Assessing Flood Risk and Emergency Preparedness in Gandak River Basin, Bihar, India using AHP

Bharvi Bhatt[1,2], Shital Shukla[2], Joshal K. Bansal[3]

[1]Symbiosis Institute of Geoinformatics, Pune, India. [2]Gujarat University, Ahmedabad, India. [3]Center of Excellence in Disaster Mitigation and Management, Indian Institute of Technology Roorkee, Roorkee, India

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Abstract

India experiences floods more frequently than any other natural disaster with Bihar accounting for 17.2% of the flood prone area. Gandak river, one of the major river basins in north Bihar presents a challenge in terms of long and recurring riverine flood. While floods cannot be entirely prevented, their impact can be mitigated through effective flood risk mapping. This study integrates Remote Sensing (RS) and Geographic Information Systems (GIS) to analyze spatial flood drivers, using Sentinel-1 SAR data processed in Google Earth Engine (GEE) and ArcGIS Pro for geospatial modelling. The study aims to contribute in better emergency preparedness by developing flood frequency (2017-2024) and flood risk map. The Analytic Hierarchy Process (AHP) was used to weight important factors (elevation, slope, drainage density, distance from stream, rainfall, population density, land use land cover, soil bulk density, flood frequency). Flood frequency map highlighted how Gandak River basin experienced flood approximately 118 times over the span of 8 years. Flood extent was maximum for 2020 followed by 2017. Map shows high values near “Ganga Gandak Milan” in Munger district and near “Burhi Gandak and Ganga River confluence”. The flood risk map was categorized into very low, low, moderate and high-risk zone. Approximately 2776.7518 km^2 of the study area lies in moderate to high flood risk which accounts for 6.27% of the total area. A major portion of the study area lies in low flood risk zone (40788.99 km^2/84.4%). Purbi Champaran has the highest area under moderate to high flood risk (691 km^2).

1. Introduction

Last few decades have seen an increase in hydro-meteorological hazards like floods, droughts, and extreme weather events with flood accounting for 47% of all natural disasters, impacting approximately 2.3 billion people globally between 1995 to 2015 (Tripathi et al., 2022), (Matheswaran et al., 2019). In South Asia, India is particularly vulnerable to floods due to its geographical location, climate variability, and geological setting (NRSC, 2022). Most common types of floods occurring in India are riverine floods, coastal floods, flash floods, urban floods, pluvial floods and dam or levee failures (NRSC, 2023). This study focuses on riverine flood.

Bihar is one of the most flood affected states in the country, accounting around 17.2% of the flood prone area (NRSC, 2020). Several Himalayan rivers, with their catchment in Nepal, drain the plains of Bihar making it the most flood-prone state in India, with 76 per cent of the state population living in flood risk areas, and 73% of the total land area being flood affected. For this study Gandak River basin and its surrounding region has been considered for analysis.

Floods are difficult to contain and control, thus effective mitigation/management of flood risk is essential. This highlights the importance of creating flood risk map for effective disaster management. Flood risk mapping is essential as it aids in efficient evaluation of drainage network infrastructure and at the same time supports development efforts needed to reduce flood risk (N. Kumar & Jha, 2023).

Global trends in flood risk mapping include traditional methods like ground surveys and aerial observations but these methods become time consuming and expensive when phenomenon is widespread (Sinha, R., Bapalu, G.V., Singh, L.K. et al, 2008). Hydrological and hydraulic modeling are essential tools; hydrological models are used to estimate runoff within a basin, while hydraulic models simulate water behavior and flow dynamics during flood events. Modern tools used are Remote Sensing (RS), Geographic information system (GIS) and multi-criteria decision analysis (MCDA) which help to give thorough data on flooding risks and can be a strong foundation for the same all over the world (V. Kumar et al., 2023). GIS and RS are frequently used to study multiple parameters and create flood risk map. Optical RS has been widely used to observe and analyse the extent of flooding, allowing for accurate mapping of inundated regions. Multi-criteria decision analysis (MCDA) methods, such as the Analytical Hierarchy Process (AHP), are used to integrate the varied factors that are responsible for flood risk, allowing for the determination of the relative importance of each parameter (Danumah et al., 2016)(N. Kumar & Jha, 2023). Thus GIS, RS and AHP have been integrated as they offer a low-cost methodology to produce flood risk maps for Gandak River Basin.

For flood risk assessment the parameters considered by various research papers can be categorized into geomorphic, hydrological, and socio-economic factors. Geomorphic factors include elevation, slope, distance to active stream, and drainage density, as these influence water flow and accumulation. Hydrological parameters, such as rainfall, river discharge, and flood frequency, are crucial for understanding the water-related dynamics of flood events. Socio-economic parameters, including population density and land use/land cover, are considered to assess the vulnerability of communities and the impact of land cover on runoff (Ghosh & Kar, 2018) (N. Kumar & Jha, 2023) (S. Kumar et al., 2025) Sinha Bapalu LK Singh B Rath et al., 2008). Combining these, total 9 parameters are considered which are elevation, slope, drainage density, distance from stream, rainfall, population density, land use land cover, soil bulk density and flood frequency.

The aim of this research was to address emergency preparedness in Gandak River Basin by generating flood frequency map using GEE for 2017 to 2024 to analyze historical flood occurrences, derive flood risk map using AHP in ArcGIS Pro and identify vulnerable areas, settlements and agricultural area lying in the flood risk zone.

2. Study Area

This study focuses on Gandak River Basin in Northern Bihar. The plains of Bihar, adjoining Nepal, are drained by a number of rivers that have their catchments in the steep and geologically nascent Himalayas. Kosi, Gandak, Burhi Gandak, Bagmati, Kamla Balan, Mahananda and Adhwara group of rivers which originates from Nepal, carry high discharge and very high sediment load and drops it down in the plains of Bihar (NRSC,

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2023). Notable flood events occurred in Bihar due to Gandak River in 1998, 2001, 2003, 2004, 2007, 2012, 2013, 2014, 2015, 2019, 2020, 2021, (NRSC, 2023). This is one of the reasons for considering Gandak River basin. Another reason is, Gandak has built an immense megafan comprising Eastern Uttar Pradesh and North Western Bihar in the Middle Gangetic Plains. The megafan consists of sediments eroded from the rapidly-uplifting Himalaya. The river's course over this structure is constantly shifting. It is said that the river has shifted 80 km to the east due to tectonic tilting in the last 5000 years (Rai et al., 2015). The Gandak River has a steep slope in the upper region where it enters India and brings heavy silt load which causes continuous

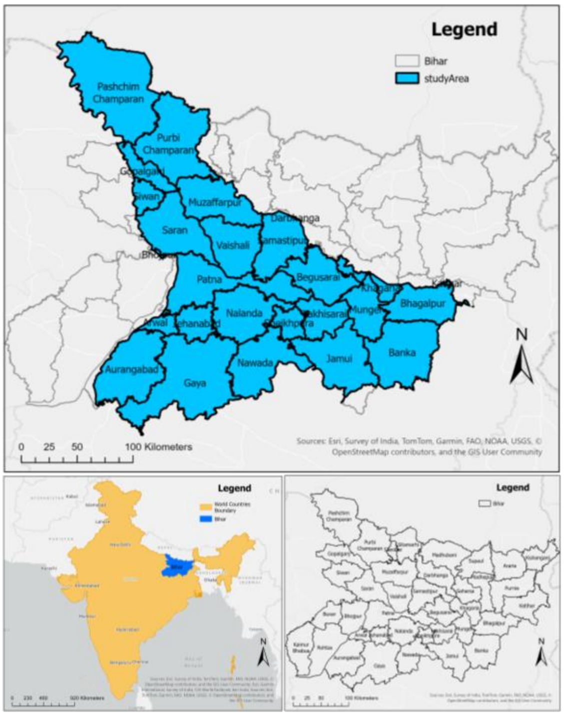

Figure 2.1 Districts in and around Gandak River Basin

morphological changes such as erosion and accretion along the river (S. Kumar et al., 2024).
Gandak is a left bank tributary of Ganga River majorly covering districts like Paschim Champaran, Purbi Champaran, Muzaffarpur, Gopalganj, Saran and Vaishali of Bihar (Rai et al., 2015). Apart from these districts other districts studied around the basin are Lakhisarai, Sheikhpura, Siwan, Begusarai, Munger, Aurangabad, Nawada, Gaya, Samastipur, Banka, Patna, Arwal, Jehanabad, Nalanda and smaller portions of districts like Bhojpur, Khagaria, Katihar, Jamui, Bhagalpur, Darbhanga nearby Gandak River basin. Figure 2.1 shows the map of districts in and around Gandak River basin. Total number of districts considered are 26. Total catchment area of Gandak is 46,300 square km, most of which is in Nepal. Gandak has a bigger catchment in Nepal but as it enters India it becomes narrow resulting in gushing of water in the river and higher chances of flood. Despite their frequent occurrence and substantial socioeconomic effects there aren't many localized research on flood risk mapping for Gandak River. Such events highlight the urgent need for comprehensive flood risk mapping that can provide actionable insights into vulnerable zones and inform disaster preparedness measures.

3. Dataset and Methodology

3.1 Dataset

NIDM defines flood risk as product of hazard, its exposure and vulnerability of exposed region, and product of flood probability and consequences. Thus, Flood Risk = Flood Hazard (Geomorphologic and Hydrologic Parameters) x Flood Vulnerability (Socio-economic Parameters)
Keeping the above concept in mind and referring to various literature, total nine parameters were taken into consideration which are categorized into hydrological, geomorphological and socio-economic (Sinha, R., Bapalu, G.V., Singh, L.K. et al, 2008), (N. Kumar & Jha, 2023), (S. Kumar et al., 2025) as shown in table 3.1.
Table 3.1 Nine parameters for flood risk mapping categorised into hydrological, geomorphological and socio-economic

Flood Hazard	*Hydrological*	Rainfall, Flood frequency
	Geomorphological	Elevation, Slope, Drainage Density, Distance from stream, Soil bulk density
Flood Vulnerability	*Socio-economic*	Population density, Land Use Land Cover (LULC)

Table 3.1 shows how flood hazard has been further categorized into hydrological and geomorphological. Hydrological parameters are associated with the behavior and movement of water in environment. It is measured by considering parameters like rainfall and flood frequency. Geomorphological parameters are the physical characteristics of earth's surface and subsurface that affect water movement, accumulation and flood susceptibility. This can be described by parameters like elevation, slope, drainage density, distance from stream and soil bulk density. Flood vulnerability can be measure using socio-economic parameters. It identifies how social and economic factors interact with flood hazard to manage the vulnerability, coping capacity and impact of flood. Parameters under this are population density and LULC.
Table 3.2 shows each parameter, its source and significance of considering that parameter.
Table 3.2 Flood parameters, its source and significance

Sr. No.	**Parameter**	**Sensor** *(resolution)* - **Source**	**Significance**
1	Flood Frequency	Sentinel 1 SAR (VH Band) *(10m)* - Google Earth Engine	It is crucial for understanding the water-related dynamics of flood events.
2	Elevation	CARTOSAT 1 DEM v3 *(~30m)* - Bhuvan	Elevation affects water flow and accumulation.
3	Slope	CARTOSAT 1 DEM v3 *(~30m)*	Slope affects the velocity of water.
4	Rainfall	Climate Hazards Group InfraRed Precipitation (CHIRPS) *(~5.55 km)*	Rainfall directly affects the amount of water in river.
5	Drainage Density	CARTOSAT 1 DEM v3 *(~30m)* – Derived using hydrology toolset of ArcGIS Pro.	The density of drainage channels affects how quickly water can move through an area.

6	Distance from river	CARTOSAT 1 DEM v3 *(~30m)* – Derived using hydrology toolset of ArcGIS Pro.	It affects the likelihood and severity of flooding. Regions close to a specified distance will have higher risk of getting inundated during flood.
7	Soil Bulk Density	SoilGrids prediction models are fitted using over 230 000 soil profile observations from the WoSIS database *(250m)*	It helps in determining the porosity of the soil, which is crucial for understanding water retention.
8	Population Density	Global Human Settlements Layers (GHSL) *(100m)*	If a region is prone to flood but no population resides there then its vulnerability is low and as a result risk will also be low.
9	Land Use Land Cover (LULC)	Sentinel 2A *(10m)* – ESRI ArcGIS Living Atlas of World	It affects the likelihood and severity of flooding. Urban areas have high risk of flash flooding due to the presence of large impervious areas and sometimes inefficient drainage system.

3.2 Methodology

The process of deriving flood risk map and flood frequency map consisted of several steps. First the study area boundary was delineated followed by identification of parameters affecting flood risk. Next step was to generate flood frequency map for 2017 to 2024 using GEE. Thematic layers were then prepared in ArcGIS Pro to serve as inputs using hydrology toolset. Finally, these parameters were integrated using AHP within the Spatial Analyst tool to produce the flood risk map.

For elevation of study area ten DEM images with approximately 30m resolution were merged into single raster. This raster was then used to derive slope. Unit of DEM and slope is meters. Annual average rainfall was taken from 2014 to 2024 (11 years) to understand rainfall pattern. Units of measurement is millimetres. Drainage density was derived from elevation raster by performing the following steps using hydrology toolset in spatial analyst of ArcGIS Pro: DEM –> Fill –> Flow Direction -> Flow accumulation -> Raster calculator / reclassify –> Stream Order -> stream to feature -> Line density. Stream feature shape file generated in drainage density was used to derive distance from stream by calculating Euclidean distance. Flood frequency can be calculated using statistical methods (e.g. gumbel's method), using rainfall run-off models or using satellite data. In this study flood frequency was calculated using satellite data for 2017 to 2024 (8 years) in google earth engine. Flood dates for given date range was extracted manually from NDEM website. Before and after images of flood were extracted for each year considering VV polarisation of sentinel 1. After flood image and before flood image were divided and a ratio-based threshold of 1.25 was taken to generate mask. Images with filtered out regions of permanent water bodies, steep slopes and isolated pixels was summed up calculate flood frequency for 8 years. The code was developed using documentation provided by Ujaval Gandhi in his course on "Flood Mapping" in Google Earth Engine.

The AHP algorithm was used where each reclassified parameter was categorized from highest priority to lowest priority using Multiple criteria decision making (MCDM). This technique is more effective to solve the problem of flood risk having several factors (S. Kumar et al., 2025). The reclassified parameters were given as input to AHP and flood risk map was generated. AHP is a technique based on ratio scales via pair-wise comparisons. The primary eigenvectors are used to create the ratio scales, whereas the principal eigenvalue is used to create the consistency index (CI) (S. Kumar et al., 2025). The weights of these criteria are determined once they have been sorted in order of importance. Following the hierarchical sorting of all criteria, a pairwise comparison matrix for each criterion is constructed to allow for a significant comparison. The relative importance of the factors is ranked from 1 to 9, with 1 representing the least important and 9 representing the most significant condition.

Table 3.3 Saaty Scale

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two elements contribute equally to the objective.
2	Weak or Slight	Slightly favour one over the other.
3	Moderate Importance	Experience or judgment slightly favours one element over another.
4	Moderate Plus	A compromise between moderate and strong importance.
5	Strong Importance	Experience or judgment strongly favours one element over another.
6	Strong Plus	A compromise between strong and very strong importance.
7	Very Strong Importance	One element is strongly favoured and its dominance is demonstrated in practice.
8	Very, Very Strong	A compromise between very strong and extreme importance.
9	Extreme Importance	The evidence favouring one element over another is of the highest possible order.
2, 4, 6, 8	Intermediate Values	Used to express nuances between the primary scale values.
Reciprocals (1/3, 1/5, etc)	Inverse Comparisons	If element A is moderately more important than B (3), then B is 1/3 as important as A.

Table 3.3 shows the Saaty Scale used for measuring the importance of each parameter contributing to the objective.

4. Results and Discussion

4.1 Thematic Layers Generation

Present study makes use of nine thematic layers which are integrated using AHP and GIS in ArcGIS Pro to produce flood risk map. The nine parameters are show in figure 4.1 along with their range of values. The layers generated using collected datasets are elevation, slope, rainfall, flood frequency, soil bulk density, distance from stream, population density, drainage density and LULC.

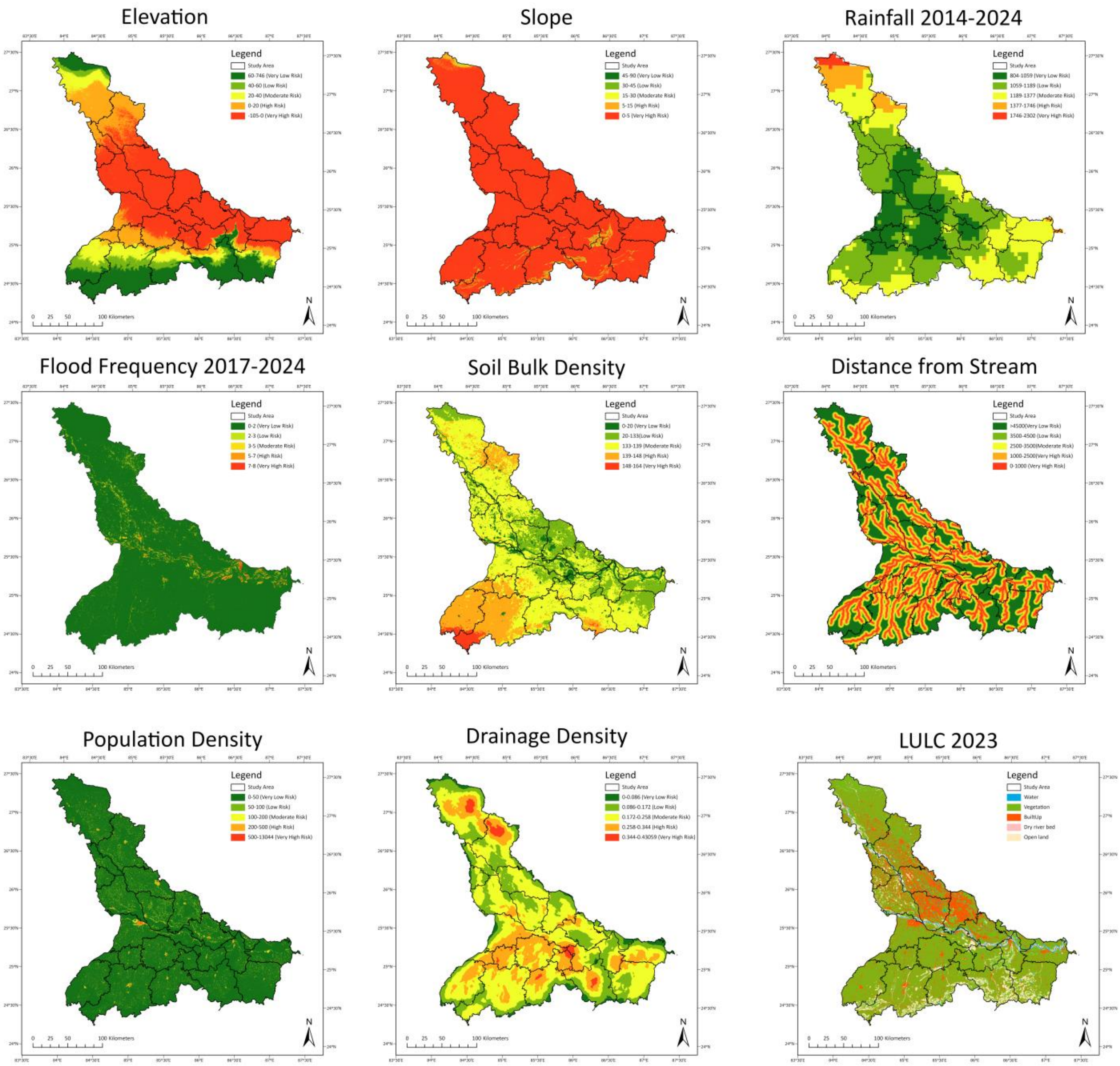

Figure 4.1 Thematic Maps

Gradual drop in elevation towards the centre can be seen in figure resulting in increased chances of water accumulation (Flood). Ganga river flows through central region with lower elevation. Highest elevation is in Jamui and lowest elevation is in Bhagalpur. Slope is steep in southern portion near Munger, Lakhisarai, Jamui and Paschim Champaran. It is maximum in Nalanda and minimum in Siwan. Higher precipitation is observed near mountains and it gradually reduces as we move towards center. Minimum is in Nalanda and maximum in Paschim Champaran. Drainage density is more near higher elevations. A higher risk of flooding is indicated by areas with extremely high drainage densities, which are commonly found in metropolitan areas, beside major roadways, and in agricultural areas. Minimum value is in Siwan and maximum in Arwal. 20% of the study area is within 1km distance from streams. Minimum value is in Jehanabad and maximum in Jamui. Projected population density is minimum in Jamui and maximum in Patna. Soil bulk density is low along the river. It is minimum in Bhagalpur and maximum in Aurangabad.

The nine thematic layers were reprojected to 45N and resampled using bilinear method to 30m resolution. They were further reclassified into five classes which were – 1) Very low risk 2) Low risk 3) Moderate risk 4) High risk 5) Very high risk as shown in the below table 4.1.

Table 4.1 Reclassified thematic parameters

Parameter	Range	Rank
Elevation	-105m – 0m	5

	0m – 20m	4
	20m – 40m	3
	40m – 60m	2
	60m – 746m	1
Slope	0 – 5	5
	5 – 15	4
	15 – 30	3
	30 – 45	2
	45 – 90	1
Rainfall	804 – 1059	1
	1059 – 1189	2
	1189 – 1377	3
	1377 – 1746	4
	1746 – 2302	5
Drainage Density	0 – 0.086	1
	0.086 – 0.172	2
	0.172 – 0.258	3
	0.258 – 0.344	4
	0.344 – 0.4305	5
Flood Frequency	0 – 2	1
	2 – 3	2
	3 – 5	3
	5 – 7	4
	7 – 8	5
Distance from river	0 – 1000	5
	1000 – 2500	4
	2500 – 3500	3
	3500 – 4500	2
	> 4500	1
Population Density	0 – 50	1
	50 – 100	2
	100 – 200	3
	200 – 500	4
	500 - 13044	5
Land use Land cover	Water	1
	Vegetation	4
	Built Up	5
	Dry river bed	2
	Open land	3
Soil Bulk Density	0 – 20	1
	20 – 133	2
	133 – 139	3
	139 – 148	4
	148 – 164	5

4.2 AHP for flood risk assessment

Using Analytic Hierarchy Process (AHP) all data was integrated in GIS environment. The flood risk assessment is the combination of flood hazard and vulnerability analyses. The analysis of a region using AHP starts with pairwise comparison matrix as show in table 4.2 followed by normalisation of that table as shown in table 4.3. Further relative weights are derived as can be seen in table 4.4. After assigning the weight, weighted overlay analysis tool available is used. The following tables 4.2, 4.3, 4.4 use abbreviations for parameter name which are written in bracket – Elevation (E), Slope (S), Rainfall (Rf), Drainage Density (Dd), Distance to River (Drr), LULC (L), Soil Type (ST), Population (P), Flood Frequency (Ff).

Table 4.2 Pairwise Comparison Matrix

Crit.	E	S	Rf	Dd	Drr	L	ST	P	Ff
E	1	1/2	1/2	2	2	5	5	5	1/3
S	2	1	2/3	3	3	6	6	6	1/2
Rf	2	1 1/2	1	2	2	5	5	5	1/3
Dd	1/2	1/3	1/2	1	1	4	4	4	1/4
Drr	1/2	1/3	1/2	1	1	4	4	4	1/4
L	1/5	1/6	1/5	1/4	1/4	1	1	1	1/7
ST	1/5	1/6	1/5	1/4	1/4	1	1	1	1/7
P	1/5	1/6	1/5	1/4	1/4	1	1	1	1/7
Ff	3	2	3	4	4	7	7	7	1
Total	9.60	6.17	6.77	13.75	13.75	34.00	34.00	34.00	3.10

Table 4.3 Normalised pairwise comparison matrix

Crit.	E	S	Rf	Dd	Drr	L	ST	P	Ff
E	0.1042	0.0811	0.0739	0.1455	0.1455	0.1471	0.1471	0.1471	0.1077
S	0.2083	0.1622	0.0985	0.2182	0.2182	0.1765	0.1765	0.1765	0.1615
Rf	0.2083	0.2432	0.1478	0.1455	0.1455	0.1471	0.1471	0.1471	0.1077
Dd	0.0521	0.0541	0.0739	0.0727	0.0727	0.1176	0.1176	0.1176	0.0808
Drr	0.0521	0.0541	0.0739	0.0727	0.0727	0.1176	0.1176	0.1176	0.0808
L	0.0208	0.0270	0.0296	0.0182	0.0182	0.0294	0.0294	0.0294	0.0462
ST	0.0208	0.0270	0.0296	0.0182	0.0182	0.0294	0.0294	0.0294	0.0462
P	0.0208	0.0270	0.0296	0.0182	0.0182	0.0294	0.0294	0.0294	0.0462
Ff	0.3125	0.3243	0.4433	0.2909	0.2909	0.2059	0.2059	0.2059	0.3231
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Table 4.4 Relative derived weights

Parameters	**Weights**
Elevation	0.122
Slope	0.177
Rainfall/ Precipitation	0.160
Drainage density	0.084
Distance to river	0.084
LULC	0.028
Soil type/ soil texture	0.028
Population	0.028
Flood frequency map	0.289

Consistency ratio (CR) was calculated for validation. Table 4.5 shows randomness index range. As the study has nine parameters, n=9 and thus RI=1.45.

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Class	**1**	**2**	**3**	**4**
Area (km^2)	4717.888	40788.99	2724.694	52.0578
Area (%)	9.771196	84.47789	5.643101	0.107817

Table 4.5 Randomness Index

n	1	2	3	4	5	6	7	8	9
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

n	10	11	12	13	15
RI	1.49	1.51	1.48	1.56	1.57

CR=CI/RI where CI= $\lambda - n / n - 1$,
where CR = Consistency Ratio, CI = Consistency Index and RI = Randomness Index, n = 9
λ= 9.276139481, CI= 0.034517435
As there are 9 parameters in this study the value of RI is 1.45.
Therefore, CR = 0.023805128. As CR < 0.1 the above AHP weights can be said to be consistent. The final step is to calculate flood risk map using weighted overlay. For further analysis on flood risk map, Zonal statistics was run on all parameters to derive district wise area. Area is calculated by multiplying pixel count into 0.0009 {1 pixel = 30m X 30m OR 0.0009 km2}.
Final output of Analytic Hierarchy Process (AHP) Flood Risk was categorized into – 1) Very Low risk 2) Low risk 3) Moderate risk 4) High risk
The category "**No Risk**" was excluded intentionally as it is not feasible to say that any region in Gandak River Basin is completely free of flood risk. Given the region's flood-prone nature, even areas with minimal flood occurrence still possess some level of flood probability.

4.3 Flood Risk Map

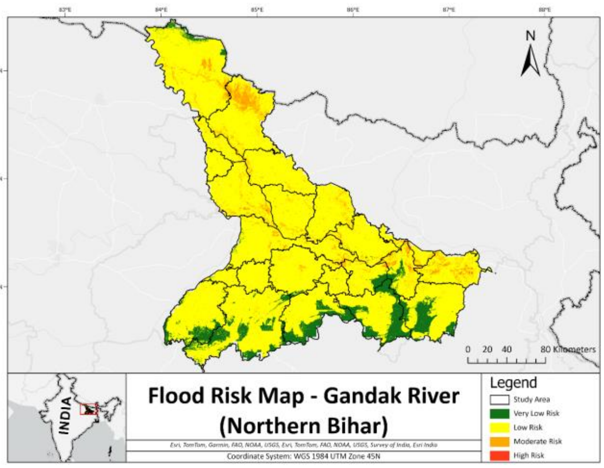

Figure 4.2 Flood Risk Map

Based on the flood risk map and from LULC map, vegetation under risk and built up under risk was derived. Reason for not considering other 3 classes of LULC was because they were not significantly vulnerable to the flood (as no one resides in those areas) despite of being risk present. The above image highlights how flood risk is less in southern portion with mountainous region. Visually looking at the map it can be identified that flood risk is more in Bhagalpur and Purbi Champaran. Also flood risk is more along the river and at confluence of river Ganga and Gandak.

Table 4.6 Flood Risk Area

Referring to above table 4.6 it can be identified that area under moderate flood risk is 2724.694 km^2 and high flood risk is 52.0578 km^2. A major portion of the study area is under low risk.
Combining flood risk map 4.2 and elevation, slope, rainfall, drainage density distance from stream, population density and soil bulk density as seen in figure 4.1, we get table 4.7 which shows how much percent area for each parameter lies in which flood risk zone. Elevation and slope have a higher percentage of area lying in moderate to high-risk zone.
Table 4.7 Out of the total flood risk area, how much area lies in which risk zone (1 to 5)

Rank	1	2	3	4	5
Parameter	Percent Area				
Elevation	18.99	6.67	10.09	19.17	45.06
Slope	0.047	0.45	1.22	1.90	96.36
Avg. Rainfall	22.80	41.68	28.4	5.96	1.11
Drainage Density	3.394	26.87	46.35	21.41	1.956
Distance from Stream	30.35	11.08	13.49	24.95	20.11
Population Density	91.85	4.595	2.372	0.95	0.21
Soil Bulk Density	6.114	22.64	49.68	19.49	2.06

Combining flood risk map 4.2 and LULC map in figure 4.1 we get table 4.8. It shows how agriculture is under high risk. LULC for year 2023 shows minimum builtup in Arwal and maximum in Samastipur.

Table 4.8 LULC v/s Percentage Area under Flood Risk

Class	1 (Water)	2 (Agriculture)	3 (Built up)	4 (Dry river bed)	5 (Open land)
Percent Area	2.13302	69.12677061	18.7783423	1.0902202	8.87164592

Combining flood risk map 4.2 and flood frequency map 4.1, we get table 4.9 as shown below.

Table 4.9 Area inundated every year from 2017 to 2024

Year	Area (Km^2)	% of total area
2017	2885.74	5.86
2018	1302.35	2.64
2019	1495.09	3.03
2020	2917.06	5.92
2021	2016.67	4.09
2022	1749.94	3.55
2023	1231.83	2.50
2024	2054.25	4.17

Above table shows flood frequency over 8 years. In this study flood frequency was calculated for 2017 to 2024 using Sentinel 1 SAR data. The results identified 2020 as the year with maximum area (2917.06 km^2 / 5.92%) under flood followed by 2017 (2885.74 km^2 / 5.86%). On verification from various news articles and government reports it is concluded that in 2020 and 2017, highest loss had been during 2017. Flood frequency map shows Munger in Bihar has high flood frequency but flood risk in Munger is moderate. As per Munger District Disaster Management Plan the reason for increasing flood frequency can be climate change and rapid unplanned urbanization. It is important to note that flood frequency is more along the river especially where the river meanders and meets Ganga River. As the elevation reduces flood frequency increases. Flood occurred 118 times over the span of 8 years. High flood frequency can be observed near Bhagalpur.

Combining flood risk map 4.2 and LULC column of table 4.8, we get a table 4.10 which shows how much area of LULC is under which risk zone. The table indicate vegetation under high risk followed by built up. Table 4.10 was calculated by using zonal statistics and then multiplying each pixel to obtain area.

Table 4.10 Flood Risk v/s LULC 2023

Row Labels	Water	Vegetation	Built Up	Dry river bed	Open land	Grand Total
Very Low Risk	35.1063	2900.2977	188.379	1.116	1592.9892	4717.8882
Low Risk	889.3503	28402.6932	8733.5199	414.9612	2348.4645	40788.9891
Moderate Risk	102.2193	2051.0388	174.3426	107.1918	289.9017	2724.6942
High Risk	0.6984	45.3204	0.4086	0.3699	5.2605	52.0578
Grand Total	1027.3743	33399.3501	9096.6501	523.6389	4236.6159	48283.6293

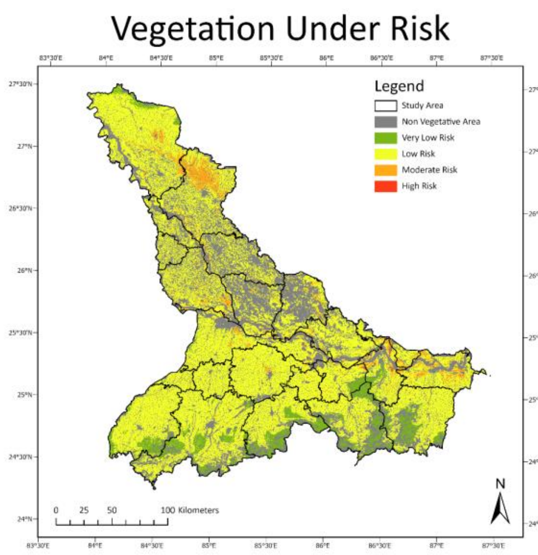

Figure 4.4 Vegetation under risk

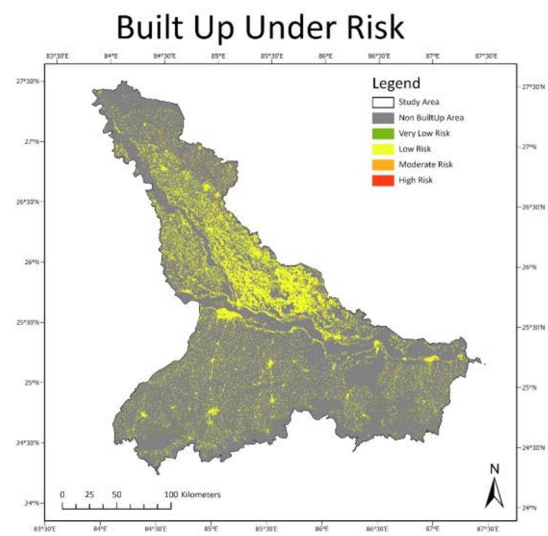

Figure 4.3 Built Up Under risk

Above figure 4.3 was obtained by reclassification and zonal statistics. It depicts how maximum area in Bihar is covered by vegetation. This can also be verified by knowing that a lot of area of Bihar is dependent on agriculture. Map highlights vegetation in Paschim Champaran and Bhagalpur is under high risk.

Figure 4.4 shows how builtup is under lower risk. Majority of the builtup is in begusarai, samastipur and Vaishali. But when compared with population density, it shows how patna has high population and high builtup.

Chart 1 shows how flood risk is spread across each district in terms of area. It is important to note that only smaller portions of districts like Bhojpur, Khagaria, Katihar, Jamui, Bhagalpur, Darbhanga which are nearby Gandak River basin are considered and not the entire district.

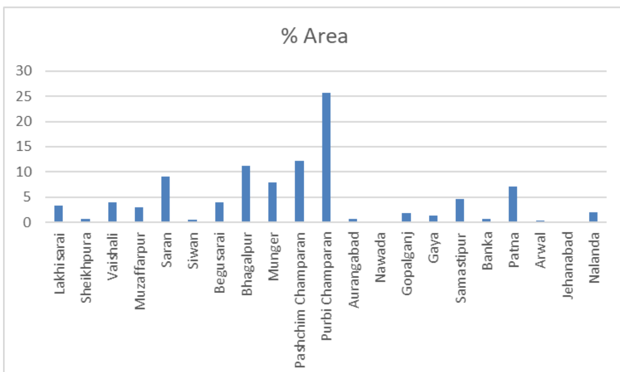

Chart 1 Flood Risk Distribution across study area

Taking a look at district wise distribution of flood risk, Purbi Champaran (691 km^2) has highest area under moderate to high flood risk followed by Paschim Champaran (329 km^2) and Bhagalpur (298 km^2). On identifying how much area of LULC is under moderate to high risk for built up 175 km^2 and for vegetation is 2096.3592 km^2.

Conclusion

Flood is unavoidable but it's impact can be addressed by making flood risk map. Present study provides a GIS and AHP based approach to integrate various hydrological, geomorphological and socio-economic parameters for deriving flood risk map of Gandak. River basin located in Bihar. Flood frequency is an essential parameter considered for deriving flood risk. Flood frequency map generated for 2017 to 2024 using GEE highlights how gandak river basin has experienced flood approximately 118 times in past 8 years. This supports the need to have a flood risk map of the region for better decision making and understanding the impact of flood. Flood frequency calculated shows high near "Ganga Gandak Milan" in Munger district and near "Burhi Gandak and Ganga River confluence". In the span of 8 years flood frequency was observed maximum for 2020 (5.92%) followed by 2017 (5.86%) where highest loss had been during 2017. Considering flood frequency and 8 other parameters, flood risk map was derived. It was categorized into very low, low, moderate and high-risk zone. Approximately 2776.7518 km^2 of the study area lies in moderate to high flood risk which accounts for 6.27% of the total area. A major portion of the study area lies in low flood risk zone (40788.99 km^2 / 84.4%). Purbi Champaran has the highest area under moderate to high flood risk (691 km^2). Gradual decrease in the elevation could be one of the reasons for it. It can be seen that regions where two rivers are meeting have a high flood risk along with regions where the river meanders. High flood risk can be seen in northern region of Purbi Champaran and Paschim Champaran as the river enters the flat plains.

The findings of this study would aid disaster management authorities in decision making and developing early warning systems. Based on the risk zone a region falls in; organizations can plan resource allocation. For example, regions under high flood risk can be high priority during resource distribution. The study can indirectly be useful for land use and crop insurance as well.

The study has a few limitations which can be addressed as a future scope. One major limitation is use of flood frequency data from only 2017 to 2024, which may not be sufficient to fully capture long-term flood patterns. GIS and AHP have been used to integrate hydrological, geomorphological, and socio-economic parameters. But the weightage of these parameters is subjective. The flood risk map represents risks as static zones, whereas, in reality, flood risk is dynamic. A key limitation of the study is the limited consideration of socio-economic parameters in the flood risk mapping process. While some socio-economic factors were included, a broader set of variables could have provided a more comprehensive understanding of the true social impact of floods.

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