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Research Article

Flood Risk Assessment of the Ladara River, Chitwan, Nepal Using Hydrodynamic Model (HEC-RAS)

Manash Osti[1], Surath Ghimire[2], Rijan Bhakta Kayastha[3]

[1]Research Assistant, Department of Environmental Science and Engineering, Kathmandu University, Dhulikhel, Nepal
[2]Research Assistant, Webster University, St. Louis, USA
[3] Professor, Department of Environmental Science and Engineering, Kathmandu University, Dhulikhel, Nepal
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I N F O

Corresponding Author:
Surath Ghimire, Webster University, St. Louis, USA
E-mail Id:
surathghimire101@gmail.com
Orcid Id:
https://orcid.org/ 0009-0009-8839-8140
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A B S T R A C T

Objective: This study aims to assess flood risks in the Ladara River watershed in Chitwan, Nepal, utilising hydrodynamic modelling to estimate flood extent and depth across different return periods.

Methods: The study employs HEC RAS software to model flood scenarios and analyse the peak discharge of the Ladara River for 2, 10, 20, 50, and 100-year return periods. Peak discharge estimates are derived using the WECS/DHM method and Modified Dicken's method, with comparisons made to the Sharma and Adhikari (2004) method.

Results: Findings indicate that the Ladara River watershed is susceptible to flooding, with significant inundation areas identified for various return periods. Vulnerability varies by land use, with agricultural lands and settlements facing the highest flood risks. The peak discharge estimates from the Sharma and Adhikari method were found to be greater than those from the other methods. Vulnerability varies by land use, with agricultural lands and settlements facing the highest flood risks.

Limitations: The accuracy of the flood risk assessment is constrained by the absence of a hydrological station in the river and the inadequate resolution of available data.

Conclusion: Flood hazard maps are identified as critical tools for public awareness, although they cannot prevent floods. The study advocates for further research to acquire high-resolution data to enhance flood risk assessments and inform effective flood management strategies.

Keywords: HEC RAS Software, Modified Dicken's Method, Hydrodynamic Modeling, Flood Risk Assessment, Flood Management Strategies

Introduction

Flooding is a significant calamity that affects Nepal annually, particularly in the Terai region. The impacts of climate change, coupled with human activities in the mid-hills and upper Himalayas, are expected to exacerbate the frequency and intensity of extreme weather events in this area.[1] The eastern Chitwan valley, located in Bagmati Province, presents an environment conducive to agriculture and water resource development, provided it is properly maintained and conserved. However, the changing catchment conditions have led to increased flood risks, particularly from rivers like the East-Rapti River. Historically, the eastern Chitwan valley has experienced several major floods, including catastrophic events in 1954, 1971, 1975, and the devastating flood of 1993, which resulted in the loss of 24 lives and destruction of 2,206 homes.[2] The population in Khairahani Municipality is growing at an annual rate of 1.6%, leading to shifts in land use patterns.[3] This urban expansion has diminished the land's capacity for water infiltration, increasing flood vulnerability. Flood hazard mapping is essential for guiding authorities in prioritising areas at higher risk and implementing effective flood mitigation strategies. While these maps cannot prevent floods, they serve as vital tools for raising public awareness about flood hazards.[4-6]

Problem Statement

The Ladara River presents a unique challenge for flood risk management due to the absence of gauging stations, making it difficult to monitor water levels and discharge rates. Despite the frequent occurrence of flooding in the region, there has been limited research focused on assessing flood risk in the Ladara River watershed. This study aims to utilise advanced modelling techniques to analyse flood inundation in the Ladara River. The findings will inform strategies to mitigate the impacts of flooding and develop management practices aimed at reducing physical vulnerability and overall flood risk. Therefore, a comprehensive study and the creation of flood inundation maps for the Ladara watershed are essential to enhance flood risk assessment and management efforts.

Research Objective

The main objective is to perform a flood risk assessment of the Ladara River, Chitwan, Nepal, using HEC-RAS.

Methods and Materials

Study Area

The study focuses on the Ladara River, located in the Khairahani Municipality of Chitwan, Nepal. The study area spans from Latitude 27°36'59.16"N, Longitude 84°33'37.70"E to Latitude 27°37'10.46"N, Longitude 84°33'50.36"E. Chitwan, situated in the Bagmati Province, features a tropical climate conducive to agriculture, influenced by the humid subtropical conditions of the central Himalayan climatic zone (Figure 1).

Figure 1.Study Area Map

Data Collection

- **Digital Elevation Model (DEM):** A 30-meter spatial resolution DEM was obtained from the United States Geological Survey (USGS) via the Shuttle Radar Topography Mission (SRTM) dataset.
- **Landsat Imagery:** Landsat 8 satellite images, acquired on November 20, 2022, were utilised for land use and land cover (LULC) classification. The images were selected for their clarity and absence of cloud cover.

Watershed Delineation

The watershed delineation was executed using the SRTM DEM in ArcGIS. The main outlet for the study area was determined at the confluence of the Ladara and Budi Rapti rivers. The DEM was reprojected to the UTM Zone 45 N coordinate system.

Land Use and Land Cover Mapping

The LULC map was created using the Landsat 8 imagery. A supervised classification approach employing the Maximum Likelihood algorithm was applied to categorise the watershed into major land use types, including forest, agriculture, barren land, and settlements. False-colour composites were generated using band combinations (5, 4, 3) for enhanced visualisation.

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Peak Discharge Estimation

Due to the ungauged nature of the Ladara River, peak discharge was estimated using three empirical methods for various return periods (2, 10, 20, 50, and 100 years):

WECS/DHM Method: Utilises regional prediction equations based on the catchment area.

$Q_2 = 1.8767 (A_{3000}+1)_{0.8783.}$

$Q_{100} = 14.639 (A_{3000}+1)_{0.7342}$

Where Q is the flood discharge in m3/sec and A3000 is the catchment area under 3000 m elevation. Subscript 2 and 100 indicate 2 Year Return Period and 100 Year Return Period respectively.

QT = exp (lnQ2+sσ)

Where QT is flood discharge for different return periods in m3/s, s is the standard normal variate whose values are given in below Table 1

Land Use Type Manning's roughness coefficient (n)

- Agriculture = 0.035
- River Channel = 0.04
- Settlement = 0.06
- Barren Land = 0.03

σ = ln(Q100/Q2)/2.32

Value of standard normal variate corresponding to different year return periods.

Table 1.Value of standard normal variate corresponding to different year return periods

T (YRP)	2	5	10	20	50	100	500
s	0	0.842	1.282	1.645	2.054	2.326	2.878

Sharma and Adhikari Method: An updated approach based on historical hydrometric data.

$Q_2 = 2.29(A_{3000})\ 0.86$

$Q_{100} = 20.7(A_{3000})\ 0.72$

Where Q is the flood discharge in m3/sec and A3000 is the catchment area under 3000 m. Subscripts 2 and 100 indicate 2 Year Return Period and 100 Year Return Period flood respectively,

QT = exp (lnQ2+sσ)

Where QT is flood discharge for different return periods in m3/s,

σ =ln(Q100/Q2)/2.32

s is the standard normal variate whose values are given in below values

Land Use Type Manning's roughness coefficient (n)

- Agriculture = 0.035
- River Channel = 0.04
- Settlement = 0.06
- Barren Land = 0.03

Modified Dicken's Method: An updated version of the original Dicken's method.

$QT = CT\ A_{3/4}$

Where Q_T = peak flood discharge (m_3/s) in T years; A = total catchment area in km_2

C_T = 2.342 log (0.6 T) log (1185/p) + 4

Where T = return period (in years) and

p = ((As+6)*100)/A

Where, p is the percentage of the snow-covered area; Permanent snow-covered area, (area covered by glaciers and/or area above 5000 m elevation for Nepalese context);

A = Catchment Area in km_2

Hydrodynamic Modeling

HEC-RAS software was employed to simulate water surface profiles, flood depth, and inundation boundaries. The DEM was processed to create contours and a Triangular Irregular Network (TIN), which were then converted to a raster format suitable for HEC-RAS.

- **Geometry Data Preparation:** River centerlines, bank lines, and cross-sections were defined in the RAS Mapper. Manning's roughness coefficients were assigned based on land use types.
- **Flow Data Entry:** Steady flow analysis was conducted using the maximum probable peak discharges derived from the empirical methods. Boundary conditions were established based on channel slope and normal depth.
- **Flood Simulation:** The flood simulation was executed in HEC-RAS, generating flood inundation maps, water surface elevations, and flood depth data.

Flood Hazard and Vulnerability Analysis

- **Flood Hazard Analysis:** Hazard classes were established based on flood depth intervals (<0.5 m, 0.5–1 m, 1–1.5 m, >1.5 m) to quantify flood hazards.
- **Physical Vulnerability Analysis:** The intersection of flood inundation boundaries with the LULC map was performed to assess the vulnerability of different land use types. The number of buildings, educational facilities, and health centres at risk was calculated based on flood inundation polygons.
- **Population Vulnerability Estimation:** The vulnerable population was estimated using the formula:

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Population vulnerable = (No. of buildings vulnerable − 10% of buildings) × 4.67 (CBS, 2021)

This methodology provides a comprehensive framework for assessing flood risks and developing effective flood management strategies in the Ladara River watershed.

Flood Risk Assessment

The Flood Risk Assessment section provides a detailed methodology for analysing and mapping flood risks, including the steps of creating flood risk maps, assessing municipalities at risk, conducting vulnerability analysis of structures, and estimating the population at risk. Figure 2: Flow chart illustrating the detailed process of the flood risk assessment methodology, outlining steps such as flood risk mapping, assessment of municipalities at risk, vulnerability analysis of structures, and population at risk estimation.

Flood Risk Mapping

The flood risk maps were generated by overlaying flood depth grids with the Land Use and Land Cover (LULC) map. The flood depth polygons created during the hazard analysis intersected with the physical vulnerability polygons derived from the LULC. This intersection was processed using the dissolve tool in ArcMap to create a unified dataset. The resulting attribute tables were then reclassified to establish the relationship between land use types and flood depth, illustrating potential flood areas categorised by both land use vulnerability classes and water depth hazard classes.[5]

Assessment of Municipalities at Risk

To evaluate the municipalities at risk, the flood depth polygons were intersected with the inundated area polygons obtained from the physical vulnerability analysis. The attribute tables of this intersection were reclassified to determine the inundated area for each municipality across various flood depth categories.

Vulnerability Analysis of Structures

The clipped points from the physical vulnerability analysis, which included buildings, educational facilities, health centres, and religious sites for the respective return periods, were intersected with the flood depth polygons. This process enabled the identification of the number of structures at risk of flooding based on classified water depth.

Population at Risk Estimation

To estimate the population at risk, the following formula was employed:

Population at Risk = (No. of buildings − 10% of buildings) × 4.67 (CBS, 2021)

In this formula, the total number of buildings at risk for each return period was reduced by 10% to account for unoccupied structures and then multiplied by 4.67, representing the average household size per building.

Data Processing and Analysis

- **Geospatial Analysis:** All spatial analyses were conducted using ArcGIS software. The flood depth grids were converted from raster to polygon format to facilitate the overlay analysis with the LULC map.
- **Flood Hazard Classification:** Flood hazard classes were established by reclassifying flood depth intervals into categories:

1. < 0.5 m (Low)
2. 0.5 – 1 m (Moderate)
3. 1 – 1.5 m (Significant)
4. 1.5 m (Extreme)

- **Vulnerability Mapping:** The LULC map was transformed into polygon format to assess the physical vulnerability of various land use types, including settlements, agriculture, forests, and barren land. The flood inundation boundaries for different return periods were intersected with these polygons to calculate the total vulnerable areas.
- **Building Vulnerability Analysis:** The flood inundation boundaries were further intersected with shapefiles from OpenStreetMap to quantify the number of buildings vulnerable to flooding. Points representing educational, health, and religious facilities were marked and analysed similarly to assess their vulnerability.

Analysis and Discussion

Watershed Delineation

The catchment area of the Ladara watershed is 37.69 sq. km. The different sub-watersheds have been delineated to calculate the flow from tributaries to the main channel of the Ladara River for various return periods. These sub-watersheds are shown in Figure 3, and their respective areas are listed in Table 2. The Chainpur Confluence will serve as the main outlet for the study area. To determine the flooded areas, we divided the river into three sub-basins and used the peak discharge from the Chainpur Confluence.

The probable discharge (m^3/s) from Chainpur Confluence, and Sharma and Adhikari (2004)[6] The method is taken for the input data for the HEC-RAS computation because we have to find the flooded area near East-West Highway, and the probable peak discharge is obtained from the Sharma and Adhikari (2004) method.

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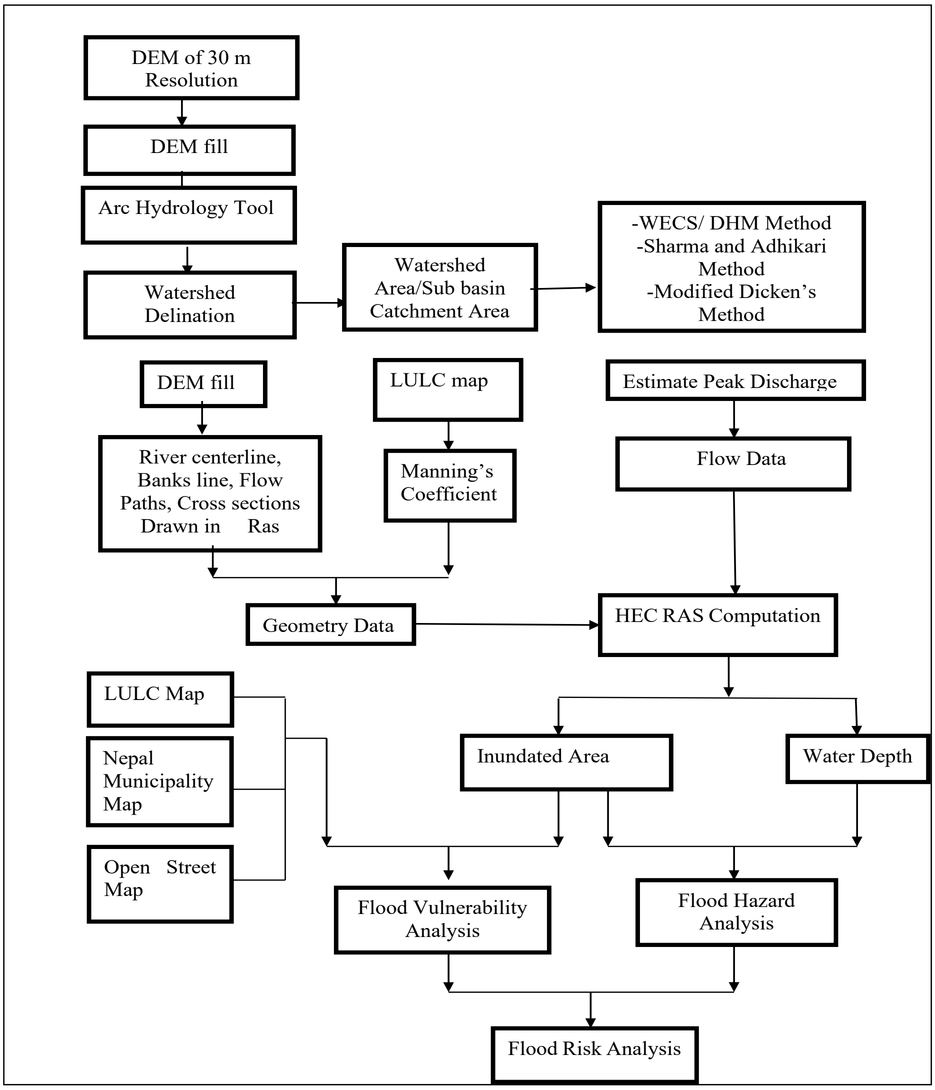

Figure 2.Flow chart showing the detailed process

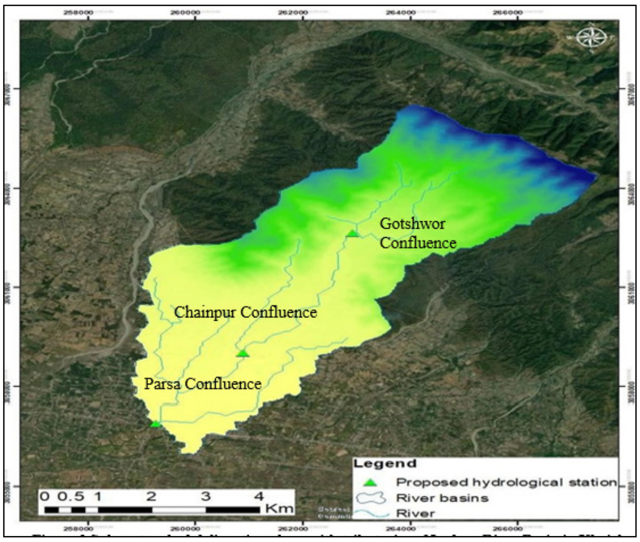

Figure 3.Sub-water shed delineation along with tributaries of Ladara River Basin in Khairhani Municipality, Chitwan

Land Use and Land Cover Map

The LULC map of the study area for the year 2022 is prepared using the Landsat 8 (2021) image in ArcGIS. Figure 4 indicates that the agriculture and barren land area covers 49% of the total watershed, which is the highest area covered among the land use types present in the area. The LULC map of the Ladara watershed for the year 2021 is shown in Figure 4.

Table 2.Sub-watershed with their respective area

S.No.	Sub-Watershed	Area (Sq. km)
1.	Gotshwor Confluence	14.7
2.	Chainpur Confluence	23.59
3.	Parsa Confluence	37.69

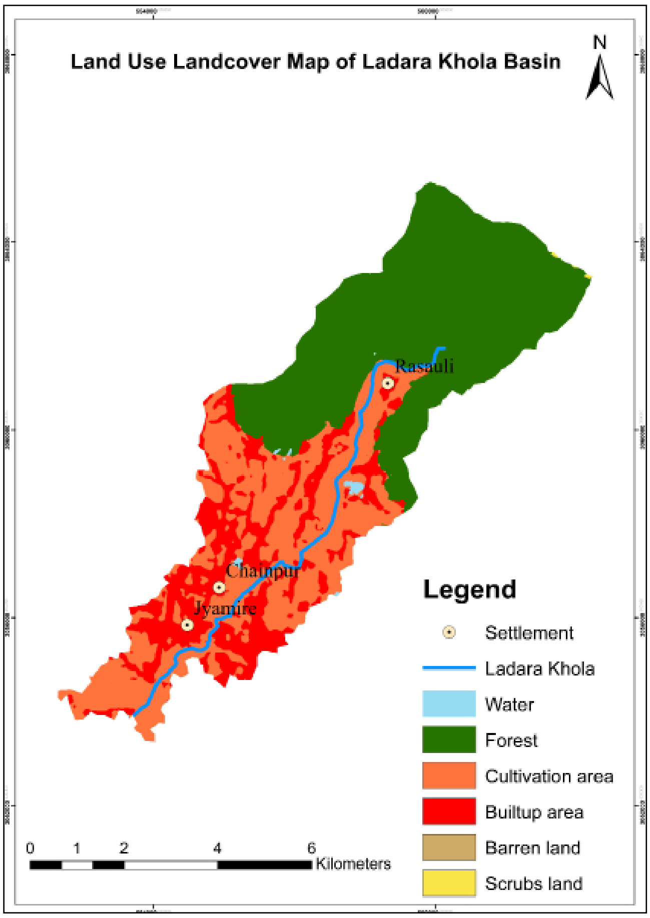

Figure 4.Land use type map of the study area classified into forest, waterbody, agriculture area built area bare land and range land

Estimating Peak Discharge

The peak discharge is estimated by using three different empirical methods: WECS/DHM (2004) Method, Sharma and Adhikari (2004) Method, and modified Dicken's method at the confluence where the tributaries met the Ladara River. The result of the estimated peak discharge for 2, 10, 20, 50, and 100-year return periods is presented in Table 3. Shows the need for eco-friendly construction,[7] (followed by labour-based construction).[8]

It is observed that probable peak discharges from the empirical method, Sharma and Adhikari (2004) Method for 2, 10, 20, 50, and 100 Years Return Periods are slightly higher compared to the results obtained from Modified Dicken's Method and WECS/DHM (1990) Method. Hence, the maximum peak discharge obtained from the Sharma and Adhikari (2004) Method is used as an input for steady flow analysis.

Steady Flow Analysis

The steady flow analysis computation showed the maximum flood level and the total inundation area for each Year's Return Period. The maximum flood level concerning different return periods is shown in Table 4.

Flood Hazard Analysis

The hazard aspect of the flooding is related to the hydraulic and hydrological parameters. Flood water depth is classified into four hazard classes: Low (0–0.5 m), Moderate (0.5–1 m), Significant (1–1.5 m), and Extreme (> 1.5 m). The results of the analysis are summarised in Table 5.

Table 3.Probable peak discharges for different return periods at various sites with different methods used

Different Methods used	Catchment Area (km^2)	Probable Discharge (m^3/s)				
		Q_2	Q_{10}	Q_{20}	Q_{50}	Q_{100}
WECS/DHM (1990)	14.7	26.75	65.27	84.02	111.68	134.94
DHM method (2004)		23.10	79.14	104.57	143.14	176.36
Modified Dicken's		40.00	64.21	74.64	88.43	94.00
WECS/DHM (1990)	23.59	31.25	75.19	96.40	127.56	153.68
DHM method (2004)		34.70	91.50	120.41	164.05	201.53
Modified Dicken's		80.77	140.85	166.73	200.94	226.81
WECS/DHM (1990)	37.96	46.82	108.59	137.80	180.23	215.45
DHM method (2004)		52.25	132.79	172.94	232.88	283.85
Modified Dicken's		66.49	113.64	133.64	160.36	180.58

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Table 4.Maximum flood level concerning year return period

S.No.	Maximum Flood level (m)	Year Return Periods
1.	1.733	2
2.	2.085	10
3.	2.498	20
4.	2.792	50
5.	2.933	100

The result shows that the area inundated at water depths <0.5 m is 10.17 ha, 3.77 ha, 2.79 ha, 4.26 ha, and 3.28 ha in 2, 10, 20, 50, and 100-year return periods, respectively. Similarly, the area inundated at water depth >1.5 m is 20.89 ha and 35.59 ha in 50 and 100-year return periods, respectively, and for 2, 10, and 20-year return periods, there is not any depth obtained above 1.5 m. The total area under water depth 0.5 - 1 m is larger, whereas the area under water with depth > 1.5 m is observed to be smaller when compared. Moreover, the area of inundation has increased with an increase in flood magnitude. The water depth is found to be maximum at the river channel, which decreased along the floodplain. Figure 5 shows the absolute and relative inundated areas classified according to hazard classes.

Table 5.Area inundated for different return periods as per depth

Water Depth (m)			Total Inundated Area (ha)							
	2 YRP		10 YRP		20 YRP		50 YRP		100 YRP	
	Area	%	Area	%	Area	%	Area	%	Area	%
<0.5m	10.17	22.45	3.77	8.00	2.79	5.78	4.26	7.06	3.28	5.19
0.5 -1 m	11.54	25.47	10.72	22.74	6.62	13.72	16.08	26.63	7.46	11.81
1-1.5m	16.22	35.80	15.32	32.49	14.55	30.15	19.15	31.72	16.85	26.67
>1.5 m	7.38	16.29	17.34	36.78	24.3	50.35	20.89	34.60	35.59	56.33
Total	45.31	100	47.15	100	48.26	100	60.38	100	63.18	100

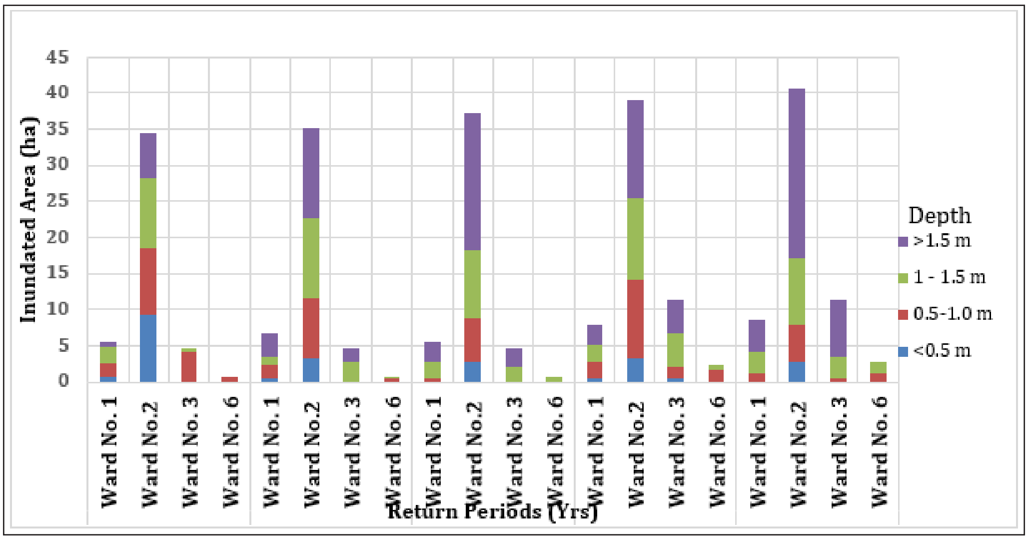

Figure 5.Inundating areas with respect to flood depth in different return periods

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Flood Physical Vulnerability Analysis

The Flood Physical Vulnerability Analysis section evaluates the vulnerability of different wards in the study area based on the extent of flooding at various return periods. This analysis helps in identifying how much land in each ward is susceptible to flooding, depending on flood depth and the frequency of the flooding event. The findings of the analysis are summarized in the following key components:

Flood Physical Vulnerability Analysis of Wards

This subsection outlines the vulnerable areas in hectares for each ward at various return periods (2, 10, 20, 50, and 100-year return periods) (Figure 6). The analysis provides insight into the vulnerability of different wards based on the extent of the flooded area. Table 6 presents the total vulnerable areas for each ward across the return periods:

The relationship between inundation area and flood depth shows that the inundation area increases slightly in all hazard classes with increasing return periods. Flood hazard maps of the study area are prepared by overlaying flood grid depths with world imagery for 2- and 100-year return periods (Figures 7 and 8). Hazard maps for the remaining return periods (10, 20, and 50-year return periods) are analysed.

Table 6.Flood physical vulnerability analysis of wards

Wards	Total Vulnerable Area (ha)				
	2 YRP	10 YRP	20 YRP	50 YRP	100 YRP
Ward No. 1	5.53	6.61	5.64	7.87	8.64
Ward No. 2	34.38	35.12	37.26	39.00	40.60
Ward No. 3	4.71	4.61	4.61	11.21	11.21
Ward No. 4	0.69	0.81	0.75	2.30	2.72
Total	45.31	47.15	48.26	60.39	63.17

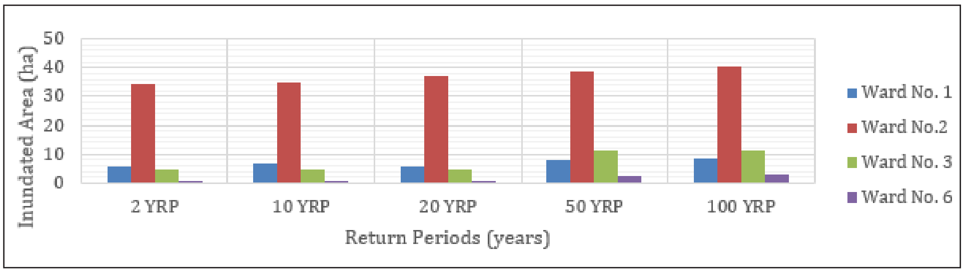

Figure 6.Inundating areas in hector concerning return period in different wards

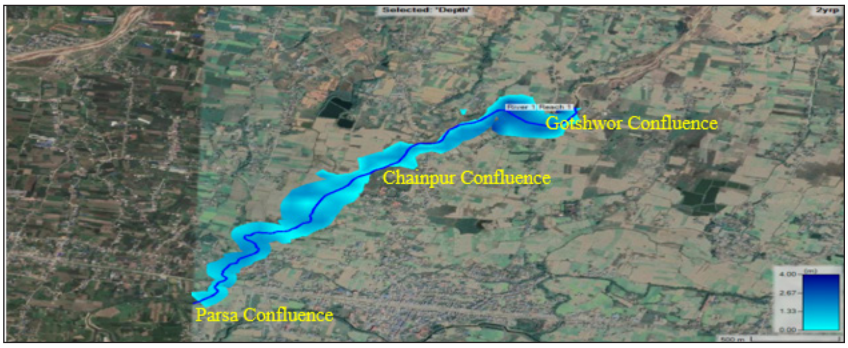

Figure 7.Flood hazard map for 2-year return period flood depth ranging from 0.68 m to 3.68 m blue line is the centerline of the river

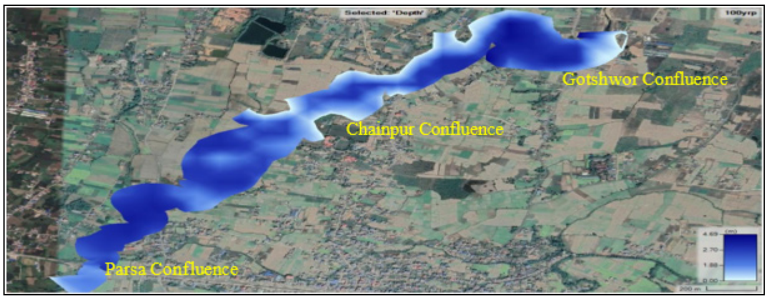

Figure 8.Flood hazard map for 100-year return period flood depth ranging from 1.88 m to 4.69 m

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Table 7.Classification of flood area according to land use vulnerability

Land Use Classification	Total Vulnerable Area (ha)									
	2 YRP		10 YRP		20 YRP		50 YRP		100 YRP	
	Area	%	Area	%	Area	%	Area	%	Area	%
Agriculture	36.59	80.75	38.11	80.83	28.63	59.32	45.93	76.07	48.03	76.03
Settlement	8.72	19.25	9.04	19.17	19.63	41.68	14.45	23.93	15.15	23.97
Total	45.31	100	47.15	100	48.26	100	60.38	100	63.18	100

Flood Physical vulnerability Analysis of land use types

The different land-use types under the influence of modeled flood and its inundated area for different Year Return Periods are summarized in Table 7.

It is observed that the settlement area is most vulnerable to flooding with an inundation area of 8.72 ha in the 2-Year Return Period and 15.15 ha in the 100-Year Return Period, followed by agricultural land with 36.59 ha in the 2-Year Return Period and 48.03 ha in the 100-Year Return Period. This indicates the potential negative impacts of the flood on livelihood and the degradation of cultivation land. From the assessment, it has been observed that a large percentage (more than 80%) of the vulnerable area is agriculture and barren land, followed by a settlement area comprising more than 22%. Figure 9 shows the absolute and relative inundated areas classified according to the land use types.

Flood Physical Vulnerability Analysis of Buildings and Population

The numbers of buildings and populations vulnerable to floods for different year return periods are summarised in Table 8. The total number of buildings vulnerable to flood is approximated by using the open street map.

Table 8.Flood physical vulnerability analysis of buildings and population

Factors	Number vulnerable to flood				
	2 YRP	10 YRP	20 YRP	50 YRP	100 YRP
Buildings	202	234	242	251	269
Population	786	910	941	976	1048

The populations affected by the 2-Year Return Period flood are 786 individuals, considering only 90% of the total buildings, that is, 202 buildings, and taking 4.32 as the average household size. Similarly, 1048 individuals are affected at the 100-year return period, considering 90% of 261 buildings.

Flood Physical Vulnerability Analysis of different types of buildings.

The numbers of building types vulnerable to flood for different year return periods are summarized in Table 9.

Table 9.Flood physical vulnerability analysis of building types

Type of Buildings	Number vulnerable to flood				
	2 YRP	10 YRP	20 YRP	50 YRP	100 YRP
Educational facilities	2	3	5	6	8
Health Centers	1	2	2	3	4
Temples	2	3	5	6	8
Industrial	1	2	9	9	11
Residential	196	224	221	227	238

Flood Risk Analysis

Flood Risk Analysis of Land Use Types

The inundated area for each land use type along corresponding water depth for floods of 2, 10, 20, 50, and 100-year return periods are summarized in Table 10.

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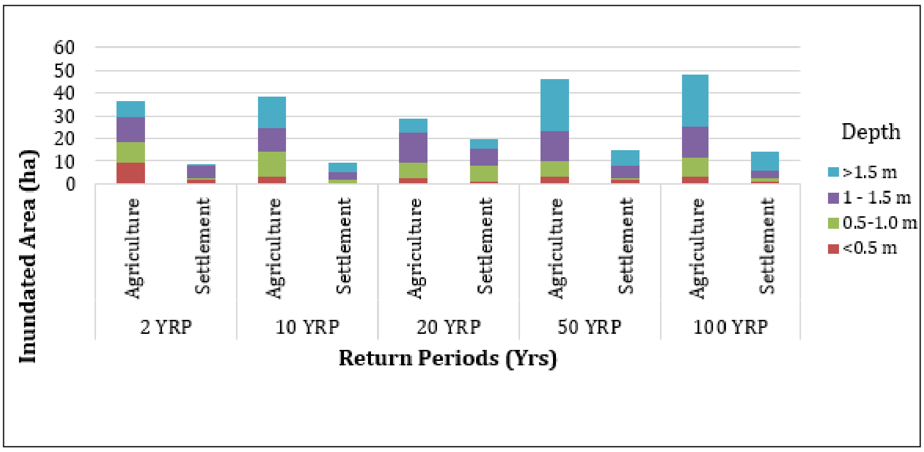

Figure 9.Return period and inundating are for different land use types like agriculture and settlement

Table 10.Flood risk classification of different land use types

Year Return Period	Depth (m)	Land use type classification	
		Total Inundated Area (ha)	
		Agricultural Land	Settlement
2	<0.5	9.00	1.55
	0.5-1	9.59	0.67
	1-1.5	10.97	5.35
	>1.5	7.02	1.16
10	<0.5	3.25	0.61
	0.5-1	11.04	1.41
	1-1.5	10.48	3.37
	>1.5	13.34	3.65
20	<0.5	2.11	0.85
	0.5-1	6.84	7.33
	1-1.5	13.66	7.49
	>1.5	6.02	3.96
50	<0.5	3.35	1.62
	0.5-1	6.73	1.07
	1-1.5	13.01	5.46
	>1.5	22.85	6.99
100	<0.5	2.85	1.32
	0.5-1	8.42	0.98
	1-1.5	13.61	3.71
	>1.5	23.15	8.43

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Inundated areas for different land use types at different classes of water depth <0.5 m, 0.5-1 m, 1-1.5 m, and >1.5 m at different return periods 2, 10, 20, 50, and 100 years are given in the table. The inundated area for forest area is found to be the least among all land uses at every return period. It means forest areas are at least more flood-prone than any land use classes. It is tabulated that the maximum amount of agriculture, barren land, and settlement areas is prone to flood risk of depth. This represents an indication that there might be potential damages and future risks in settlement and agriculture, causing negative effects on the livelihoods (Figure 10).

The water depth-wise inundation bar graph for different year return periods of settlement shows that maximum inundation is for the 100-year return period in an area of 3.8 ha. The inundated area of 8.4 ha has a depth greater than 1.5 m in 100 YRP. The water depth-wise inundation bar graph for the different year return periods of agriculture shows that maximum inundation could happen for an area of 10.86 ha for 1-1.5 m depth at a 20-year return period and an area of 24.01 ha for a 100-year return period. This represents an indication that there might be potential damages and future risks in agriculture, causing problems in the livelihoods (figure 11).

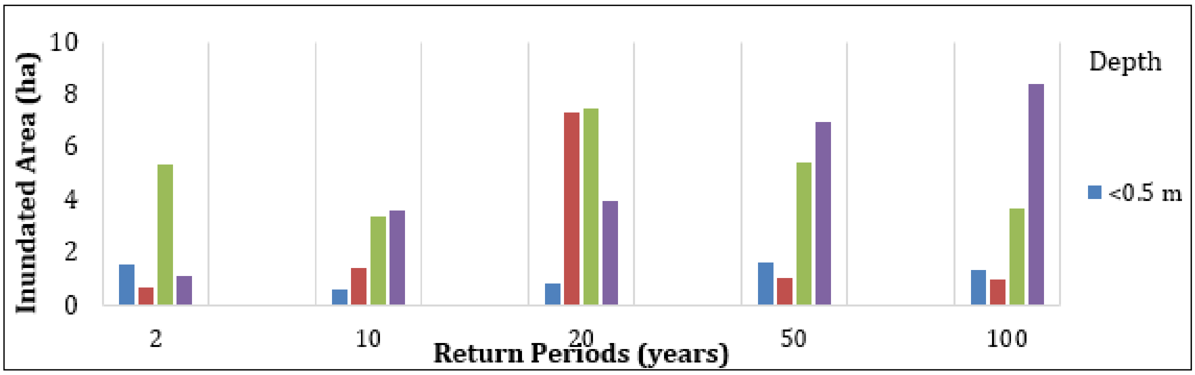

Figure 10.Inundating areas of settlement in different return periods with respect to depth

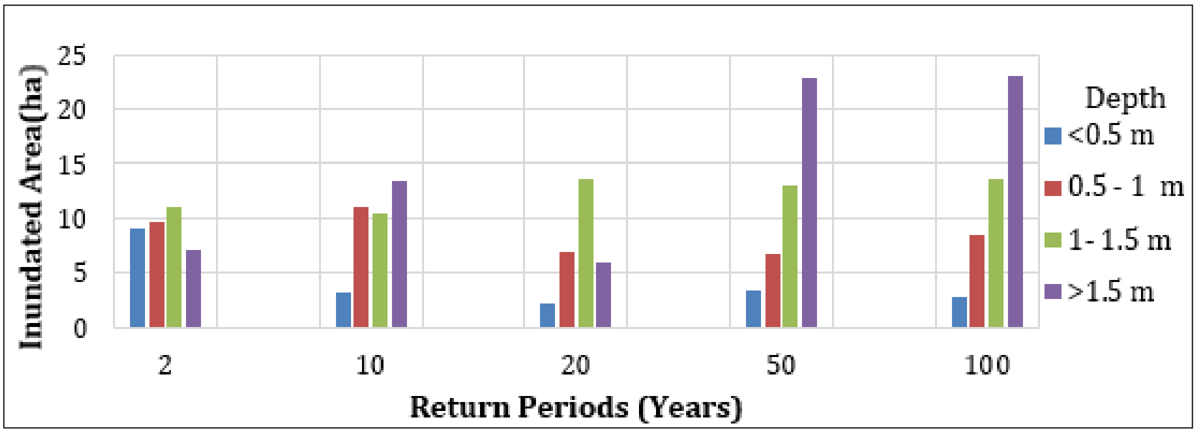

Figure 11.Inundating areas for agricultural land in different year return periods with respect to flood depth

Table 11.Flood risk analysis of buildings

Water Depth (m)	Number of Buildings				
	2 YRP	10 YRP	20 YRP	50 YRP	100 YRP
0.5	52	47	47	35	28
0.5 – 1	42	42	48	29	32
1 – 1.5	83	98	100	73	88
> 1.5	25	47	47	114	121
Total	202	234	242	251	269

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Flood Risk Analysis of Buildings

Table 11 shows the number of buildings at risk due to 2, 10-, 20-, 50-, and 100-year return periods concerning corresponding water depth. The maximum number of buildings at risk is in the low hazard class, i.e., a depth of < 0.5 m. 61, 71, 77, 100, and 119 buildings are found to be vulnerable to flood in 2, 10, 20, 50, and 100-year return periods, respectively (figure 12).

The relationship between the number of buildings, water depth, and return period shows that the number of buildings at risk increases with increasing return periods as shown in the above figure. The number of buildings at different hazard classes also has increased with increasing return periods indicating the increasing trend of risk corresponding to water depth.

Flood Risk Analysis of the Population

Table 12 summarizes the number of populations at risk to flood in 2, 10-, 20-, 50-, and 100-Year Return Periods concerning corresponding water depth.

The results show that most of the population affected is at a water depth of <0.5 m with 226 individuals for 2 Year Return Period and the most population affected for 100 Year Return Period is at a water depth of 0.5 – 1 m with 300 Individuals. Most of the population is affected by the flood of 100 Year Return Period due to the increase in the magnitude of the flood.

The relationship between the population, water depth, and return period shows that the number of populations at risk increases with increasing return periods, as shown in Figure 13.

Flood Risk analysis of wards

This table 13 summarizes the inundated area of wards at risk of flood in 2, 10, 20, 50, and 100Year Return periods concerning corresponding water depth.

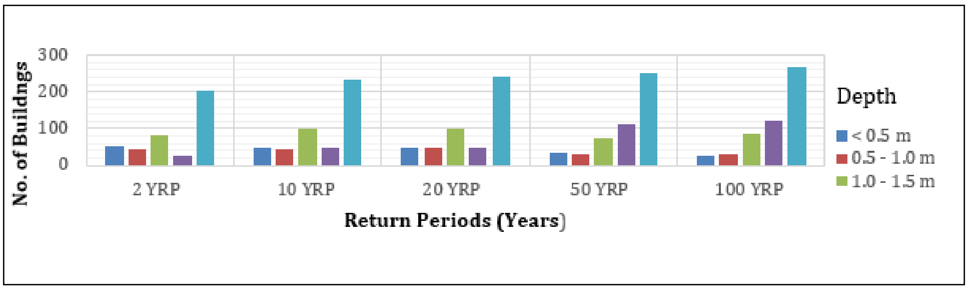

Figure 12.Flood risk classification of numbers of buildings with respect to flood depth

Table 12.Flood risk analysis of population

Water Depth (m)	Number of People				
	2 YRP	10 YRP	20 YRP	50 YRP	100 YRP
<0.5	203	183	183	137	109
0.5 – 1	164	164	187	113	125
1 – 1.5	323	382	389	284	343
> 1.5	98	183	183	444	471
Total	788	912	942	978	1048

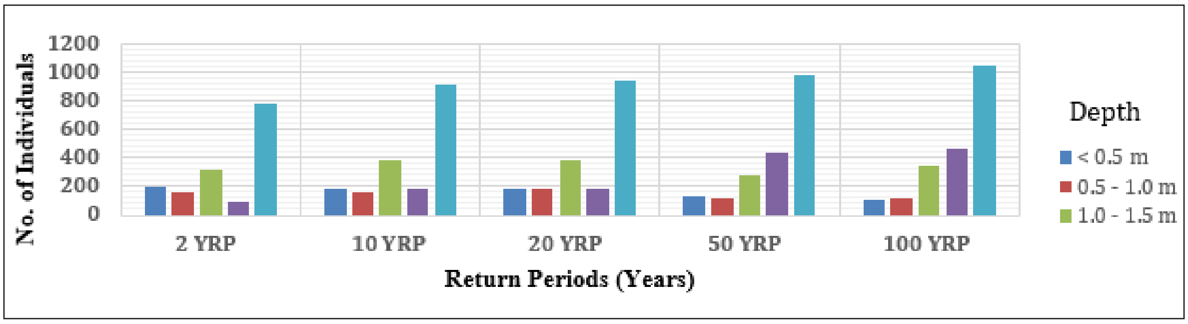

Figure 13.Population at risk to flood and flood depth

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Table 13.Flood risk analysis of wards

Return Period	Depth (m)	Wards			
		Total Inundated Area (ha)			
		Ward No.1	Ward No. 2	Ward No. 3	Ward No. 6
2	<0.5	0.77	9.35	0.05	-
	0.5-1	1.66	9.19	4.17	0.69
	1-1.5	2.33	9.72	0.49	-
	>1.5	0.77	6.13	-	-
10	<0.5	0.49	3.23	0.05	-
	0.5-1	1.92	8.42	0.01	0.37
	1-1.5	1.09	10.96	2.83	0.44
	>1.5	3.10	12.52	1.72	-
20	<0.5	-	2.74	-	-
	0.5-1	0.46	6.13	0.05	0.03
	1-1.5	2.35	9.42	2.07	0.72
	>1.5	2.84	18.97	2.49	-
50	<0.5	0.49	3.28	0.49	-
	0.5-1	2.30	10.72	1.53	1.53
	1-1.5	2.30	11.49	4.60	0.77
	>1.5	2.79	13.51	4.60	-
	<0.5	-	2.79	-	-
100 1-1.5 >1.5	0.5-1	1.19	5.09	0.49	1.19
	3.06	9.19	3.06	1.53	
	4.39	23.54	7.66	-	

Discussion

There is a significant increase in inundation area from the flood of 2 Year Return Period to 100 Year Return Period, due to the increase in the magnitude of the flood. Most of the inundated area has a water depth of anywhere around 0.5-1.5 meters. Floods during all the return periods have depths greater than or equal to 1 m, as shown in Table 8, which shows that low-lying areas are at higher risk due to floods. The result shows considerable flooding in the area even at a flood discharge of 2 years return period, which implies that the channel capacity is small to carry the floodwater discharge of lower-magnitude floods, making it more difficult to carry discharge of higher magnitude. Factors such as urbanisation, road construction, and the river basin have encroached, resulting in the river channel getting occupied quickly, resulting in overflow leading to flooding in nearby low-lying areas. Physical vulnerability assessment for different land use types and key facilities is done by overlaying the HEC-RAS simulation results with the LULC map and the LULC map. From Table 9, it has been observed that a large percentage (more than 75%) of the vulnerable area is settlement area, followed by agriculture

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and barren land comprising more than 22%. The identification of flooded areas is very important because they are input data for spatial analysis to assess flood impact and calculate the damage and risks in the present and future.[10] To manage the negative consequences of flooding in the Ladara River, both structural and nonstructural measures can act as key factors to minimise the flood hazard. The results can also be used to identify areas to focus on in case of emergency and for risk reduction programs.[11] However, further research is needed to obtain more accurate and high-resolution data to improve the risk assessment. The reviewed studies collectively highlight advancements in sustainable infrastructure and community resilience in Nepal, focusing on low-cost flood mitigation using locally sourced materials like bamboo, demonstrating a 64-83% cost reduction in eco-friendly latrine designs,[6]and identifying 10-15% higher initial costs but 50% lower operational expenses for eco-friendly buildings compared to conventional structures.[12, 13] Research on flood impacts reveals acute nutritional deficiencies in children, with flood-affected regions showing 21.85% higher embodied energy costs in housing, while labour-based road construction approaches show mixed community impacts requiring adaptive management strategies. For further research, critical gaps include longitudinal studies on bamboo-based flood control durability, development of cost-neutral transition models for eco-construction materials, and randomised trials testing biofortified food interventions in flood-prone nutritional hotspots. Techno-legal research priorities include AI-driven monitoring systems for building code compliance (Mishra & Aithal, 2021) and circular economy models integrating bamboo waste from flood controls into affordable housing materials, coupled with cross-sectoral policy analyses linking disaster resilience frameworks with nutrition security programs.[14-16]

Conclusion

This study presents a systematic approach to preparing hazard, physical vulnerability, and risk maps for the Ladara River in Chitwan district, Nepal, utilising a hybrid methodology that combines ArcGIS and the one-dimensional steady flow model HEC-RAS. The floodplain mapping and analysis conducted through these tools yield standardised and effective results for flood risk assessment.

The peak discharge estimates for the Ladara River across various return periods (2, 10, 20, 50, and 100 years) indicate that the values derived from the Sharma and Adhikari (2004) method were consistently higher than those obtained from the Modified Dicken's method and the WECS/DHM (1990) method. Consequently, the peak discharge values from Sharma and Adhikari (2004) were utilised as inputs for the HEC-RAS model. The maximum flood depth ranged from 0.5 to 1.5 meters for the 2-year return period, extending to greater depths for the 100-year return period.

Flood hazard maps were generated by overlaying flood depth grids from HEC-RAS with flood inundation area polygons, allowing for a comprehensive analysis of flood hazards. The classification of flood depths into categories of <0.5 m (low hazard), 0.5–1 m (moderate hazard), 1–1.5 m (significant hazard), and >1.5 m (extreme hazard) revealed that the largest area fell within the low hazard class, while the least area was classified as extreme hazard.

The assessment of physical vulnerability highlighted the impact of flooding on various land use types, structures, and populations. The most affected areas, totalling 63.18 hectares at the 100-year return period, primarily impacted downstream regions rather than upstream settlements. The analysis indicated that settlements, followed by agricultural and barren lands, were most vulnerable to flooding, with a maximum inundation depth of 4.69 meters at the 100-year return period. The study identified 202 buildings as vulnerable, with an estimated 786 individuals affected during this return period. Key facilities, including educational institutions and industries, were also at risk, underscoring potential disruptions to education and agricultural productivity.

To enhance flood management and mitigate risks, it is recommended that a hydrological gauge station be established to collect and validate hydrological data. Additionally, community awareness campaigns and river cleaning initiatives should be implemented to improve drainage systems and reduce flooding risks. Overall, this research contributes valuable insights into flood risk management in the Ladara River watershed, providing a foundation for future studies and interventions aimed at reducing flood impacts in the region.

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