building scale during flood events.

Figure 5 illustrates the vulnerability curve for residential buildings. Complete collapse or dysfunction of residential structures is projected at an inundation depth of 6 meters. Substantial damage, around 50%, is expected at just 1 meter of inundation. Notably, while the curve accounts for average damage in Asian buildings, the endorsement of earthquake-resistant construction systems in major urban areas of Nepal might slightly overestimate damage. Nevertheless, the potential for damage cannot be disregarded. Similarly, the vulnerability curve for commercial buildings, including hotels, restaurants, and other commercial spaces, indicates that 50% damage can occur at depths before reach-

Table 3. Summary of estimated flood discharge

River	Location	Catchment area (km^2)	50 yr flood discharge (cumecs)	100 yr flood discharge (cumecs)
East Rapti	Start Point, Hetauda - 1	447	2231	2478
East Rapti	Rajaiya, Hetauda	579	2890	3210
Manahari	Manahari	427	1270	1390
East Rapti	After Manahari confluence	1216	5028	5560
Lothar	Lothar	169	710	780
East Rapti	After Lothar confluence	1510	6256	6912
Dhungre	Sauraha	106	313	359
East Rapti	After Dhungre confluence	1866	7585	8397
Budhi Rapti	Sauraha	230	621	713
East Rapti	After Budhi Rapti confluence	2096	8206	9110



Figure 3. Schematic of the major river system considered for design purpose

ing 1 meter, with complete collapse anticipated at 6 meters. Due to non-building items, the damage factor for commercial buildings surpasses that of residential ones due to the absence of specific construction regulations.

The vulnerability function for traditional wattle and daub constructions indicates complete damage at a depth of 1.7 meters, with 50% damage anticipated at 1 meter depth.

3.4. Vulnerability Classification

Qualitative assessment of vulnerability plays a pivotal role in guiding decision-making processes. In line with this objective, a score-based vulnerability assessment was implemented, encompassing various buildings within the neighborhood. Table 4 illustrates the adopted scheme for this assessment. Previous research has shown that such evaluations frequently combine multi-criteria decision-making frameworks with geospatial methodologies to effectively assess flood risks and vulnerabilities (de Brito and Evers, 2016; Nasiri et al., 2016). Flood maps were carefully constructed to represent the 100-year flood discharge in both the East Rapti and Dhungre Khola rivers.

Additionally, flood depth rasters for return periods of 2, 5, 10, 25, 50, and 100 years were prepared. Research has

highlighted the significance of flood depth rasters in evaluating the scale of inundation and potential damage associated with different return periods (Hoque et al., 2019). Subsequently, a vulnerability map was generated based on the flood depth raster corresponding to the 100-year return period. Figure 6 and Figure 7 showcase these Vulnerability maps, utilizing a color-coded scale to denote the scale of damage, with green indicating very low vulnerability and red representing very high vulnerability. The vulnerability classification of existing building structures is summarized in the table below. Notably, 75% of the total flooded buildings were categorized as falling within the very high-risk category for flood vulnerability. Table 4 encapsulates the vulnerability assessment of the existing building structures in Sauraha concerning the 100-year return flood in the East Rapti River.

4. Conclusion

The prevailing flood threat often denotes a 100-year return period. Alarmingly, 75% of the current buildings lining the riverside exhibit an extreme vulnerability to floods within this 100-year return period. Most structures along these riverbanks serve commercial purposes, operating as

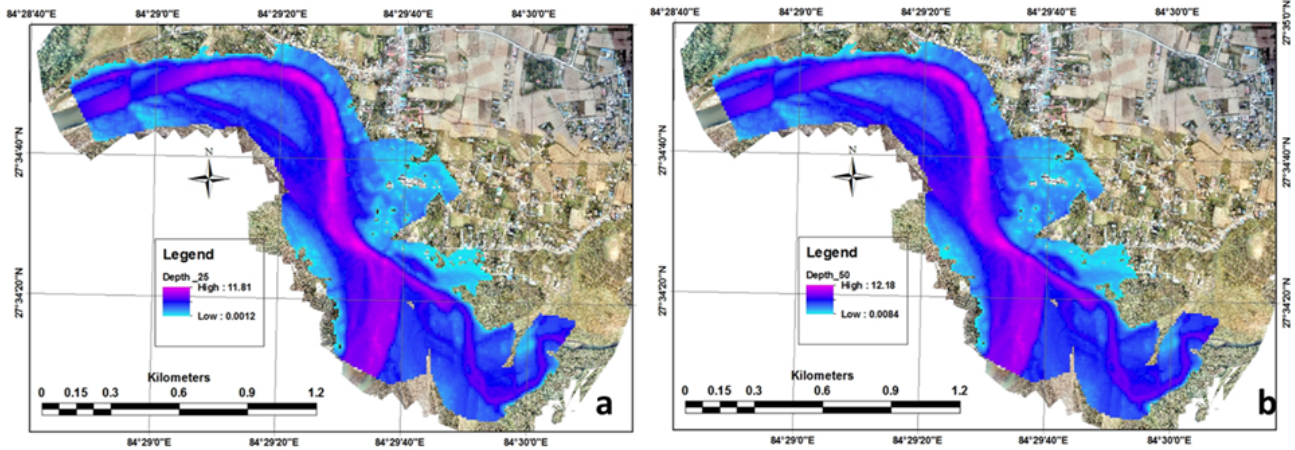


Figure 4. Flood vulnerability map with depth raster a) for 25 years flood; b) for 50 years flood

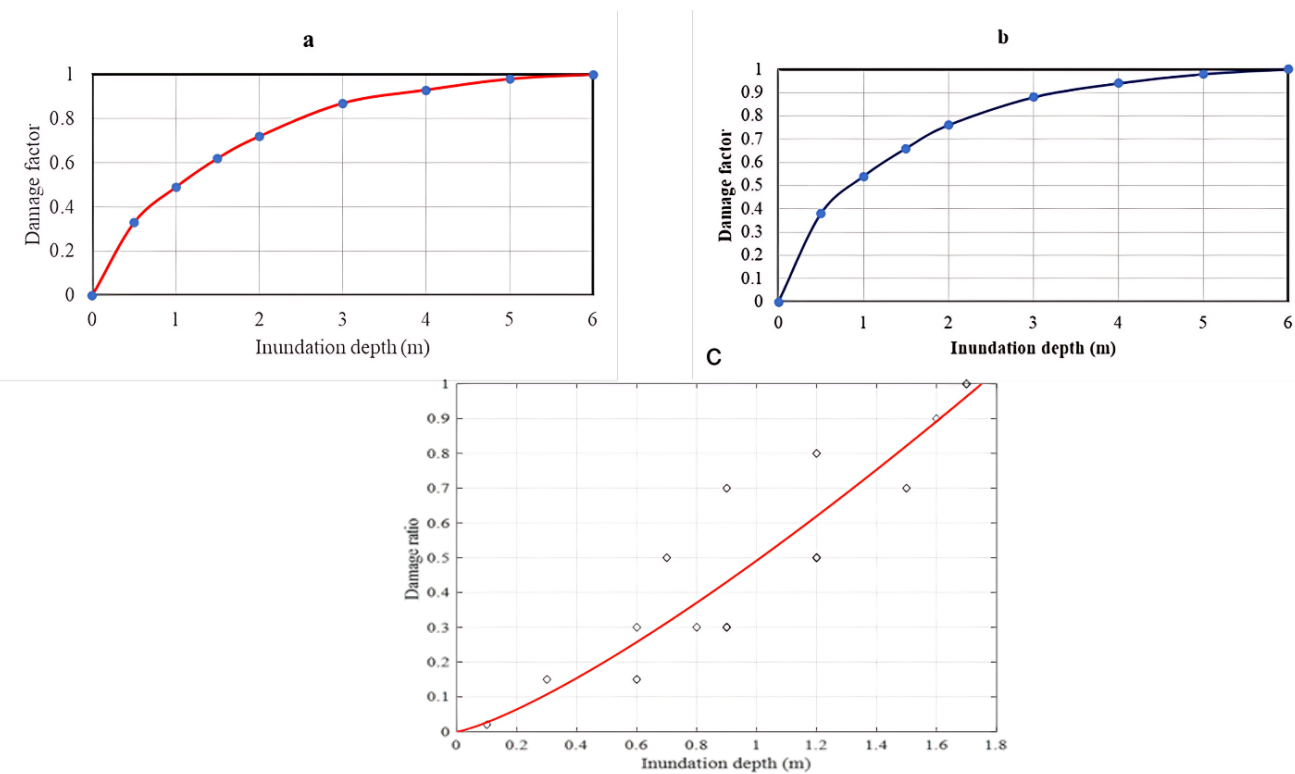


Figure 5. Vulnerability function (depth-damage curve) for residential buildings (after Huizinga et al., 2017) (a), commercial buildings (after Huizinga et al., 2017) (b) and wattle and daub houses at Sauraha (after S. Thapa et al., 2020)

hotels, restaurants, or businesses. Any loss of functionality in these buildings not only impacts their physical structures but also disrupts materials and services, significantly affecting the tourist attractions of that area. Urgent initiatives are imperative to safeguard these structures and economic activities, especially along the riverbank. Even well-designed structures are expected to endure substantial losses and damages. Therefore, mandating flood resilience

in building designs, particularly in coastal areas, is crucial to ensure structural integrity despite potential functionality losses.

Implementing robust hydraulic protections can significantly mitigate flood risks in coastal regions. However, it's crucial to preserve the natural drainage systems within the neighborhood. The depletion or extinction of these systems prolongs inundation, exacerbating functionality loss. Revi-

Table 4. Classification of building structures according to the vulnerability of 100 years return flood

Vulnerability class	Damage ratio	Number of buildings	Weightage of total buildings
Very low Vulnerability	<0.05	6	2%
Low vulnerability	0.05-0.2	21	8%
Moderate vulnerability	0.2-0.4	23	8%
High vulnerability	0.4-0.6	21	8%
Very high vulnerability	>0.6	209	75%

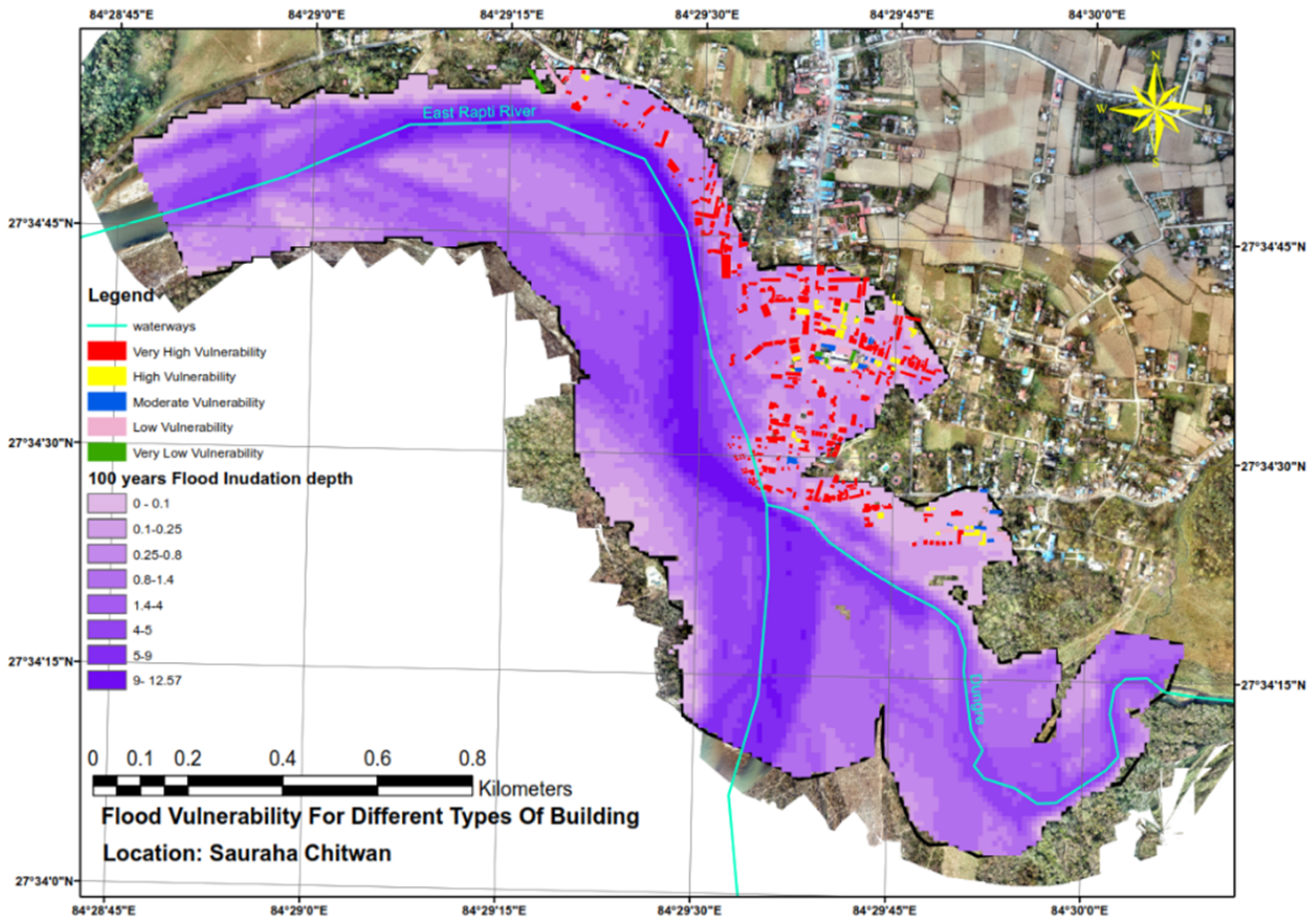


Figure 6. Flood Vulnerability map with depth raster for 100 year flood

talizing natural drainage systems and delineating construction sites while preserving these drainage systems would serve as an ideal strategy to safeguard the neighborhood.

While this research simplifies the complex dynamics of floods, there's ample room for enhancement. Upgrading flood models, extending analyses, and enhancing catchment characterization would bolster the reliability of assessments. Detailed assessments and aerial surveys, along with periodic discharge measurements and the development of catchment-scale rating curves, could substantially improve outcomes. Deploying analytical flood vulnerability models

could also enhance results significantly. The research conducted quantified the magnitude of flood risk and levels of vulnerability, highlighting the ongoing severity caused by complex flood dynamics in the commercial area of Sauraha. This study represents an essential initial phase in addressing the issue. The implications of this study can pave the way for designing flood protection structures. However, a comprehensive assessment, encompassing sophisticated hydrological, hydraulic, and structural modeling and analysis, is urgently required. Thus, the findings of this study should be seen as a starting point, prompting further detailed assess-

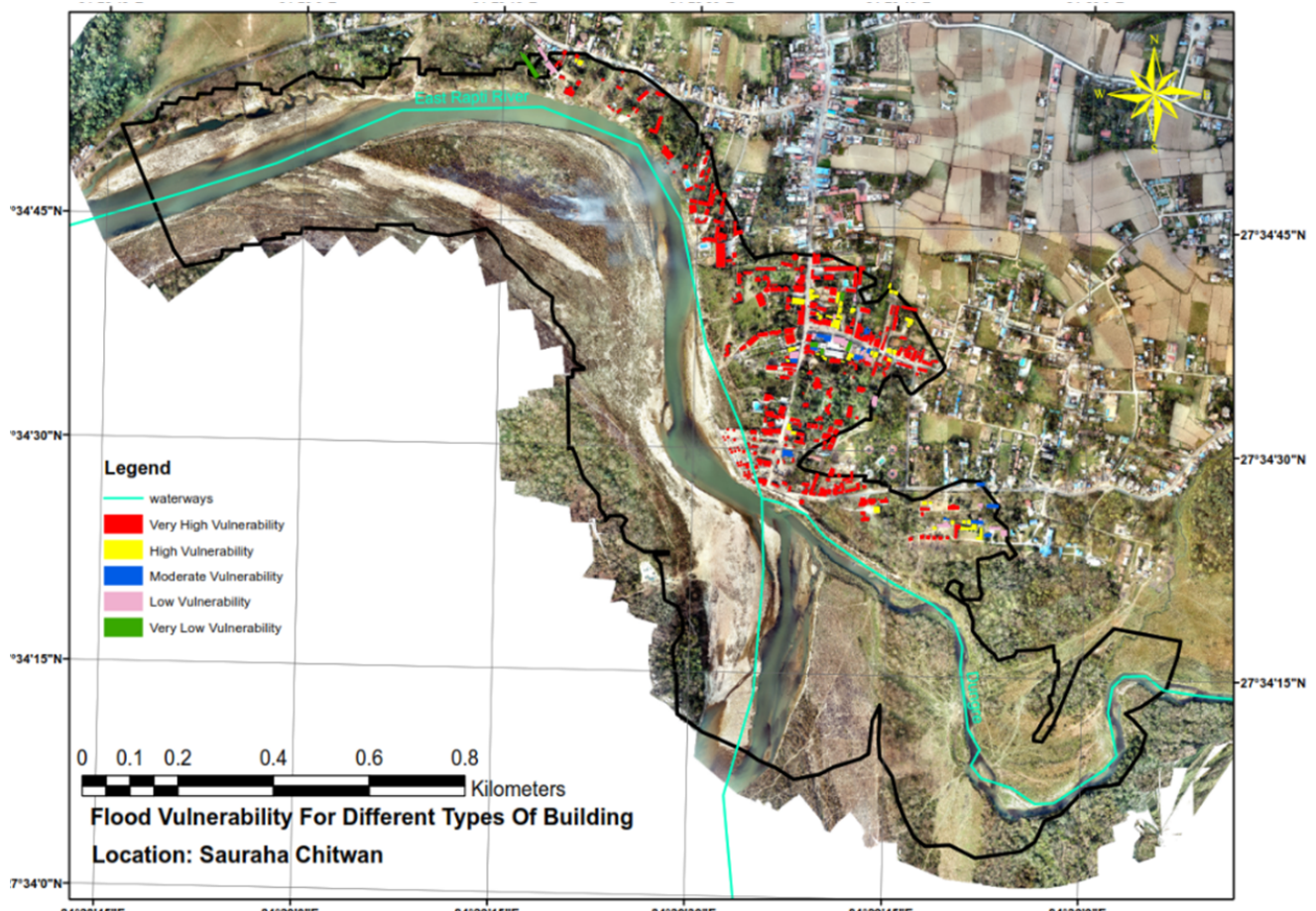


Figure 7. Flood vulnerability map – Sauraha for 100-year flood

ments and strategic interventions.

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