Unguarded refugees of deep waters: Flood vulnerability analysis of Kosi embankment through the lens of Hydro-geomorphological and Socio-economic parameters through GIS analysis

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Abstract

The Kosi River basin is one of the most flood-affected regions in India. The first victims of these frequent floods are nearly 8 lakh people stranded between the Kosi river embankments in the Saharsa and Supaul districts of Bihar. These individuals face a trifecta of issues, including regular flooding, scarcity of basic amenities, and loss of livelihood, all of these are exacerbated by climate change impacts. The population living outside, too, had no respite due to frequent embankment breaches and waterlogging due to these structures. The region went through numerous flood-related research based on geomorphology, hydrology, and other physical factors; however, the flood impact assessment of embankments and its role within the socio-economic dimension remains unexplored. The present study unpacks flood vulnerability in 283 villages within the Kosi embankment. The study combines and analyzes thirteen attributes, including eight socio-economic and five hydro-geomorphic parameters, incorporating Sentinel-2, IMD, FMIS, and the 2011 census report and other survey reports. It employs GIS analysis to develop a socio-economic, hydro-geomorphic, and composite vulnerability map based on the weightage assigned to the aforementioned attributes. The analysis highlights that nearly the entire population in the embankment region is susceptible to the effects of flooding, with ~66% of the region having high and very high flood risk and ~26% in areas with moderate risk. The study's outcomes could contribute to directing the effects and exclusion created by flood control infrastructure. They can also help to develop a comprehensive flood adaptation and resilience program for the Kosi River basin.

1. Introduction

Rivers play a fundamental element civilizations since they provide water, ecological services, and foster cultural and economic growth along their banks. Rivers are affected by natural events such as floods and human interventions such as embankments and dams. Embankment are one of flood control interventions that constructed along the river to control floods and maintain river channels. (CITEATIONS). Floods are natural process that submerged land under water for shorter periods, however these event cause devastating impacts on region causing loss of lives, economic and ecological damage. (CITATION)

The vast Himalayan rivers, heavy rainfall, and the fact that a sizeable portion of the population lives in areas that are very prone to floods make India one of the worst-most flood-affected countries in the world (Kumar, 2017). Floods account for 48% of all natural disasters in India, inflicting havoc on the floodplains of North Bihar, particularly the Kosi River basin (Purohit & Suthar, 2012). During the last two centuries for which records are available, the Kosi River has changed its course westerly and laterally moved nearly 150 kilometres (Sinha3, 2008; Sinha et al., 2008). Following the devastating Kosi floods of 1953, embankments were constructed from 1954–1956 to protect the region from future devastating floods and channelize its flow between the two decks. The Kosi embankment initially spans 125 km on the eastern bank of Kosi and 126 km from Bhardah in Nepal to Ghonghepur in Saharsa (Mishra, 2008; Sinha, 2019). However, the total embankment in North Bihar stands at more than 3400 km (Sinha2, 2008). Kosi is one of the highest silt-carrying rivers. It transports around 43MT/year suspended loads at the downstream region (Sinha and Friend, 1994), whereas the annual suspended loads of the Kosi river near mountain front (Barahkshetra) is around 119MT/year (Nayak 1996; Jain et al., 2018). This high siltation increase the height to river bed which causes the annual floods in the embankment areas.(CITE) The extreme rainfall events are the major reason of floods and future climate projections are predicting increase in such extreme events which will makes Kosi river floods more disastrous in future.

This frequent and devastating flood leads to immense economic and human loss. The Kosi basin is home for farming communities who highly vulnerable to flood exposure(North bihar ki vulnrablity stuty CITE) Floods and their behaviors in Kosi basin has been widely explored by hydrologists, geomorphologists, geoscientists, social scientists, and so on. (Chakraborty et al. (2010), Sinha et al. (2014), Devkota et al. (2018), Sahana & Patel (2019), Sinha et al. (2019), Mishra et al. (2019)). Most of the studies focused on hydrological and geomorphological aspects and only few incorporated the socio-economic elements to assess the flood vulnerability. However, the region inside the Kosi embankment has rarely undergone socio-economic research; as a result, the flood impacts and vulnerability of the residents based on these combined parameters remain unexplored. Some studies including, Tripathi et al. (2022) in North Bihar districts, India; Sharma SV et al. (2017) in the Kopili river basin, Assam and Meghalaya, India and Dandapat & Panda (2017) in Paschim Medinipur district, West Bengal, India studied the combine socioeconomic and geophysical vulnrabilites of floods, which provided valuable insights for assessing flood impacts and preparing adaptation plans..

This present study explores the flood vulnerability assessment of the people living inside the embankment by mapping the region from the socio-economic, hydro-geomorphic, and composite flood vulnerability. The study attempts to understand the Kosi embankment region to understand the trapped populations' challenges inside the Kosi embankment, their vulnerability and risk to floods through an interdisciplinary approach incorporating methods from GIS and socio-economic and analytical hierarchy process (AHP). The study incorporates hydro-geomorphic (physical parameters such as slope, elevation, LULC, flood inundation, and so on) and socio-economic attributes, including inundation area, elevation, land use, sex ratio, population density, labor population to analyze flood vulnerability and perspectives of challenges to the region's population.

2. Contextualizing embankment and multidisciplinary vulnerability in context of Kosi river

2.1 Embankments as a flood control measure and the debates around it

Embankments are one of the interventions used to 'manage floods' or 'confine the flood' inside a specific area in the construction of embankments (Citation). These are being built worldwide to lessen losses due to flood events However, they are not popular because of their efficacy but due to being cheap and quicker to construct (Semar et al., 2013). Embankments are criticized for denying fertilizing silt to the flood plains, hampering land building by rivers, raising river beds, particularly in aggrading ones, blocking natural drainage from the countryside, and causing damages occurring despite their construction (Sinha[1], 2008, Sinha[3], 2008). Some examples include the Nile River in Egypt (Semar et al., 2013), the Mississippi River in the United States (Dixit, 2009), Jamuna, Meghna, Padma, Gumti, and so on (Hossain et al., 2008), and most of the Himalayan rivers in India namely Ghaghra, Rapti, Gandak and Kosi rivers, and some of their tributaries in India (Dixit, 2009).

In the context of the Kosi River, the embankments on both sides have been designed to protect 2800 km^2 of land in North Bihar and Nepal (Mishra, 2008; Sinha et al., 2008). These settlements within the embankments largely depend on agriculture, and the flash floods and long inundation periods severely damage the crops if not destroyed. Between 1956 and 2008, eight significant flood events occurred due to the Kosi embankment breach (refer to Table 1 & Fig. 1) (Mishra, 2006; Dixit, 2009). The Kosi embankment area also exhibits a high waterlogging risk, lasting three months in some areas and up to six months in other low-lying regions (Mishra, 2006). During the monsoon, people in certain areas must relocate from the embankment and return once the floods have subsided.

The regions within the embankment lack basic facilities and infrastructures such as roads, hospitals, schools, and banks, indicating the region's social and economic backwardness (Singh, 2009). Accessibility remains problematic; short distances to the administrative headquarters take considerable time. Throughout the year, some villages can only be reached by boat; these factors further aggravate the flooding vulnerability in the region (Mishra, 2008). The Kosi embankment project, which was initially targeted to protect 2,14,000 hectares of land, ironically ended up being the fundamental cause of losing nearly 4,20,000 hectares of land in the Kosi basin due to waterlogging, erosion, and sand casting, which affects the fertile land inside the embankment (Mishra, 2006; Mishra, 2008, Dixit, 2009, Singh, 2009).

Similar observations were also found in embankment development programs in Bangladesh. Choudhary et al. (2004) found that floods' severity has increased after embankment development to control the river flow after many devastating floods. Choudhary et al. (2004) found that the inundation period, which was 2–3 days in pre-embankment, increased to a month-long after embankment construction. Bhattacharyya (2013) highlighted other contributing factors to the flood, such as rainfall intensity, deforestation, increased built-up area, and improper drainage system planning. Additionally, there is little or no way to discharge excess water within the embankment through canals, increasing the severity and duration of floods (Choudhary et al., 2004). This realization was further strengthened by the experiences of the 1993 Mississippi floods, different floods in Bangladesh after embankment construction, and, most importantly, varied experiences from several floods of Kosi and its tributaries, mainly in 1966, 1987, 2000, and 2008 (Bhattacharyya, 2013).

The embankment that prevents the river from spreading also blocks drainage from either side of the river, leading to the emergence of waterlogging and even flooding in areas "protected" by the embankment, which was the case of Kosi embankment breach in 2008 when nearly 35lakhs people we impacted of Kosi floods (Iyer, 2008; Moench, 2010). These devastations necessitate additional research incorporating a plethora of multi-dimensional attributes rather than limiting to the unidimensional approaches employed in previous studies.

Table 1
Summary of past Kosi embankment breaches

(Source: Dixit (2009))

Year	Past breaches
1963	West Embankment, Dalwa, Nepal
1968	West Embankment, Jamalpur, Darbhanga, Bihar (breached at five places)
1971	Near East Embankment, Matniyabandha, Bihar
1980	Near East Embankment, Baharawa, Bihar
1984	East Embankment, Hempur, Bihar
1987	Gandaul and Samani, Bihar
1991	East Embankment, Joginiyan, Nepal
2008	East Embankment, West Kushaha, Nepal

Figure 1: Kosi embankment breach (Source: Dixit (2009))

2.2 Multidisciplinary perspectives of flood vulnerability

The definition of vulnerability changes over time. In the last two decades, several studies and organizations comprehensively assessed and analyzed the concept of vulnerability (Cutter, S. L.,1996; Brooks et al., 2005; Adger, 2006). Flood vulneability primarily refers to the degree to which hydro-geomorphic, biological, and social systems are susceptible to and unable to cope with any hazard exposure (Füssel et al., 2006). Flood vulnerability is the measure a region, its residents, its physical structures, or its financial resources are to sustaining loss, harm, or destruction due to exposure from hazard, and it is the function of geography, demography, social structure, and economic capacities (Tripathi, 2022; Dandapat & Panda, 2017).

Moreover, floods and droughts are particularly destructive hazards because they erode the ability of marginal groups to improve their livelihoods and economic perspectives (long-term effects) (Dilley, 2005). To unfold the dimensions of flood vulnerability, socio-economic investigation in cohesion with hydro-geomorphic parameters provides more valuable insights. In this regard, Balica et al. (2013) categorized people based on socio-economic challenges, inaccessibility of resources, and income slabs. Molloy et al. (2017) worked in vulnerability sciences by assessing social, physical, environmental, and economic elements. Liu et al. (2018) add this notion by emphasizing the need to link ecological and socio-economic characteristics in flood vulnerability assessment. The present investigation assessed the flood vulnerability of the region trapped by the Kosi embankment using multi-dimensional concepts from above discussed theoretical frameworks. A multidisciplinary perspective is essential because flood vulnerability assessments are ubiquitous, limited to environmental factors, and use a one-dimensional approach limited to environmental factors (Lyu et al., 2020).

3. Study area

Kosi River embankment, located within Supaul and Saharsa districts of Bihar, between 25°20’20” North and 26°20’40” North latitude and 86°0’0” E and 87°0’0” East longitude. It covers 283 villages within the two districts (Supaul and Saharsa) with a geographical area of 899 sq km.

The embankment boundary is determined by analyzing the literature on the study area, google earth imagery, Landsat, and FMIS maps, and a shape file is created using the USGS map dataset. The embankment on the Kosi River passing through Supaul and Saharsa encompasses 283 villages, verified from the works of Mishra (2008), who substantiated the data based on block and district administrative data. The village list further went under confirmation from the History of Kosi Embankment report prepared by the Water Resource Department, Government of Bihar, in 2002. The 2011 census report provides the most reliable and comprehensive data for these villages; however, there are 11 villages in the study area for which no population is recorded; these may have been abandoned due to frequent flooding or the Kosi shifting its course through these villages.

4. Materials and Methods

The study explores the multidisciplinary perspective of socio-economic and hydro-geomorphic attributes and their impact on the flood susceptibility of communities. Information pertaining to the study has been sourced from various literature and datasets, including meteorology, hydro-geomorphic, socio-economic, and remote sensing products, to fulfill the required attributes. The study then divides the attributes into two broader sections, i.e., socio-economic and hydro-geomorphic characteristics. The GIS analysis uses an Analytical Hierarchy Process (AHP) to prioritize multidisciplinary attributes and prepare flood vulnerability maps of the Kosi embankment region.

4.1 Preparation of Socio-economic Parameters

Table 2

Dataset used in this study and their characteristics

Source	Parameters	Data type	Scale	Acquisition Date
DEM (SRTM)	Slope	Grid	30 x 30	Apr-15
	Elevation	Grid	30 x 30	
	Flow length	Grid	30 x 30	
Sentinel 1 image	Flood Inundation area	Point	10x10	2020 (May and July)
Land type	LULC	Grid	30 x 30	2020
Socio-economic and Demographic data	Census parameters	Grid	Village Level	2011
Road Network	PMGSY	Lines	30 x 30	2022

The study took eight village-wise socio-economic and demographic criteria, i.e., Population density, sex ratio, total literacy rate, female literacy rate, housing conditions, agricultural labor, and cultivator population. Several other works on flood vulnerability, such as by Tripathi et al. (2022), Sharma SV et al. (2018), and Dandapat & Panda (2017), were also employed to assess people’s vulnerability. In addition, the study used and examined data from various sources, including the Census (2011), Economic Survey of Bihar (2019-20), Flood Atlas Bihar (2019), and secondary literature on the Kosi Basin.

4.2 Hydro-geomorphic data

Nature of flood depends on the hydrogeomorphological and climatic features of the region. To analyze hydro geomorphological features, the Digital Elevation Model (DEM) is the foundation. USGS provides 30 meter resolution DEM from its SRTM observations which is widely used in performing GIS analysis to prepare hydrogeomorphological parameters such as slope, flow length, elevation etc. A Sentinel-1 Ground Range Detected (GRD) scene (10m resolution) with vh-band was obtained from Google Earth Engine for 26th May 2020 and 26th July 2020. The images were smoothened with a radius of 50 m to minimize the speckle noise. The datasets were then assigned a threshold of 1.25 to distinguish between flood and non-flood pixels, identify the flooded region, and calculate the final result.

LULC is another integral component of vulnerability assessment; a 10m-resolution ESA Sentinel-2 imagery of the embankment area was created with 2021 data to analyze land use/land cover (LULC). These datasets were used to prepare embankment area maps and categorize distinct land types using supervised classification algorithms in the highly susceptible and data-scarce region. According to Roy et al. (2016), the approach is highly accurate and suitable for classifying various land features.

4.3 Preparation of the vulnerability map using AHP

The study used the AHP method to estimate vulnerability using interdisciplinary characteristics commonly used in flood vulnerability assessments (Tripathi, 2022; Tripathi, 2017; Ramanathan, 2001). They proposed employing aspects of a region’s socio-economic risk assessment and a conceptual framework to prioritize the parameters. These studies revealed that evaluating the regional variability of socio-economic data is more relevant and provides the notion of connecting hydro-geomorphic factors to determine vulnerability. In order to conduct vulnerability assessments, preprocessing is performed, including preparing each parameter’s raster layer, followed by layer reclassification. The study primarily employed the AHP approach for computing associated weighting and priority order for socio-economic, hydro-geomorphic, and composite vulnerability assessment. Based on an exhaustive literature review, previous studies, and consideration of local conditions, the associated weightage of all thirteen variables was assigned relative priority. These were then subdivided into sub-criteria and given individual weightage based on the assumption of their relative importance in assessing socio-economic impact.

The composite map is prepared by combining the values assigned to the socio-economic and hydro-geomorphic parameters in ArcGIS software. A village-level vulnerability map is prepared, which shows the flood vulnerability of people living in the villages. Nevertheless, the risk of flood vulnerability and community coping capacity also depends on their geographical location, socio-economic class, per-capita income, institutional response, connectivity in these remote locations, and so on.

Table 3
Semantic scale of the AHP method.

Source: Ramanathan (2001)

Comparative importance	Definition	Description
1	Equal Importance	Two indicators equally influence the parent decision
3	Weak importance	One factor is moderately influential over the other
5	Essential or equal importance	One factor is strongly favored over the other
7	Demonstrated Importance	One decision factor has a significant influence over another
9	Absolute Importance	Evidence favoring one decision factor over the other is the highest order of affirmation
2, 4, 6, 8	Intermediate	When compromise is needed, values between two adjacent judgments are used
Reciprocals	If Ai is the judgmental value when i is compared with j, then Aj has the reciprocal value when compared to Ai	A reasonable assumption

Table 4
Pairwise comparison matrix for socio-economic vulnerability indicators (CR: 0.015415)

Sr. No.	Housing conditions	Population density	Sex ratio	Road connectivity	Agricultural labourers	Total literacy	Cultivators population	Female literacy
1	1	1	1	1	1	2	2	2
2	1	1	1	1	1	1	2	2
3	1	1	1	1	1	1	1	2
4	1	1	1	1	1	1	1	1
5	1	1	1	1	1	1	1	1
6	0.5	1	1	1	1	1	1	1
7	0.5	0.5	1	1	1	1	1	1
8	0.5	0.5	0.5	1	1	1	1	1
Overall weightage	0.16	0.15	0.13	0.12	0.13	0.11	0.10	0.10

Table 5
Pairwise comparison matrix for composite vulnerability indicators (CR: 0.013031)

Sr. No.	Flood Inundation area	LULC	Slope	Elevation	Flow length
1	1	3	5	6	2
2	1/3	1	1	1	1
3	0.5	1/5	1	1	1
4	0.33	1/6	1/6	1	1
5	0.25	1/2	1/2	1/2	1
Overall weightage	0.235	0.197	0.197	0.197	0.174

Table 6
Pairwise comparison matrix for composite vulnerability indicators

Sr. No.	Housing condition	Population density	Flood Inundation area	LULC	Road connectivity	Sex ratio	Agricultural labourer	Total literacy	cultivators population	Slope	Female literacy	Elevation
1	1	1	1	Jan-00	2	2	2	3	3	3	4	4
2	1	1	1	1	1	2	2	2	3	3	3	4
3	1	1	1	1	1	1	2	2	2	3	3	3
4	1	1	1	1	1	1	1	2	2	2	3	3
5	0.5	1	1	1	1	1	1	1	2	2	2	3
6	0.5	0.5	1	1	1	1	1	1	1	2	2	2
7	0.5	0.5	0.5	1	1	1	1	1	1	1	2	2
8	0.33	0.5	0.5	0.5	1	1	1	1	1	1	1	2
9	0.33	0.33	0.5	0.5	0.5	1	1	1	1	1	1	1
10	0.33	0.33	0.33	0.5	0.5	0.5	1	1	1	1	1	1
11	0.25	0.33	0.33	0.33	0.5	0.5	0.5	1	1	1	1	1
12	0.25	0.25	0.33	0.33	0.33	0.5	0.5	0.5	1	1	1	1
13	0.25	0.25	0.25	0.33	0.33	0.33	0.5	0.5	0.5	1	1	1
Overall weightage	0.143	0.130	0.115	0.105	0.092	0.08	0.07	0.06	0.052	0.045	0.040	0.036

5. Results

Socio-economic characteristics are crucial for evaluating the flooding hazards and determining the vulnerability to flooding impacts. When paired with socio-economic parameters, the hydro-geomorphic parameters were more pertinent and effective in vulnerability assessment.

Table 7
Socio-economic vulnerability map and the outcomes

Sr. No.	Indicators	vulnerability parameters	Vulnerability Index
1	Sex ratio	0-850	Very High
		851–900	High
		901–950	Moderate
		951–1000	Low
		1001–1168	Very Low
2	Population Density	0-200	Very low
		201–400	Low
		401–500	Moderate
		501–600	High
		601–1100	Very High
3	Total Literacy rate	0–12	Very High
		13-30.7	High
		30.8–47.6	Moderate
		47.7–52.5	Low
		52.6–69.5	Very Low
4	Female Literacy Rate	0–25	Very High
		26–35	High
		36–40	Moderate
		41–45	Low
		46–55	Very Low
5	Kaccha houses	Jun-45	Very low
		45–64	Low
		65–78	Moderate
		79–90	High
		91–100	Very High
6	Cultivators population	0–5	Very High
		6.0–10.0	High
		Nov-15	Moderate
		16–20	Low
		21–50	Very Low
7	Agricultural Labourers	0–10	Very low
		Nov-20	Low
		21–30	Moderate
		31–40	High
		41–65	Very High

5.1 Socio-economic vulnerability map and the outcomes

A section of society with low-level socio-economic potential suffers more in natural disasters (Kahn, 2005). The social vulnerability criteria in the present study is an amalgamation of eight different parameters (Table 4). Based on these parameters, the vulnerability zones were distributed throughout both districts, with Supaul receiving a mixed bag of vulnerability zones and Saharsa confined to regions with high and very high impact of flooding vulnerability. The parameters included:

5.1.1 Sex ratio

Gender is one of the most crucial elements in assessing natural disasters' social impact. In terms of vulnerability, the higher the proportion of males to females, the more vulnerable society is to flooding (Ikhvan & Mera, 2021). In our study, regions with low sex ratios, i.e., less than 850 females/males, were considered the most vulnerable. In contrast, the least vulnerable are those with a sex ratio higher than 1000 (Table 7).

5.1.2 Population density

The population density component in the flood-vulnerability assessment indicates community exposure. The larger the population density per square kilometer, the more vulnerable it is to disasters (Ikhvan & Mera, 2021). The population density was prioritized due to the difficulties its more prominent number poses during planning, mitigation, evacuation, and overall economic losses (Dandapat et al., 2017). The population density map of the embankment area shows that villages in Saharsa district have comparatively higher population density than villages in Supaul, making earlier villages more vulnerable to flood impacts (Fig. 5, Table 7).

5.1.3 Total literacy rate

The number of illiterate people (men and women) was assessed with the presumption that those without literacy rely on others to help them prepare for hazards and evacuate themselves in the event of a disaster (Dandapat & Panda, 2017). The 2011 Census report suggests that villages in the study area have an overall literacy rate of 39.6%, significantly lower than the state average of 61.8% and the National average of 74%. The study highlights that Supaul has a relatively moderate total literacy level, making it less vulnerable (Fig. 5, Table 7).

5.1.4 Female Literacy Rate

Women are more vulnerable to natural catastrophes than men in the social structure; they have to spend more time caring for their families and have fewer opportunities for educational and economic activities (Ikhvan & Mera, 2021). Low literacy and flood awareness among women who are already suffering from social backwardness and equality issues exaggerate the flood impacts. They often suffer domestic abuse and harassment during floods, making them dependent and powerless (Islam, 2017). These trends indicate a similar direction as the female literacy rate in the study area of 32%; at the same time, the national average was double. The flood vulnerability map suggests Saharsa was majorly on the higher side of flood vulnerability in comparison to Supaul (Fig. 5, Table 7).

5.1.5 Housing types

Rural areas are usually dominated by Kaccha-style dwellings, which are highly vulnerable since they are built on floodplains or near rivers and streams (Dandapat & Panda, 2017). Households with grass or bamboo roofs are notably vulnerable to flooding because they are primarily damaged during flooding. The kaccha house is a risky shelter alternative during flooding. Some regions in the study area have an upper limit of 90% kaccha houses, making them the most vulnerable (Table 7).

5.1.6 Road connectivity

Infrastructure facilities such as roadways and rail networks are considered "lifelines" and play an essential role in evacuation, post-event relief, and rehabilitation. Since these networks are critical in determining a community's lifeline (Gulati et al., 2019). Within the research area, road connectivity is extremely poor, rendering the region highly vulnerable to flood impacts (Fig. 3).

5.1.7 Cultivators population

Agriculture is a significant contributor in Kosi region's economy and impact of floods on farmlands increases the cultivators socioeconomic status as well as the dependant family and farm laborers income (Singh, 2009). Therefore, villages with higher cultivator populations (21%) are considered most affected by floods, while less population with a cultivator (5%) suffers less economic impact due to flooding (Table 7). However, a sizable proportion of individuals rely on employment in the agricultural sector as farm labourers, which is covered in more detail in the following section.

5.1.8 Agricultural labour population

Higher population concentration on the agricultural field makes the local economy more dependent on agriculture, which enhances flood vulnerability (Tripathi et al., 2022). Therefore, areas with a large population of agricultural labourers, i.e., more than 41%, were considered most vulnerable to flooding. In comparison, areas with less than 10% population are considered the least vulnerable (Table 7). In this regard, most regions within the study area, and Supaul in particular, are highly vulnerable to flood impacts (Table 7, Fig. 5).

5.2 Social vulnerability of Kosi river embankment region

The Social vulnerability map further demonstrates that Saharsa's embankment regions have higher and extremely high vulnerability locations resulting from higher vulnerabilities of population density, sex ratio, total literacy rates, female literacy rates, kaccha houses and population of agricultural labourers. The Supaul embankment, in contrast, has a mixed sensitivity to the effects of floods, with parts of the settlements being extremely vulnerable while others are less so. It is due to some parameters being on the higher vulnerability side, increasing the overall flood vulnerability of the region (Table 10, Fig. 6).

5.3 Hydro-geomorphic Vulnerability to the flood impacts

Hydro-geomorphic vulnerability characteristics are crucial in determining intensity and extent of flood over the region. It includes the following attributes:

5.3.1 Flood Inundation

Flood inundation is a significant determinant of flood risk in a specific area. Our study examined the flood inundation of the Kosi embankment area, employing satellite data from 2020 (Table 2). In this study, we have used SAR (Synthetic Aperture Radar) data from Sentinel-1A in vh-band for two different months, i.e., 26th May 2020 and 26th July 2020, and the difference of their pixels highlights the inundated area within the Kosi River embankment. The Saharasa region within the embankment receives discharge contributions from the upstream region through the Kamla-Balan and Adhwara Rivers and experiences backflow from the Kosi River during the Monsoon period. Hence, water remains in the area for a longer time, forming several marshes, swamps and ponds and is characterized by poor drainage systems (Jain and Sinha, 2005). On the other hand, the Kosi River is the primary cause of flood inundation in Supaul, and there are no other rivers to supplement it; as a result, a relatively smaller area is affected.

5.3.2 Slope

The slope is a crucial attribute that considerably impacts the characteristics of flood hazard. However, unlike other parameters, the slope does not highlight any significant impact on flood vulnerability in the region, as the slope difference is minimal in our study area (Fig. 8).

5.3.3 Flow length

The river's flow length is the distance measured along the stream channel from the source to a specified point or to the outlet. The present study used DEM to prepare the flow length of Kosi, to calculate the flow length of the main channel. Moreover, overbank flooding occurs when discharge exceeds the bank full capacity of the river channel. As a result, any river's flow length is a significant cause of flooding (Tripathi et al., 2022). In the present study, flow length is vital to flood vulnerability. GIS analysis of the embankment highlights that the flow length of Kosi varies from 0 km to 0.876 km (Fig. 8, Table 9). The river has the most extensive flow length, right in the centre of the embankment, so the areas are most susceptible to flooding.

5.3.4 Elevation

Flood disasters occur in regions with low topographic elevations or lower catchment areas (Jati et al., 2019). The elevation in our study area is the highest on the northern side, i.e., in Supaul, with the highest level of 87m, and least on the southern side, i.e., Saharsa, with a minimum elevation of 31m (Table 9). As a result, regions of embankment within Supaul are less vulnerable to floods in terms of elevation, while Saharsa has a high vulnerability.

5.3.5 Land Use Land Cover

The study used Sentinel's LULC tiles, which allow reclassification based on local land types and are considered highly accurate on the kappa coefficient by Roy et al., (2016). It further uses land categorisation based on the study of Periyasamy et al. (2018) to analyze vulnerability based on LULC. It dissects the physical attributes into different classes, i.e., crops and habitations, water bodies, rangelands, bare ground (Sand cover), and flooded vegetation and tree cover. Water bodies were assigned the highest flood vulnerability parameter, while crops and habitations were assigned high vulnerability parameters, rangelands with moderate, flooded vegetation, and tree cover with the low and bare ground with the least vulnerability to flooding impacts (Table 8).

Table 8
Land Use Land cover Analysis

Parameters	Vulnerability Index	Area (Sq Km)	Percentage (%)
Bare Ground, Sand	Very Low	111.15	15.41%
Flooded Vegetation, Tree cover	Low	3.52	0.49%
Rangeland	Moderate	122.53	16.98%
Built Area	High	352.73	49.89%
Water bodies	Very High	131.56	18.23%

5.4 Hydro-geomorphic Flood Vulnerability Index (HGVI)

HGVI refers to flood vulnerability as determined by AHP composite preferences assigned to various attributes based on their potential impact on flooding conditions within the study area. Hydro-geomorphic parameters are as crucial as social vulnerability parameters as they define and determine the intensity of flooding in a geographic location. The results of the hydro-geomorphic parameter suggest that Saharsa is highly vulnerable due to its large extents inundated by flooding and higher built-up area, which gets enumerated by other parameters being on the higher side. On the contrary, embankment within Supaul embankment has mixed vulnerability patches due to the lower vulnerability extent of parameters such as flood inundation area, lower built-up area, and so on.

Table 9
Hydro-geomorphic Parameters

Sr No.	Parameters	Very low	Low	Moderate	High	Very High
1	Flood inundation area	Land area		River flow		Inundated area
2	Slope	0–2	2.1–3.6	3.7–5.8	5.9–9.3	9.4–29.8
3	Flow Length	0–8	8.1–18.2	18.3–36.4	36.5–56.2	56.3–86.1
4	Elevation	69–87	61–68	55–60	45–54	31–44
5	LULC	Barren Land	Flooded Vegetation	Rangeland	Crop and Habitation	Water

5.5 Composite Vulnerability to the flood impacts

The composite vulnerability map is a culmination of socio-economic and hydro-geomorphic parameters, which brings us to an altogether new dimension in terms of vulnerability to flood impacts in the study area. Most high and very high flood vulnerability regions are confined in Saharsa. It is evident from the results mentioned above that the physical flood vulnerability parameters were lower on the northern side of the embankment area. The overall impact of these parameters resulted in a highly vulnerable composite flood map for embankment, with some regions falling under moderate and low vulnerability zones (Fig. 10, Table 10).

Table 10
Vulnerability Mapping Results

Vulnerability Index	Socio-Economic Vulnerability results (area in sq km) (%)	Hydro-geomorphic vulnerability results (area in sq km) (%)	Composite vulnerability Map (area in sq km) (%)
Very low	21.30 (2.37%)	45.23 (5.09%)	7.84(0.88%)
low	138.20 (15.37%)	259.05 (29.14%)	62.72 (7.05%)
Moderate	170.35 (18.94%)	299.35 (33.66%)	231.26 (26.01%)
High	408.02 (45.37%)	195.23 (21.96%)	374.92 (42.17%)
Very High	161.43 (17.95%)	90.24 (10.15%)	212.40 23.89%)

6. Discussion

6.1 Spatial distribution of vulnerability within the embankment area

The degree of vulnerability is variable within the embankment area in terms of socioeconomic and hydro-geomorphological parameters. Villages of Saharsa are more vulnerable to flooding impacts in the context of socioeconomic datasets, high population density, lower total and female literacy rates, lower sex ratio, inadequate housing facilities (a large portion of the population does not have access to the pucca house), and greater reliance on agriculture are the main causes for higher vulnerability in Saharasa. In terms of hydro-geomorphological vulnerability, the embankment within Saharsa is more vulnerable to flooding impacts due to lower elevation; land use land cover (LULC) (significant portions of Saharsa embankment are built-up, and agricultural lands, making it more vulnerable to floods), and flood inundation. Tributary contribution in downstream reaches of the Kosi River (Fig.) also causes high discharge at downstream reaches and hence more flooding in the Saharsa district. As a result, Saharsa's overall composite vulnerability is exacerbated by the high socioeconomic and hydro geomorphological vulnerability.

In contrast to the scenarios prevailing in Saharsa, Supaul has a smaller population within the embankment, which reduces the vulnerability to flooding in terms of socioeconomic parameters. Similarly, Supaul has a higher elevation, smaller built-up area, and lesser agricultural lands as its LULC. Further, the absence of major tributaries' confluence with the Kosi River consequently reduces its hydro-geomorphological vulnerability, which further reduces the region's composite vulnerability to flooding impacts.

According to the assessment report, the Himalayan glaciers will begin melting faster, reducing Kosi's lean season flow in the long run (Moench, 2010). It implies that there will be a multifaceted impact on the Kosi embankment's population, while the reduced flow due to faster glacier melting will hamper the agricultural sector, while increased rainfall in response to climate change will aggravate the flooding scenario, negatively affecting the Kosi River basin's population (Moench, 2010).

6.2 Effectiveness of embankments as flood remedial measures

The current study's findings suggest that increased flood vulnerability within the Kosi embankment, whether in hydro geomorphological or socioeconomic parameters, is primarily driven by human interventions such as flow control infrastructure, unplanned construction along the river's course, and a lack of political commitment to long-term safety.

Previous research by Leichenko & Sliva (2014); Mansur et al. (2016) demonstrates that poor hydrogeomorphic characteristics exacerbate socioeconomic vulnerability. This is also evident in our study, where the majority of hydro-geomorphic attributes, such as slope, inundation area, and land use land cover, exhibit that the region is highly vulnerable to flooding, which influences and worsens socioeconomic attributes including access to education, gender ratio, health access, agriculture land degradation, and poor housing and basic infrastructure.

On the other hand, the regions outside of embankments are not adapted to floods, despite being safe from yearly flooding. The embankment provided a false sense of security and protection, causing flood losses to become more significant and disastrous, which is evident from breaches in 1956-57, 1966, 1987, 2000, or 2008 (all after embankment construction) (Sinha[3], 2008; Dixit, 2009; Sinha, 2019), most of these circumstances acted as a catalyst, and the impact of the catastrophe exacerbated.

The history of Bangladesh's embankments and their failure in the early 2000s warns as a flood control measure and think for the other solutions (Saha, 2003). If there is a lesson to be drawn from the Kosi disaster, we need to shift toward a strategy emphasizing "river management" rather than "river control." Even the international community has questioned the embankment strategy, citing failures in the Mississippi and three major Chinese rivers **(**Dixit, 2009; **Bhattacharya, 2013).** Our experience shows that even after the construction of embankments and dams, there has been no discernible flood mitigation in the Kosi and other rivers of north Bihar.

6.3 Adaptive measures and present issues with people of Kosi

In comparison to national and state averages, the socioeconomic status of the villages covered in our study is extremely poor. For example, the embankment region's average female literacy rate is 32%, compared to the national average of 66%; there is also a substantial reliance on agriculture; amid uncertainty due to flooding, the region has become a migration hub.

People in the region adopted various strategies to cope with the Kosi's constantly shifting courses, flooding, waterlogging, and sand casting. Farmers here employed a variety of cropping patterns to adapt to the prevailing circumstances and deal with climate variability. Crops are still at risk, affecting crop productivity and farmers' economic well-being. The principal crop in these regions is paddy and wheat, and to protect the crops from flood hazard, farmers began growing a new variety of paddy known as "Garama Dhan" before the monsoon to protect the crops from flood hazard; they also introduced sunflower and early maize into the cropping cycle, began growing 'Makhana' or 'fox nut' and water chestnut in waterlogged areas, and began cultivating fruits and vegetables on sand casted lands (Singh et al., 2009).

Despite the various coping strategies, factors such as poor market access and insufficient food storage infrastructure are adaptation barriers especially in Supaul district (Fig. 11.). Inadequate regional roadways and transportation infrastructure have a direct impact on market access. As a result, most producers are forced to sell their products close to or within the village, limiting their ability to negotiate prices. Also, there are no major cold storage facilities in the region; farmers are frequently forced to sell their crops soon after harvesting when supply exceeds demand, lowering the product's market value (Singh et al., 2009). Moreover, the Bihar Special Survey Settlement Rules 2012 mandates that any farmland submerged in the Kosi River becomes the property of the state government, and the original owner must relinquish their claim to the land. Farmers along the Kosi River in Bihar argue that the law requiring them to give up their land appears unjust when the river continually shifts its course (Singh, 2009)**)**.

Nevertheless, the region has made little progress despite millions of rupees having already been spent on development projects (Moench, 2010)). Our study highlights that poor socio-economic development, such as low female literacy, greater reliance on agriculture, deplorable housing conditions, and poor road connectivity needs to be focussed. These parameters need to be improved to enhance people's resilience in this area. A socio-economic impact assessment is urgently needed to quantify the loss and rehabilitation of people living inside the embankment. The emphasis should be on improving education quality in flood-prone areas with low literacy and fewer educational institutions because people have to travel long distances to access them. There should also be an effort to improve housing conditions in the region, as kaccha houses were encountered in as many as 90% of the villages in the study area. Finally, the development of road connectivity should be prioritized within the embankment because it can bring growth and prosperity to the region by fostering the economic sector and acting as a lifeline during flood mitigation and evacuation.

7. Conclusion

The study demonstrated the flood vulnerability of communities living inside the Kosi embankment and the impact of flood hazards on the community's resilience through a multidisciplinary perspective. The study's primary aim was to develop a composite flood vulnerability map for the Kosi embankment region wherein incorporating a comprehensive thirteen parameters dataset, i.e., eight socio-economic parameters from village-level data and five hydro-geomorphological ones within the Kosi embankment.

The socio-economic vulnerability key findings suggest that more than 60% of the area within the embankment is under high and very high flood vulnerability, with 19% under moderate and low vulnerability zones merely crossing the 15% threshold. The study finds that the people's failure to respond to flood impacts demonstrates their social backwardness. A substantial chunk of the agriculture and related occupation-dependent population and poor literacy levels, particularly among women, pose significant obstacles in establishing resilience to flood losses. The geophysical vulnerability assessment, too, does not provide encouraging prospects. It revealed that nearly one-third of the population was high and very highly vulnerable to flooding, and approximately 34% were moderately vulnerable based on five crucial indicators employed in the study, i.e., slope, flow length, inundation area, land use, and elevation (refer to Table 10). According to the study area's composite vulnerability, 65% of the area is high and very vulnerable to the effects of flooding, and roughly 26% is moderately vulnerable. It means nearly the entire embankment is susceptible to flooding, and even the slightest of floods could have disastrous impacts.

Furthermore, the study attempts to assess the flood vulnerability of people living within the Kosi embankment, where the structure was built to protect them from the wrath of Kosi floods. Contrary to its specified objective, the embankment multiplied the flooding impacts and increased the socio-economic vulnerability, as most parameters suggested in the study. Although, the study faces numerous challenges in this attempt, primarily due to a lack of data in the study area and the use of the Kosi embankment as a study border. It is essential because the research area does not cover the entire river basin or use a district as an administrative boundary; instead, it focuses on the 283 villages and 8 lakh people who reside within the embankment. As a result, our work is significant and challenging, and it may lead to fruitful conversations and discussions about multidisciplinary flood control impact assessments. However, more such research, particularly on Indian river basins, is required to understand flooding processes, their impacts, and mitigation better. On the research and policy front, more field-level qualitative research is needed to assess the socio-economic effects of flood control infrastructure and guidelines for essential infrastructure services in these regions designed to operate in flood situations.

Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception and design. **Ajay Devda:** Material preparation, data analysis and writing. **Vishal Verma:** Material Preparation, Analysis and Writing. **Vikrant Jain:** Writing, Supervision and Editing.

Compliance with Ethical Standards

This work does not involve the use of any human participants or animals. This research article is original and has not been published nor is it being considered for publication elsewhere. All the authors mutually agree to this submission.

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Figures

Figure 1

Schematic representation of Kosi river embankment and lack of access to basic services

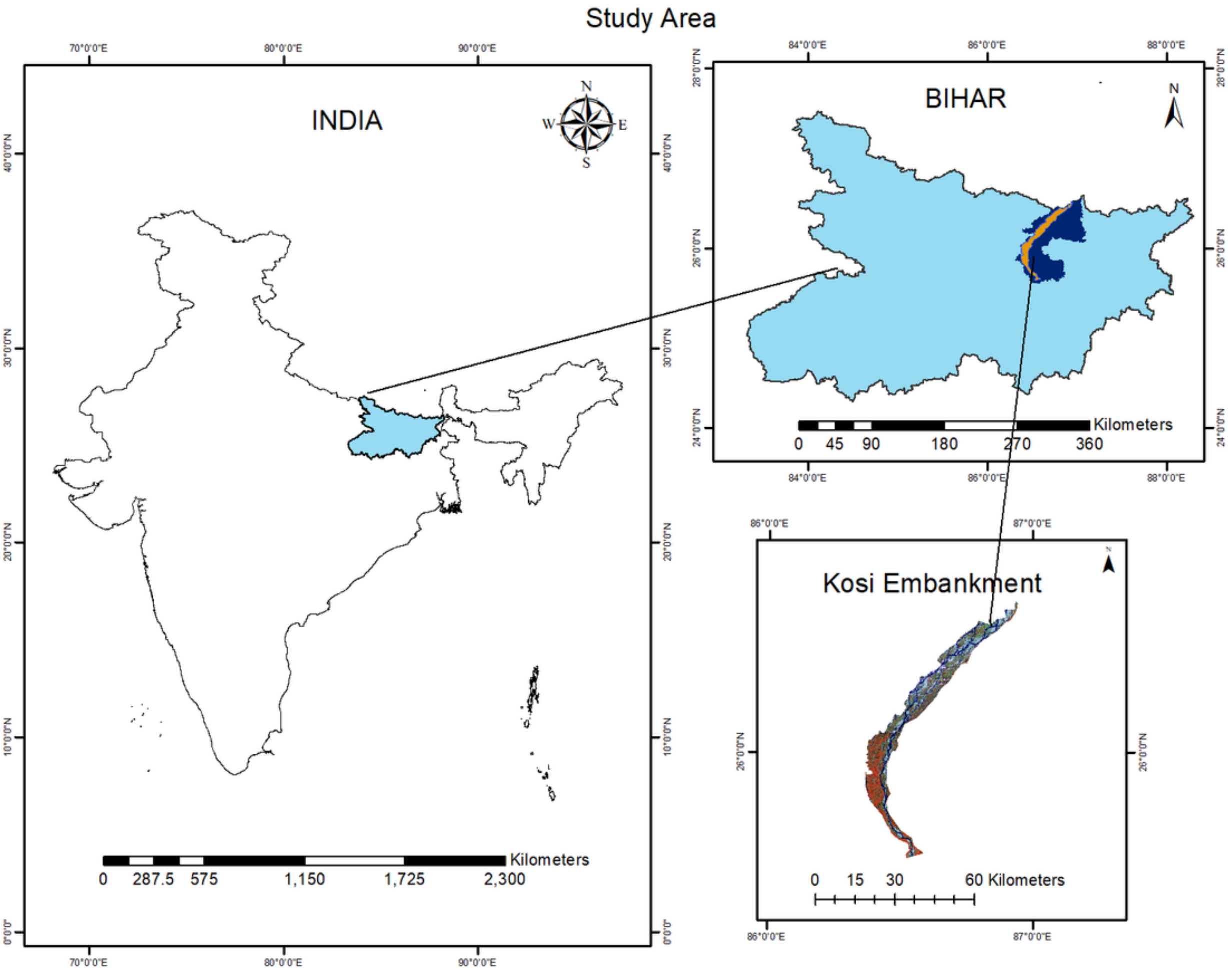

Figure 2

Study Area Map

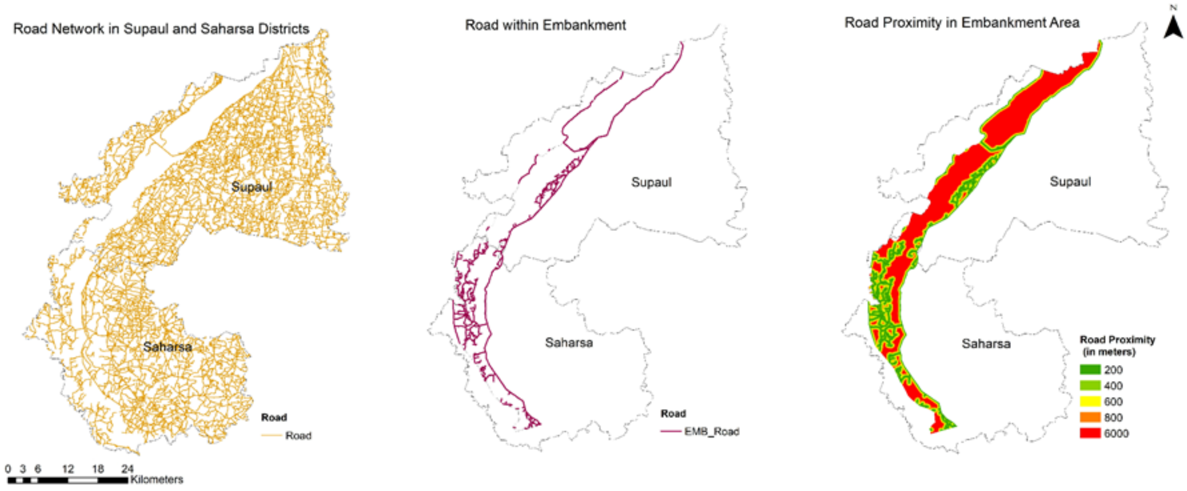

Figure 3

a. Road network in Supaul and Saharsa districts b. Road connectivity within the embankment c. Vulnerability based on road proximity within the embankment area.

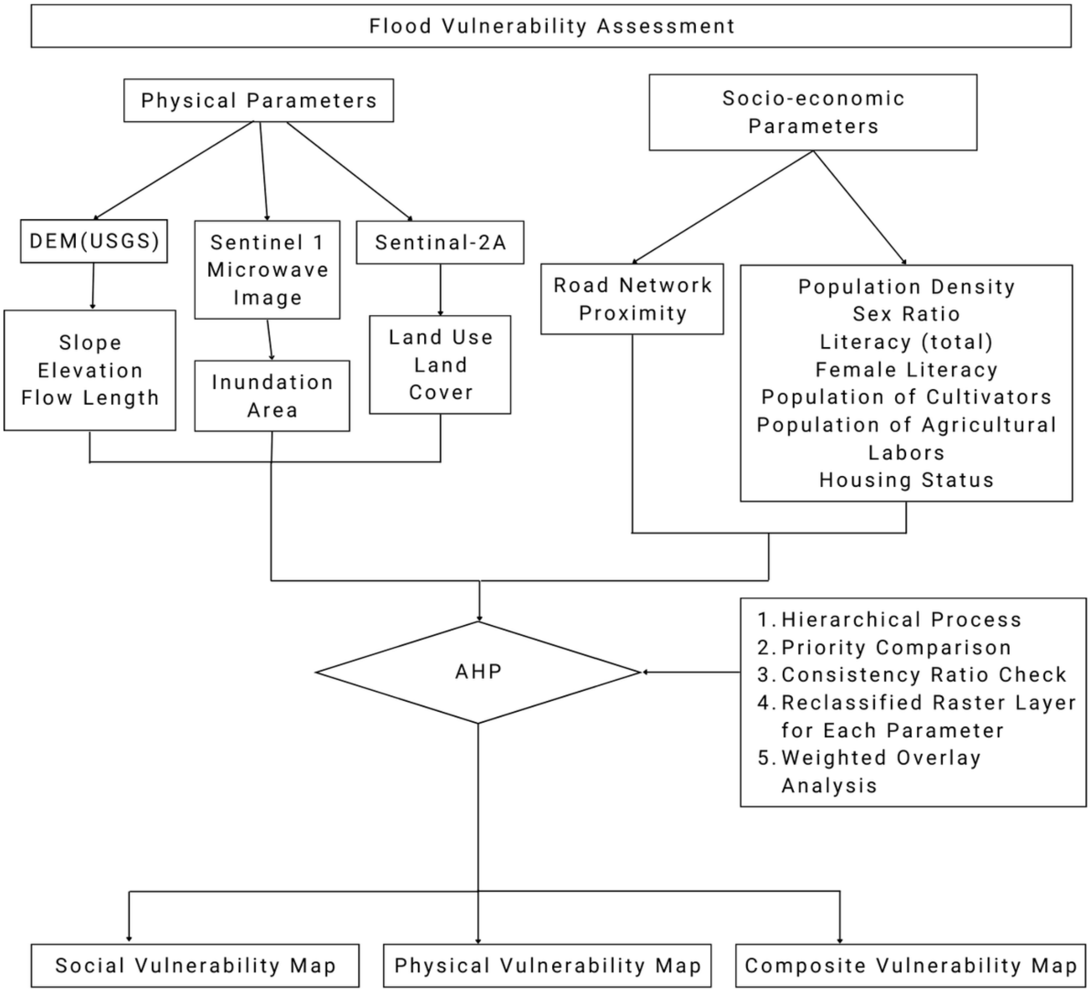

Figure 4

Fig. 3: Methodology flow chart

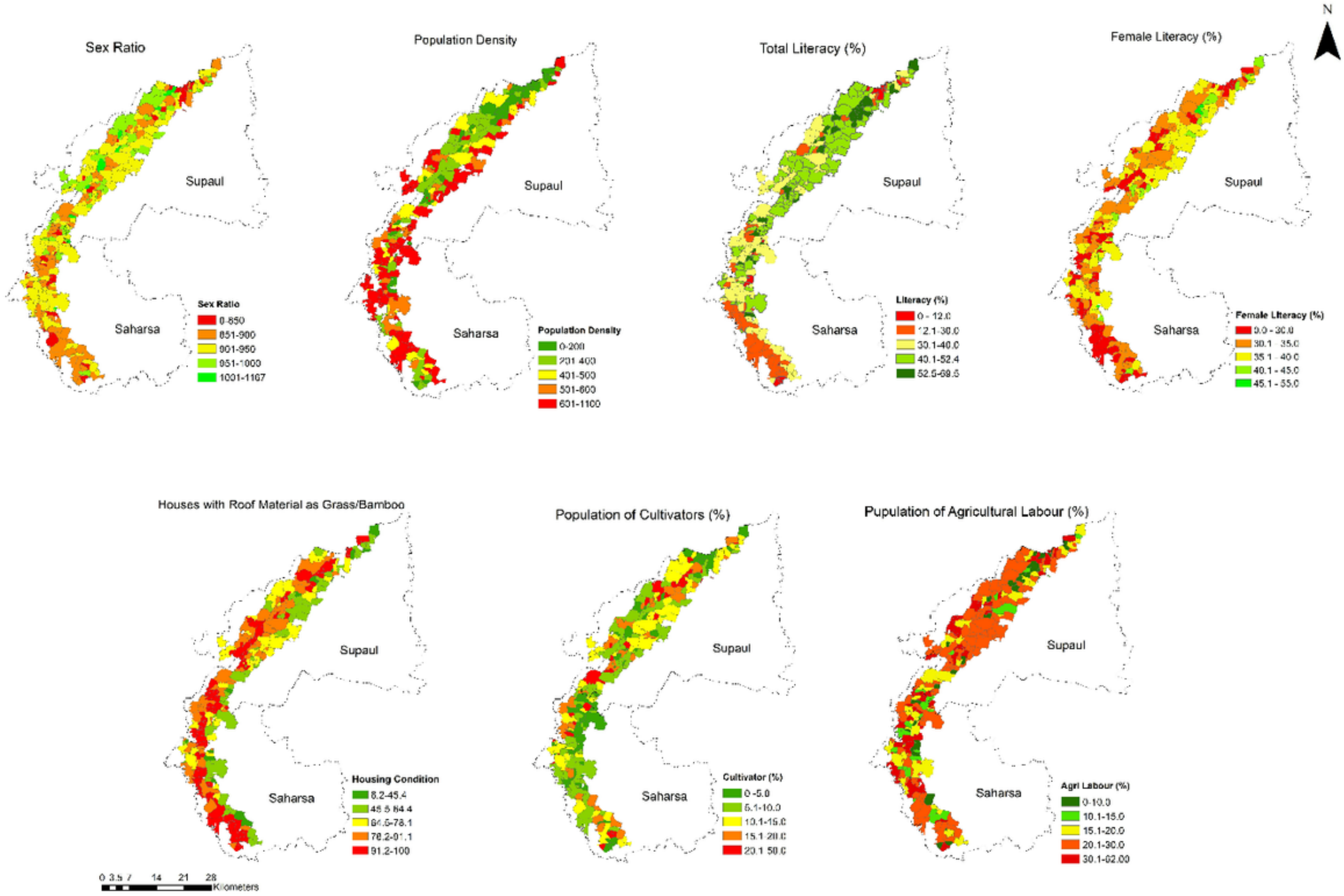

Figure 5

Socio-economic Vulnerability parameters

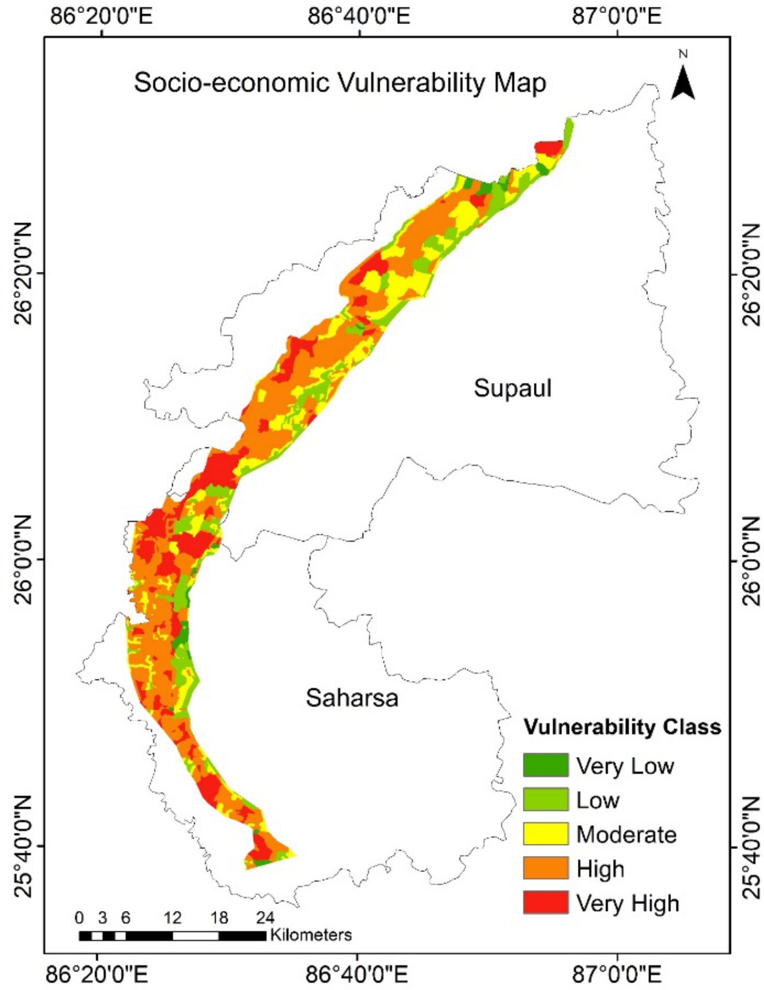

Figure 6

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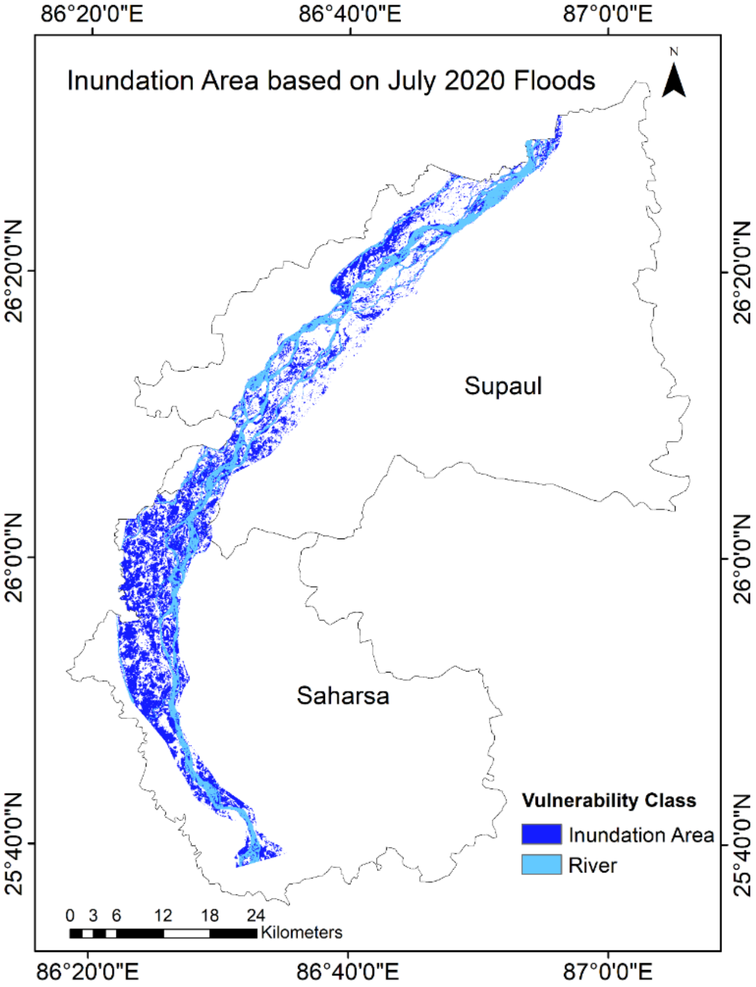

Figure 7

Flood Inundation area

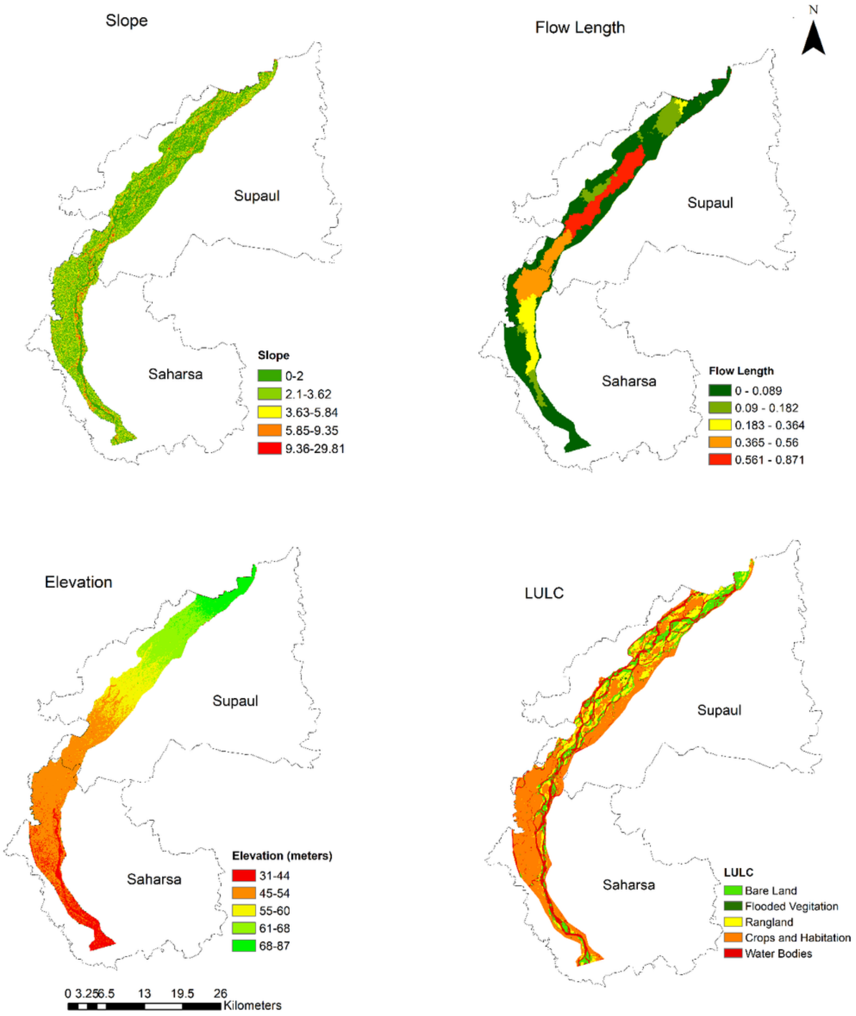

Figure 8

Hydro-geomorphic vulnerability parameters

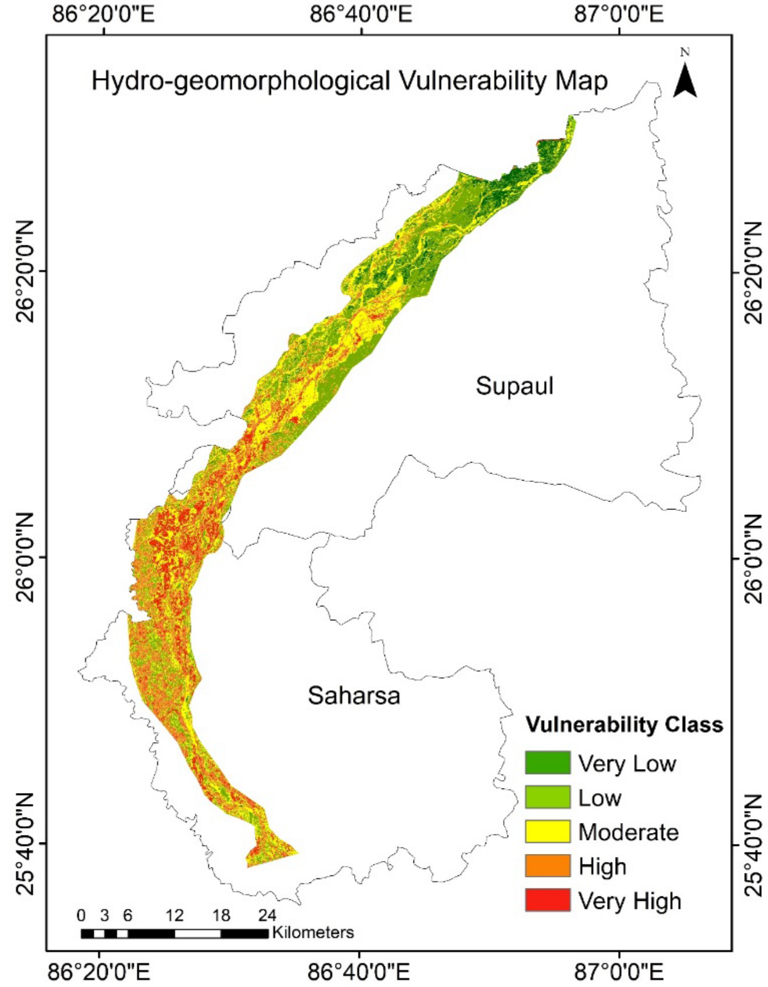

Figure 9

Hydro-geomorphic vulnerability Map

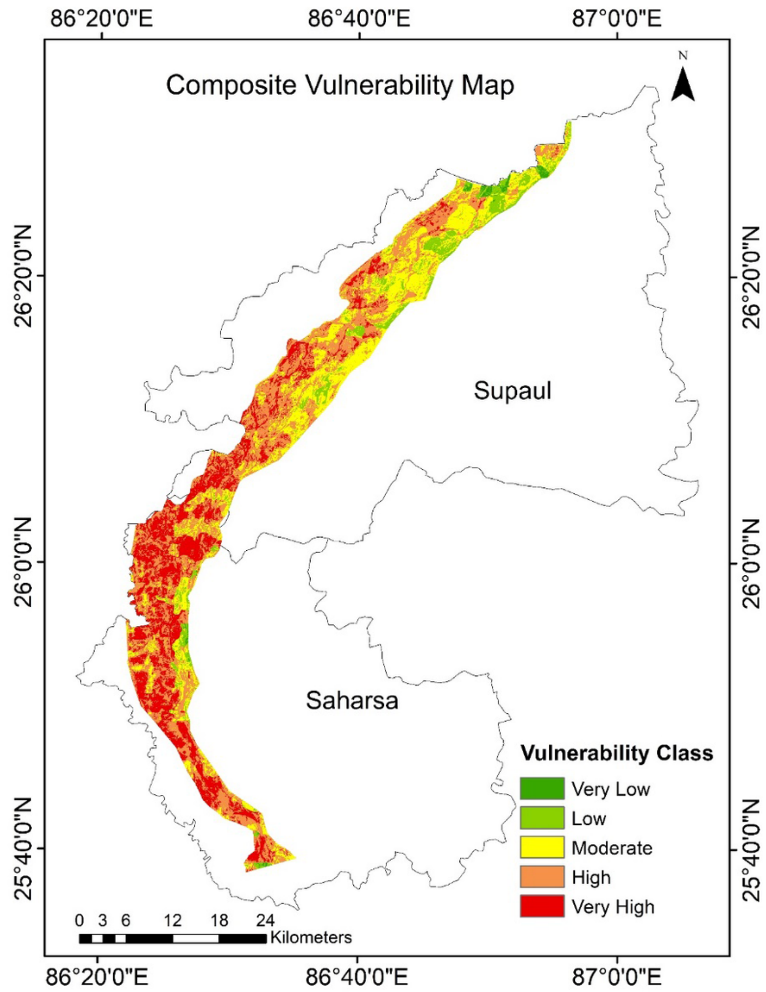

Figure 10

Composite vulnerability Map

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Figure 11

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