



Assessing flood risk using analytical hierarchy process (AHP) and geographical information system (GIS): application in Coochbehar district of West Bengal, India

Subhankar Chakraborty^{1,2} · Sutapa Mukhopadhyay¹

Received: 17 July 2018 / Accepted: 2 August 2019 / Published online: 10 August 2019
© Springer Nature B.V. 2019

Abstract

Floods are recurrent events in the floodplains of Coochbehar district inundating and damaging considerable quantities of standing crops and hampering the livelihoods of thousands of peoples. This paper addresses an efficient and reliable methodology for preparing flood risk map for the Coochbehar district based on two essential concepts of hazard and vulnerability. With the aid of analytical hierarchy process, a variety of hazard and vulnerability defining criteria have been weighted according to their contributions and were further processed in the geographical information system environment to observe and assess spatial characters of flood hazard index (FHI) and flood vulnerability index (FVI) that collectively have defined the flood risk index (FRI). Accordingly, the eastern, southeastern, southern, central and north-central parts of the district are prone to frequent floods while vulnerability levels are higher at areas locating particularly along the India-Bangladesh international border in the south, southeast and southwest and in some isolated clusters in the central and north-central parts. The influences of these FHI and FVI in shaping the FRI distribution were observed to be varying at places. The Tufanganj subdivision is found to be the least safe administrative unit followed by the Coochbehar Sadar, Mathabhanga and Dinhata subdivisions. The rest, i.e., the Mekliganj subdivision is observed to be relatively safe but is not immune at all. The flood risk distribution yielded the information of 58 (4.91%) settlements with higher FRI scores followed by 145 (12.29%) villages/towns with moderate and 456 (38.64%) villages/towns under low flooding risks.

Keywords AHP · Coochbehar · Hazard · Flood risk · Flood vulnerability

✉ Subhankar Chakraborty
subhageographervb@gmail.com

¹ Department of Geography, Visva-Bharati, Santiniketan, West Bengal 731235, India

² Dhupguri, Jalpaiguri, India

1 Introduction

Flood as a frequently occurring hazardous phenomena often results in immeasurable human sufferings and economic losses (Qi and Altinakar 2011; Balica et al. 2013) throughout the globe; however, its intensity varies with time and spaces. Since last three decades, the trends in flooding have increased globally and this increase is comprehensively due to the effects of climate change, changes in landuse and other human intervention activities (Kourgialas and Karatzas 2011). It is predominantly the developing countries particularly those situated in the Asian continent that experience around 90% of such natural disasters and 95% of resultant life losses (Gupta et al. 2003). As floods are perhaps impossible to be prevented completely and their negative consequences can be experienced (Dewan et al. 2007) and evaluation and management of future floods is therefore, a more feasible option (Kourgialas and Karatzas 2011). It lays the evolution of the approach of ‘flood risk management’ which comprises of two basic foundations namely—(a) flood risk assessment and (b) flood risk mitigation (Schanze et al. 2006; Kazakis et al. 2015). Undoubtedly, flood management strategies at any scales demand the identification of flood prone areas (Tehrany et al. 2013) at the beginning to provide early warning, facilitate quick response and reduce the impact of possible flood event. Besides the comprehensive mapping of flood vulnerable locations, flood risk maps are essentially critical tools to check the effectiveness of the existing flood defense systems. Hopefully, in recent years the flood prevention and mitigation strategies took a u-turn from the classical ‘*flood defense*’ approach that have emphasized solely in controlling the floods through some structural measures to a ‘*flood management approach*’ which relies on integrated risk assessment studies and cost-benefit analyses (Merz et al. 2010; Dottori et al. 2018).

In recent years, the flood vulnerability and risk analysis/mapping studies have seen rapid methodological development (Tehrany et al. 2017). Numerous studies have been made to assess flood vulnerability and risk of different parts of the world (Hu et al. 2017) and different techniques and approaches have been employed to identify flood risk and delineate them into maps, e.g., Multiple Criteria Analysis (Hazarika et al. 2018; Sharma et al. 2018); Frequency Ratio, Cluster Analysis, Principal Component Analysis and varied statistical models (Fernandez et al. 2016a; Khosravi et al. 2016; Mollah 2016; Rahmati et al. 2016a); Analytical Hierarchy Process (Hu et al. 2017); Indicator based indexing (Balica et al. 2009; Balica 2012a, b; Balica et al. 2012); and a variety of modelling approaches applied in the GIS environment (Sanyal and Lu 2006; Tehrany et al. 2013, 2014). Out of these set of methods, the analytical hierarchy process (AHP) is been used widely for flood risk assessments (Sinha et al. 2008; Fernandez and Lutz 2010; Kazakis et al. 2015; Elkhrachy 2015; Rahmati et al. 2016b; Hu et al. 2017; Ghosh and Kar 2018) because of its clear and strong practical applications and realistic reflection of the elements of floods and its affected systems (Hu et al. 2017).

Usually, floods are multidimensional and have spatial components indicating the flood risk studies to understand their causative factors that are further characterized by some complex multiplicity in terms of their sources, types, scales and resolutions. Therefore, they need to be geographically correlated to each other (Rahmati et al. 2016b). GIS as an integrated domain consisting of an information database and analytical tools with its use as a decision support system is getting much popular in vulnerability and risk assessment studies (Sanyal and Lu 2006; Dewan et al. 2007; Qi et al. 2009; Tehrany et al. 2013, 2014; Rahmati et al. 2016a; Khosravi et al. 2016; Tehrany et al. 2017) in recent times. Besides, GIS not only can locate the flood vulnerable areas but can also predict future flood

scenarios and thus, reinforcing the flood preparedness through providing early warning and emergency response during crucial events (Kia et al. 2012; Tehrany et al. 2013). The efficiency of the coupling of AHP with GIS has been validated in several studies, e.g., Fernandez and Lutz (2010) found that the flood hazard map obtained by combining MCDA (AHP) with GIS for the Tucumán province of Argentina contained good degree of accuracy proving it as a powerful method for such tasks. Rahmati et al. (2016b) observed that the coupling of AHP with GIS is capable in yielding reliable prediction of flood extent and mapping of flood hazard potential areas, particularly for data-lacking regions.

India is a 'land of monsoon' (Subrahmanyam 1986) where monsoon is regarded as a boon due to its prominent influence upon the agricultural productivity and economy of the nation (Paul et al. 2016). However, monsoon also denotes a season of anxiety for about 32 million people of the country who are subjected to annual average flood inundation (Kale 2004). The eastern Indian state of West Bengal has been no exception as about 55.80% area of the state is susceptible to floods (Nath et al. 2008) with average inundation extent of 0.799 million hectares influencing the livelihood of 4.07 million people annually (Central Water Commission 2018). Unlike its southern counterpart (tract lying south to the Ganga River) the northern and northeastern parts of the state (collectively termed as North Bengal) possess unique physiographic and orographic setting controlled by the eastern Himalayas. Numerous small to medium streams coming down from this giant landmass meet at the foothills and form large, wandering or braided rivers like the Teesta, Jaldhaka, Torsha, Raidak and Sankosh all of which finally debouch into the mighty Brahmaputra river. These rivers brought immense load from the Himalayas in forms of boulders, gravels, sand and silt and deposit the coarser ones at the foothills in the extreme north due to lesser slopes (Starkel et al. 2008) while accrete the finer particles in the south (parts of Darjeeling, Jalpaiguri and Alipurduar districts and entire Coochbehar district) to form and shape their wide, flat and almost monotonous floodplains subjected to inundation for multiple times even in a single monsoon season hampering the livelihoods of the floodplain dwellers. This backdrop makes it utmost necessary to determine and map this flood risk and its underlying elements of flood hazard and vulnerability with a few prioritize objectives designated for this present work: (a) identifying and selecting suitable indicators or variables capable of explaining the hazard intensities and flood vulnerabilities; (b) weighting these indicators according to their significance and correlating them geographically; (c) mapping and analyzing the hazard intensities, vulnerabilities and flood risk levels spatially and identifying the key areas that need priorities in flood management policies.

2 Study area

The study has been carried out in the northeastern district of Coochbehar that roughly corresponds to the positional extent between 25°57'47"N and 26°36'20"N latitudes and 88°47'44"E and 89°54'35"E longitudes covering an area of 3388.34 km². Coochbehar is internationally bordered by Bangladesh from the south, southwest and southeast directions while Assam sets the eastern interstate limit and the remaining northern and northeastern neighborhoods are formed by Alipurduar and Jalpaiguri districts, respectively (Fig. 1).

The entire landmass of the Coochbehar district is drained by seven Himalayan rivers making it a land of seven rivers namely Teesta, Jaldhaka (also known as Mansai near Mathabhanga and as Singimari near its exit point to Bangladesh), Torsha, Kaljani, the ana-branches of the Raidak viz. (1) Raidak-I and (2) Raidak-II, and Sankosh from the west to

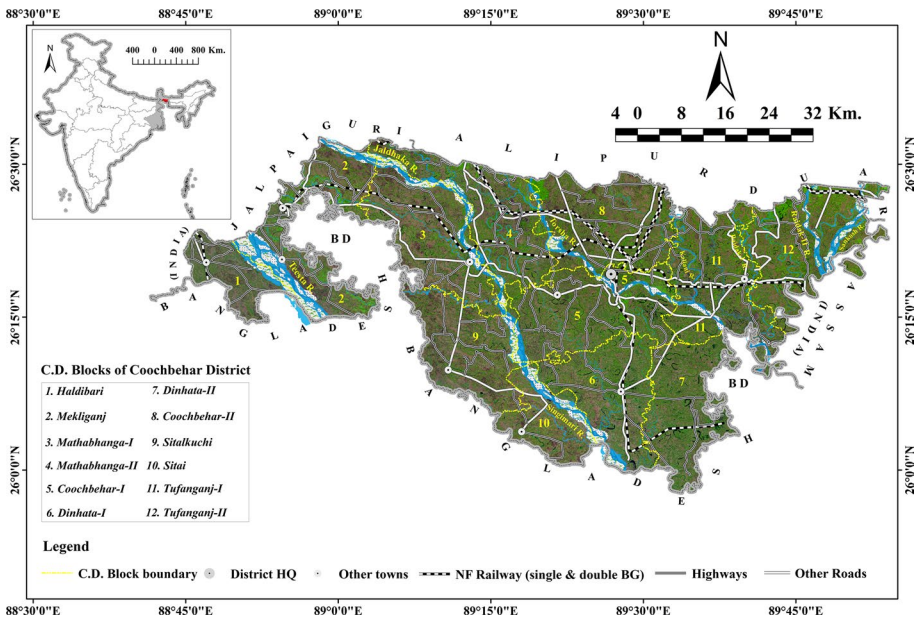


Fig. 1 Location map of the Coochbehar district

east following the regional slopes toward the south and southeast. The district is an amalgamation of wide, flat and merely elevated floodplains (mostly ranges within 1 to 5 meters) developed and replenished by these seven rivers and their numerous perennial tributaries (Table 1) of varying sizes. The physiographic monotony is faded away only by the lateral oscillations of these plentiful rivers resulting into the formation of large numbers of abandoned and paleo channels, meander scrolls, neck and chute cut-offs—collectively called as ‘beels’ or ‘nala’. All the large rivers and a majority of their medium sized tributaries such as Shaniajan, Sutunga, Jarda, Duduya, Mujnai, Dolong, Buri Torsha, Ghargharia, Giridhari, Dharala, and Baniadaha remain partly wetted for most part of the dry seasons but start swelling immediately with the onset of southwest monsoon. Because of structural weakness (Jana 2002), rapid changes in hydrologic regimes and higher rates of river bed siltation and resultant river bed rise, these rivers frequently shift their courses (Jana 1997; Sarkar 2008). Besides due the excessive meandering (e.g., Baniadaha has a sinuosity index (SI) of 2.19, Ghargharia has a SI of 1.98, Gadadhar and Sutunga have SIs of 2.13 and 1.74 respectively) the small and medium sized channels are featured by sluggish flows and frequently migrates into the immediate riparian neighborhoods that have been mostly altered into croplands during high flow events. On an average, there are about 102 rainy days in a year yielding an average annual rainfall of 2945 mm that increases up to 3200 mm in the north and decrease to nearly 2600 mm at the Indo-Bangladesh border in the south. An annual rainfall trend analysis for 1950–2013 (Fig. 2a) suggests a slightly increasing linear trend ($R^2=0.353$) while the concern is the higher rainfall intensity (Sarkar 2008) as it is frequent in the monsoons to record rainfall of more than 100–200 mm in a span of 24 h (frequently continues for several days) initiating a quick swelling of the river waters.

The economy is primarily agricultural with some minor contribution from agricultural, food processing and allied industries. The former princely state (before August 28, 1949) of Coochbehar, now transformed into a district constitutes of five major subdivisions that

Table 1 Brief description of the community development blocks of Coochbehar district

Sl. No.	C.D. block name	Area (km ²)	Population	Major river basin	Tributaries
1	Haldibari	152.38	103,969	Teesa (1)	Giria
2	Mekliganj	302.07	155,250	Teesa (1) and Jaldhaka (2)	Sati, Shamiyan (1); Jarda, Sutunga (2)
3	Mathabhanga-I	319.39	218,191	Jaldhaka (2)	Sutunga, Jarda, Nenda
4	Mathabhanga-II	309.99	227,397	Jaldhaka (2) and Torsha (3)	Duduya, Mujnai Dolong (2); Buri Torsha (3)
5	Coochbehar-I	361.17	326,558	Jaldhaka (2) and Torsha (3)	Dharala, Baniadaha (2)
6	Dinhata-I	279.67	286,269	Jaldhaka (2)	Dharala, Baniadaha
7	Dinhata-II	246.98	244,066	Jaldhaka (2)	Baniadaha
8	Coochbehar-II	385.38	343,901	Torsha(3)	Mara Torsha, Ghoramara, Ghargharia, Kaljani
9	Sitalkuchi	262.51	185,353	Jaldhaka (2)	Dharala, Bura Dharala, Satimari, Khutamara, Girdhari
10	Sitai	160.82	110,333	Jaldhaka (2)	Girdhari, Maldah
11	Tufanganj-I	317.00	248,595	Torsha(3)	Ghargharia, Kaljani, Gadadhar, Raidak-I, Bura Raidak
12	Tufanganj-II	265.69	186,726	Torsha (3) and Sankosh (4)	Raidak-I, Bura Raidak (3); Raidak-II (4)
	Municipal areas	25.29	182,478		
	District total	3388.34	2,819,086		

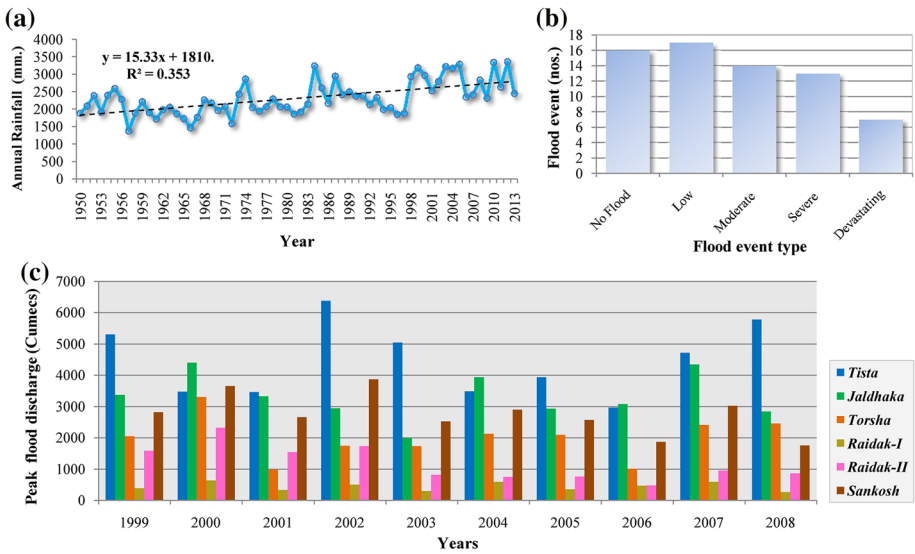


Fig. 2 Nature and elements of flood hazard in Coochbehar: **a** trend analysis of annual rainfall (1950–2013), **b** frequencies of different magnitude floods (1950–2017), **c** observed peak river discharge of the seven major rivers during flood events (1999–2008)

include 12 Community Development Blocks (Table 1) namely (a) Mekliganj Subdivision: Haldibari and Mekliganj C.D. blocks, (b) Mathabhanga Subdivision: Mathabhanga-I and II and Sitalkuchi C.D. blocks, (c) Dinhata Subdivision: Dinhata-I and II and Sitai C.D. blocks, (d) Coochbehar Sadar (Headquarter) Subdivision: Coochbehar-I and II C.D. blocks and (e) Tufanganj Subdivision: Tufanganj-I and II C.D. blocks. The total population is little more than 2.8 million with a density of 832 persons per square Kilometer.

Floods are common and regular phenomenon for the Coochbehar district in the monsoon scenario. Floods here germinate either slowly or seasonally but continue for a few days (mostly 2–4 days) to weeks long. As the major river basins are funnel shaped, the runoff disposal is poor resulting into prolonged stagnation in the floodplain areas (Jana 1997). As far as the flood frequency is considered, there were 67 floods occurred in between 1950 and 2017 (Fig. 2b). However, not all of these events were widespread and disastrous rather some remained purely local, while some had only impacts on some neighboring settlements situating along the floodways (Chakraborty 2017).

The changes in river water volumes are rapid and largely controlled by the incoming rainfall and water from the tributaries. As the volume and concentration of rainfall increase, the peak flow (Fig. 2c) accelerates and encroaches toward its either bank and spills where there are no embankments, the rivers flush into the settlements or croplands through breaching the weaker sections or existing raincuts of the embankments. Although, these floods were mostly caused by hydrometeorological and physiographic drivers, the anthropogenic sides cannot be overlooked. The human influences are mainly seen in worsening of the flood situations due to indiscriminate human occupation of the floodways by agricultural–settlement encroachment and rapid landuse–landcover alteration. In India, flood management has been mostly emphasized on traditional structural measures rather than non-structural ones (Mohapatra and Singh 2003), and therefore, construction of flood protection embankments is given utmost importance to contain

the swelling rivers. Meanwhile, these embankments are mostly found close to the river channels enhancing deposition and substantially increasing the rising river bed levels (Chakraborty 2017). Thus, at some locations, the rivers are found to be flowing above or almost at the same benchmark of neighboring settlements, e.g., Jaldhaka/Mansai river near Dewanbas and Singijani villages (Mathabhanga-II C.D. block) or near Silduar (Sitai C.D. block).

The flood event of August 12–16, 2017, has been designated as the largest flood of last two and half decades prior to the 1993 floods as far the consequences are concerned, however no data for the 1993 event is with us. The catastrophic flood of 2017 occurred as a result of heavy intensive rainfall spelled for a 3 day, i.e., 10–12 August. Irrigation and Waterways Department's (IWD) Records showed that the rain gauges within the district such as Mathabhanga, Coochbehar and Tufanganj received 471.8 mm, 586.1 mm and 870.2 mm rainfall within this short span while the nearest rain gauges (in the north) like Hasimara, Alipurduar and Barobisha (Alipurduar district) recorded 835.4 mm, 778.4 mm and 719 mm of rainfall. This torrential rainfall caused all the rivers to rise beyond their extreme danger levels (EDL) and most of them particularly Jaldhaka (Mansai), Torsha, Kaljani and Raidak-I remained above their prefixed EDLs for several days culminating widespread flooding. Except these large rivers their smaller and medium tributaries which mostly have no embankments along their stretches spilled away their immediate vicinities. It was reported that all the twelve C.D. blocks went under flood water affecting the livelihoods of 1.3 million people (46.13% of district population) and damaging standing crops of about 184,910 hectares (State Inter Agency Group 2017).

3 Data sources and methodology

Natural hazards such as floods are multidimensional, and hence, any analysis and mapping of these events require a comprehensive database. An accurately demarcated district map including the C.D. blocks and villages/towns therein was the first requisite in this work and was obtained from the District Census Handbook (DCHB) of Coochbehar published by the Census of India for the year 2011. A set of demographic and other socioeconomic data regarding literacy, working population etc were compiled from this DCHB (2011). The next task was to append all of these data in a geospatial attribute table. The base map was georectified (RMSE-0.6 of a pixel) using the Universal Transverse Mercator (UTM) projection (Zone 45N) with WGS-84 datum in the ArcGIS™ 10.3.1 software. The onscreen digitization was done manually for features like rivers, streams, road and rail networks at a fixed scale of 1:5000 based on five scenes acquired by the IRS P6 (Resourcesat-1) satellite with sensor LISS-4 (paths and rows 107/53d, 108/53a, 108/53b, 108/53c, 108/53d with cell size-5.8 m) of February, 2014. While the landuse/landcover classification utilized a georectified Landsat 8 OLI/TIRS satellite image (Path and Row Id-138/42, cell size-30 m) for November 24, 2017 (post-monsoon season), which was further atmospherically corrected by using the Semi-Automatic Classification Plugin (SCP) version 5.3.8 in the QGIS version 2.2 (Valmiera) environment. Three Shuttle Radar Topography Mission (SRTM) Digital Elevation Models (DEM) of 1 arc second horizontal resolution were reprojected using the UTM projection (Zone 45N) and the void filling was done by the ArcGIS Hydrology toolset while the DEM mosaicing and extraction were done by the data management tool of the same software.

3.1 Hazard, vulnerability and risk: conceptual definitions

In present academic contexts, the term ‘risk’ is multidimensional as it is interrelated with safety, economic, environmental and social issues and thus has a range of meanings (Samuels 2006). Careful review of a plentiful scientific works revealed that three basic elements are associated with modern flood management system: Risk (R), Hazard (H) and Vulnerability (V) and can be expressed in a simple form (Wisner et al. 2004; UNISDR 2009; Masood and Takeuchi 2012)-

$$R = H \times V \quad (1)$$

It is only over the last few decades when the geographical approach of risk has developed (Defossez et al. 2017). As stated above the term ‘*risk*’ is multidimensional indicating its multiple definitions. However, the commonality is seen in its inherent elements of hazard and vulnerability based on which most of the definitions have emerged.

For the present context, the definitions given by the United Nations International Strategy for Disaster Reduction (UNISDR 2009) have been followed: The definitions are—(a) Hazard: “A *dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage*”. (b) Vulnerability: “*The characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard.... Vulnerability varies significantly within a community and over time*”. Flood risk management needs a better understanding of vulnerability as a hazard turns into a disaster only after it hits a system or community that is vulnerable to its effects (de Brito et al. 2018). However, the assessment of vulnerability and its combination with the hazard to obtain risk differs with natural events. Thus, defining vulnerability essentially depends on the purpose of the assessment. Vulnerability is in fact hazard-specific—‘*it is perfectly possible for a system to be vulnerable to one hazard yet resilient in the face of another*’ (Ciurean et al. 2013). (c) Risk: “*The combination of the probability of an event and its negative consequences*”. A methodological workflow comprising of a few consequent tasks has been designed to assess the flood risk and its hazard and vulnerability components for the Coochbehar district (Fig. 3).

3.2 The hazard and vulnerability indicators

Indicators are actually simple numbers and inherent features of a system which reflects reality and quantitatively estimate the state of a system and generally highlight minor, reasonable and palpable telling pieces to represent a bigger complex situation in simple terms to a broader audience (Balica 2012a, b; Balica et al. 2012). The indicators here include both the representatives of hazard and vulnerability—that define the flood risk. The flood hazard incorporates a group of indicators (criteria) that consist of both the ‘*disaster-inducing factors*’ and ‘*disaster forming environments*’ (Hu et al. 2017). Since vulnerability is not an observable phenomenon, its indicators include the operators or simple functions of certain variables capable of predicting some future state that might or might not occur (Hinkel 2011). A total 16 indicators have been opted initially after going through a careful literature review and later were grouped as hazard indicators ($N=8$) and vulnerability defining indicators ($N=8$) based on their functions and functional relationships.

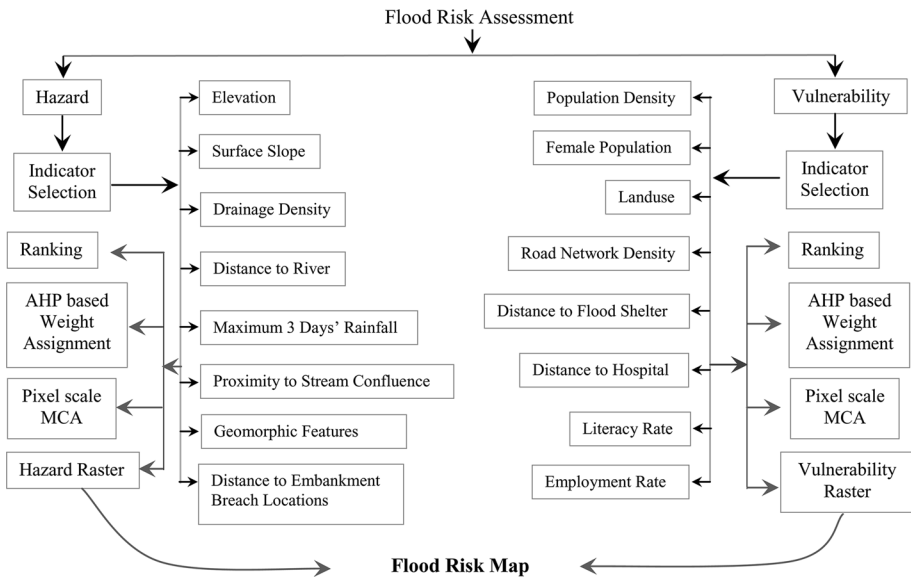


Fig. 3 Flood risk assessment framework

The hazard inducing as well as disaster forming indicators or criteria (Table 2 and Fig. 4a–h) include predominantly the physical elements—(a) *Elevation* (based on zonal statistics of SRTM 1arc Sec void filled and mosaiced DEM), (b) *Surface slope* (obtained by applying ArcGIS surface analysis tool for the SRTM 1arc Sec void filled and mosaiced DEM), (c) *Drainage density* (ArcGIS density analysis tool is used for the stream layer created from IRS P6 LISS-4 scenes), (d) *Distance to river* (applying multi-ring radial buffers for distances of 100, 250, 500, 1000 m), (e) *Maximum 3 days' Rainfall* [Inverse Distance Weighting (IDW) interpolation of 3 days maximum rainfall amounts recorded during August 10–12, 2017, at the rain gauges], (f) *Proximity to stream confluence* (250, 500, 1000, 2000 m multi-ring buffer analysis), (g) *Geomorphic features* [based on manual digitization of georectified scanned map prepared by National Bureau of Soil Survey and Landuse Planning (NBSS and LUP) and image-based visual analysis supported by field surveys conducted between September, 2013 and May, 2018], and (h) *Distance to embankment breach locations* (500, 1000, 2000, 5000 m multi-ring buffer analysis of flood-breached points reported by the IDW, Government of West Bengal and field surveys).

The vulnerability indicators (Table 3 and Fig. 5a–h) emphasize more on the exposed assets and on the resilient elements or criteria of coping abilities and therefore comprise of—(a) *Population density* (village level census data compiled from DCHB 2011 of Coochbehar), (b) *Female population* (village level census data of 2011), (c) *Landuse* (maximum likelihood classification of Landsat 8 OLI/TIRS image of November 24, 2017), (d) *Road network density* [ArcGIS density analysis tool is used for the road networks (all weather roads only) manually digitized onscreen], (e) *Distance to flood shelter* (250, 500, 1000, 2000 m multi-ring buffers generated based on points denoting useable flood shelters during emergency such as schools, colleges and dedicated flood shelters reported in the District Disaster Management Plan of Coochbehar (2016) with coordinates information), (f) *Distance to hospital* (multi-ring buffers of 500, 1000, 2000, 5000 m around government

Table 2 Summary of the hazard indicators

Indicator	Significance	Functional relationship	References
Elevation	Inundation extent	Inverse	Sinha et al. (2008), Tehrany et al. (2017), Hazarika et al. (2018), Ghosh and Kar (2018)
Surface slope	Surface runoff	Inverse	Fernandez and Lutz (2010), Kazakis et al. (2015), Rahmati et al. (2016a, b), Tehrany et al. (2017)
Drainage density	Hydrological response time	Direct	Meeraj et al. (2015), Hu et al. (2017)
Distance to river	Inundation extent	Inverse	Fernandez and Lutz (2010), Elkhrachy (2015), Rahmati et al. (2016a, b), Tehrany et al. (2017)
Maximum 3 days' rainfall	Runoff generation	Direct	Tang et al. (2018)
Proximity to stream confluence	Inundation extent	Inverse	Hazarika et al. (2018), Ghosh and Kar (2018)
Geomorphic features	Surface runoff	Direct	Sinha et al. (2008), Ghosh and Kar (2018)
Distance to embankment breach locations	Inundation extent	Inverse	Hazarika et al. (2018)

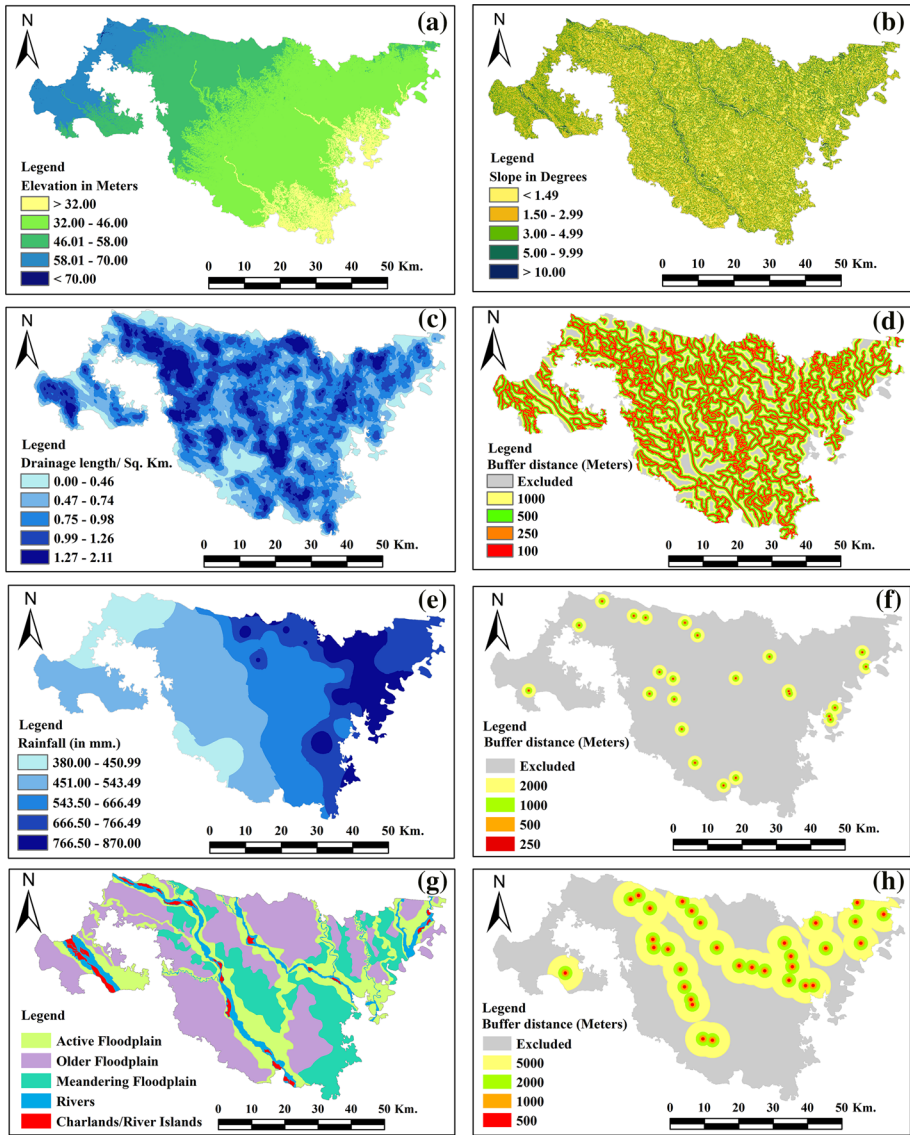


Fig. 4 Hazard inducing and forming criteria: **a** elevation, **b** surface slope, **c** drainage density, **d** distance to rivers, **e** maximum 3 days’ rainfall, **f** proximity to stream confluence, **g** geomorphic features, **h** distance to embankment breach locations

hospital or health center placemarks found on the Google Maps and web database), (g) *Literacy rate* (village level census data of 2011), (h) *Employment rate* (calculated based on village level working population information provided in DCHB 2011).

These indicators contain multidimensionality in their character as they originate from varying sources as well as they also vary in their scales. The geographical correlation of these multiple criteria was done within the ArcGIS platform where each

Table 3 Outline of the vulnerability defining criteria

Indicator	Importance	Functional relationship	References
Population density	Flood consequences on demographic and socioeconomic assets	Direct	Sanyal and Lu (2006), Sinha et al. (2008), Balica et al. (2009), Molah (2016)
Female population	Higher perception of risk; roles in flood resilience; slower recovery due to family care responsibilities; social deprivation regarding the patriarchal setup	Direct	Cutter et al. (2003), Fekete (2009), Fernandez et al. (2016b), UNISDR (2016), Sharma et al. (2018)
Landuse	Infiltration and surface runoff; economic assets under flooding	Inverse	Sinha et al. (2008), Fernandez and Lutz (2010), Elkhrachy (2015), Khosravi et al. (2016), Ghosh and Kar (2018)
Road network density	Rescue, evacuation or distribution of relief	Inverse	Sanyal and Lu (2006), Hu et al. (2017)
Distance to flood shelter	Rescue, safety and security of flood victims	Inverse	Hazarika et al. (2018), Ghosh and Kar (2018)
Distance to hospital	Control of hygiene, sanity and prevention of waterborne diseases	Inverse	Introduced
Literacy rate	Level of socioeconomic attainment; public awareness regarding floodplain use (pre- and post-flood); prompt decision making for individual or community safety and rescue (during flood)	Inverse	Fernandez et al. (2016b), Ghosh and Kar (2018)
Employment rate	Local economic health and flood loss recovery	Inverse	Introduced

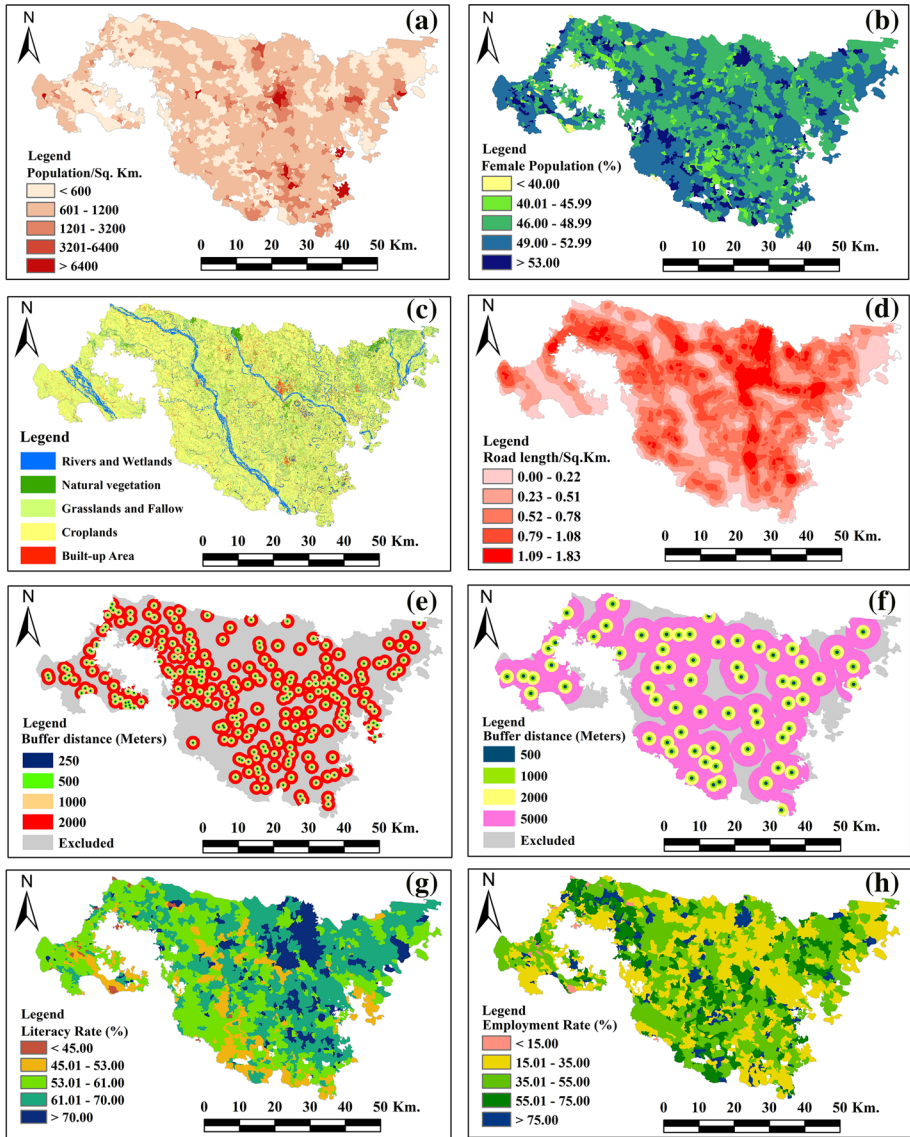


Fig. 5 Vulnerability indicators: **a** population density, **b** female population, **c** landuse, **d** road network density, **e** distance to flood shelter, **f** distance to hospital **g** literacy rate, **h** employment rate

indicator or criteria were reclassified and ranked from 1 to 5 indicating very low to very high hazard/vulnerability. All the reclassified rasters were further converted into 30 m × 30 m individual raster grids.

Table 4 Saaty's scale of preference

Intensity importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong or demonstrated importance
9	Extreme importance
2,4,6,8	Intermediate values
Reciprocals	Inverse comparison

3.3 AHP and indicator weighting

Developed by Saaty (1977), AHP is a multi-objective, multi-criteria decision analysis that uses a pair-wise comparison process to arrive at a scale of choices among a set of alternatives (Fernandez and Lutz 2010). It utilizes a basic scale of absolute numbers (Table 4) to represent individual preferences (Saaty 2008).

AHP also provides a numerical process to judge the consistency of the preferences (Fernandez and Lutz 2010). The consistency of the judgment or of the comparison matrix can be checked by the consistency ratio (CR) that allows the judgment or the preference to be consistent only if the $CR \geq 0.10$. The consistency ratio is defined by:

$$CR = CI/RI \quad (2)$$

where CI is the consistency index and RI is the random index whose value is defined by the number of criteria (n). The consistency index is expressed by:

$$CI = (\lambda_{\max} - n)/(n - 1) \quad (3)$$

where λ_{\max} is the largest eigenvalue of the comparison matrix and n is the number of criteria (here $n = 8$).

For this present work, the consistency ratio (CR) was calculated as 0.0428, consistency index (CI) as 0.060 while the random index (RI) for $n = 8$ was 1.41 for both hazard and vulnerability indicators. The reclassified indicator rasters were assigned their respective weights (W) based on the consistent comparison matrix.

3.4 Calculating hazard, vulnerability and flood risk indices

As mentioned above, the numerical expression of risk is given in terms of its inherent elements of hazard and vulnerability. Therefore, it is evident that formulation of the risk index is the end product preceded by the determinations of the hazard and vulnerability indices. All these indices are in fact the results of the indicator ranks and their corresponding weights obtained by AHP. Here, the hazard index has been defined by:

$$\begin{aligned} \text{Flood Hazard Index (FHI)} = & (w_{ELV} \times ELV) + (w_{SL} \times SL) \\ & + (w_{DD} \times DD) + (w_{DR} \times DiR) \\ & + (w_{RI} \times M3DR) + (w_{CON} \times CON) \\ & + (w_{GEO} \times GEO) + (w_{EMB} \times EMB) \end{aligned} \quad (4)$$

where ELV, SL, DD, DiR, M3DR, CON, GEO and EMB refer to elevation, surface slope, drainage density, distance to river, maximum 3 days' rainfall, proximity to stream confluence, geomorphic features and the distance to embankment breach locations and w_{ELV} , w_{SL} , w_{DD} , w_{DiR} , w_{M3DR} , w_{CON} , w_{GEO} and w_{EMB} are their corresponding weights. Vulnerability index was calculated by:

$$\begin{aligned} \text{Flood Vulnerability Index (FVI)} = & (w_{POP DEN} \times POP DEN) + (w_{FEM} \times FEM) + (w_{LU} \times LU) \\ & + (w_{ROAD} \times ROAD) + (w_{SHEL} \times SHEL) \\ & + (w_{HOS} \times HOS) + (w_{LIT} \times LIT) + (w_{EMP} \times EMP) \end{aligned} \quad (5)$$

where POPDEN, FEM, LU, ROAD, SHEL, HOS, LIT and EMP indicate population density, female population, landuse, road network density, distance to flood shelter, distance to hospital, literacy rate and employment rate while $w_{POP DEN}$, w_{FEM} , w_{ROAD} , w_{SHEL} , w_{HOS} , w_{LIT} and w_{EMP} are the weights of each.

The resultant index scores of both hazard and vulnerability were normalized (dividing individual class values with the maximum class value) and were formatted into GRID rasters of 30 m × 30 m spatial resolution to minimize the chances of misalignment (Hazarika et al. 2018). The flood risk index (FRI) was calculated based on Eq. 1 and with the aid of ArcGIS Map Algebra tool. The FRI here is expressed as:

$$\text{Flood Risk Index (FRI)} = \text{FHI} \times \text{FVI} \quad (6)$$

The FRI scores were normalized using the similar method mentioned above, and rasters of equivalent spatial resolution were created for regional and sub-regional analyses.

3.5 Efficiency assessment of the flood risk model

The primary goal of flood risk assessment studies comprises of attaining the information on the areas or locations that might get inundated by future flooding. Therefore, it is essential to determine the validity of the models irrespective of the methodologies employed in such studies in regard to unknown future flood events (Rahmati et al. 2016b). However, for data-lacking regions this is indeed much painstaking such as the present one where data on flood depths and/or flood impacts at micro levels are mostly unavailable hindering numerical judgments such as flood frequency analyses. Therefore, the validation of the results were done only by a database compiled from the reported flood prone areas by the Disaster Management Section, Office of the District Magistrate, Coochbehar, Government of West Bengal (2016) along with the flood locations reported by the local media houses during 2013–2017. The District Disaster Management Section has reported a total of 280 settlements (incorporates 15 field verification locations) as flood prone while from media reports another 29 (28 have been verified in the field) such inundation-prone settlements have been identified aggregating a totality of 309 locations. These 309 locations, converted as georectified points were brought into the ArcGIS environment. As the flood risk output developed from the datasets cannot represent the model's efficiency, it was suggested as unable for validation (Tehrany et al. 2017). Thus, a set of points have been generated only for the settlements having low to very high flood risk by using the mean center function form the spatial statistics tool of ArcGIS. To assess the efficiency of the flood risk model, indirect methods of relative mean error (RME) and root of mean-square error (RMSE) have been tested with minor modifications (the reported locations were considered as observed locations while the modeled locations as predicted ones) utilizing the following equations:

$$\text{RME} = \frac{1}{n} \sum \text{RE}_i \quad (7)$$

$$\text{RE}_i = \frac{(\text{Observed locations} - \text{Predicted locations}) * 100}{\text{Observed locations}} \quad (8)$$

where RE_i is the relative error in percent for the flood risk model.

$$\text{RMSE} = \left(\frac{1}{n} * \sum \text{SE}_i \right) 0.5 \quad (9)$$

$$\text{SE}_i = (\text{Observed locations} - \text{Predicted locations})^2 \quad (10)$$

where SE_i is the squared error in percentage for the flood risk model.

4 Results and discussions

4.1 Intensity distribution of flood hazard

A district level flood hazard intensity map (Fig. 6) comprising of five classes ranging from very low to very high intensity has been prepared based on the grid raster incorporating the FHI scores for the Coochbehar district. It reveals that the Tufanganj subdivision is the most flood prone area with exactly 50% (64) of the villages/towns comes under moderate to very high and 35.48% (44) settlements under low flooding intensity classes. Mathabhanga marks the second most flood prone subdivision within the district where around 35 vil-lages/towns (13.01%) are under the threat of moderate to very high flooding intensity fol-lowed by the Coochbehar Sadar subdivision having only 33 villages/towns (12.54%) under similar hazard intensities. 56.86% of the settlements falling under the Dinhata subdivision

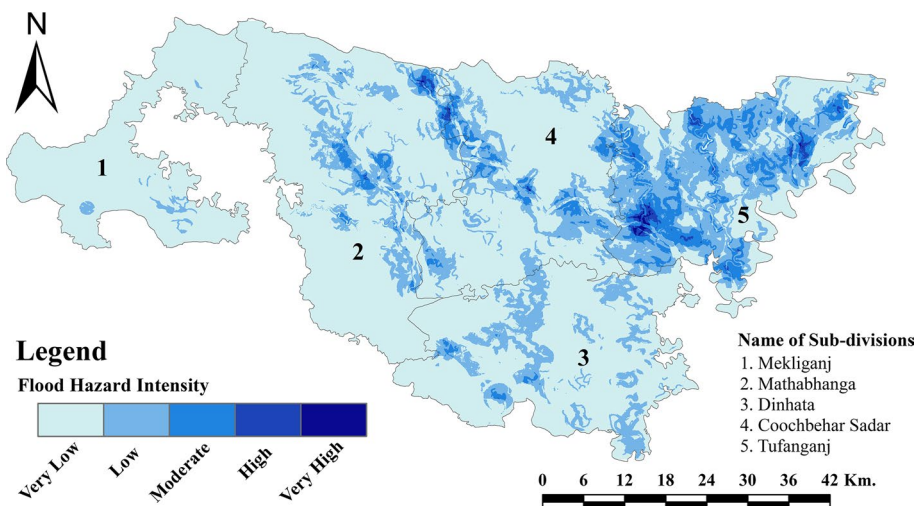


Fig. 6 Spatial distribution of flood hazard intensity over the Coochbehar district

are marked with low to moderate flooding intensities. Most of the villages/towns of the Mekliganj subdivision are found prone to very low flooding intensities but are not immune at all. In a nutshell, there are only 28 out of 1180 census villages/towns (2.37%) that are marked by high to very high FHI scores and majority of them belong to the Tufanganj-I (11), Mathabhanga-II (7), Tufanganj-II (6) and Mathabhanga-I C.D. blocks while the rests are situated in the Coochbehar-I and II C.D. blocks. Settlements prone to moderate intensities of flooding record a totality of 111 (9.40%) coming particularly from Tufanganj-I (30), Coochbehar-I (18), Tufanganj-II (17), Coochbehar-II (15), Mathabhanga-II (15), Mathabhanga-I (8), Dinhata-I (4) and Sitai (3) C.D. blocks. 442 villages/towns that are marked by low FHI scores inclining partial inundation only during large magnitude floods such as the August, 2017 flood and are distributed especially over the eastern, southeastern, southern, central and north-central parts of the district and along all the major rivers. The largest clusters of such settlements have been found in the Dinhata-II (73), Dinhata-I (72), Coochbehar-I (66), Mathabhanga-II (50), Mathabhanga-I (42), Coochbehar-II (34), Tufanganj-I (26), Sitalkuchi (19) and Tufanganj-II (18) C.D. blocks.

It is evident that most of the flood prone areas are situated in the inter-fluvial domain of the Torsha and Sankosh rivers and within Jaldhaka-Torsha rivers while only a few flood prone areas are found along the right bank of the Jaldhaka river. In case of the Teesta, the largest river of the region, only a few villages are there located along left bank of the river near the Indo-Bangladesh border.

As far the causative factors behind the spatial distribution of FHI scores are considered, it is found that the ‘*disaster-inducing*’ element, i.e., the maximum 3 days’ rainfall plays the most significant role here. The rainfall volume as seen during August, 2017 flood event tends to decrease substantially from the east to west (Fig. 4e). The ‘*disaster forming*’ factors such as elevation and slope plays vital role in transforming the flood hazards into disasters. The altitudinal variations between the northwestern parts and the southeastern parts or the eastern stretches are much profound if compared carefully (Fig. 4a). Surface slopes are also much lesser in the eastern and southeastern parts of the district (Fig. 4b). These two indicate (a) poor disposal of surface runoff, (b) greater chances of inundation due to lower elevations and (c) pronounced stagnation of flood waters. The indicators of drainage density and distance to river (Fig. 4c, d) demonstrated good control in FHI scores but only in areas that are pre-weakened by lower elevation and lesser slopes.

Relatively significant influences in FHI scores were exhibited rather by the elements of nearness to stream junctions, geomorphic features and the proximity to embankment breach locations. Around 237 streams and rivers drain the plains of Coochbehar however, only the 24 major confluence points were taken into consideration (Fig. 4f) and they were found in exhibiting good degree of influence on the spatial distribution of FHI. The FHI scores are found within moderate to very high classes near the confluences of rivers Raidak-II and Sankosh, Raidak-I and Torsha, Kaljani and Torsha, Gadadhar and Raidak-I, Buri Torsha and Torsha, Mara Torsha and Torsha, Duduya-Jaldhaka, Mujnai-Jaldhaka, Dolong-Jaldhaka, Dharala-Jaldhaka, Sutunga-Jaldhaka, Jarda-Jaldhaka and Giridhari-Jaldhaka. As most of the major rivers now have elevated bed levels, the tributaries failed to flush their waters into their main streams. Moreover, back thrusting is very usual phenomenon around such rivers’ convergence locations causing temporary tributary flow jamming for several hundred meters to a few kilometers in the extreme lower reaches that ultimately results in waterlogging and overbank spilling (Chakraborty 2017). The FHI hotspots were mostly observed over and along the young active floodplains (Fig. 4g) that are habituated with seasonal inundation. As mentioned above, the rivers of this region are experiencing rapid siltation; therefore, avulsive movements and resultant shifting or adjustments in

the river courses are usual during high flows (Sarkar 2008) that often convert a seasonal flood into a griming one. The meandering floodplain as the name implies is dotted with numerous beels and nalas (paleo channels and meander cut-offs), most of which have been partially converted or filled for settlement and cultivation (Sarkar 2008) and have been detached from their sources. These beels and nalas become parts of active fluvial environment as soon as the monsoon arrives and as they have been choked at most places, and overbank spilling is initiated with increasing rainfall volumes. The older floodplains mostly undergone pluvial inundation caused by waterlogging due to lesser slopes and poor drainage configurations as the rivers flowing over these older floodplains are featured by sluggish flows due to excess meandering and temporary flow jamming for either elevated trunk riverbeds or check dams. Most of the reported breach locations are also found in association of the areas that have recorded moderate to very high FHI scores. Embankments serve as the primary support in flood mitigation in the plains of Coochbehar but during each monsoon incidents of breaching are reported by the decision managers. It is usual to assert that the flashy rivers which are flowing over elevated beds, blocked by huge in-channel deposition in the form of bars and islands and marked by pronounced variation in their hydrological regime definitely sneaks into the raincuts on the embankments and cut through them and devastating their immediate vicinities, e.g., breaching of the left side embankment by the Jaldhaka/Mansai river near Baraibari of Mathabhanga-II C.D. block on August 12, 2017, and resultant damage of a portion of the Falakata-Mathabhanga road and further inundation of several villages for up to 3/4 days. The positions of such breach locations (Fig. 4h) and the associated moderate to very high FHI scores are therefore, inherently correlated.

4.2 Spatial distribution of flood vulnerability

The flood vulnerability map (Fig. 7) based on the FVI scores obtained by indicator ranking and AHP also incorporates five vulnerability classes ranging from very low to very

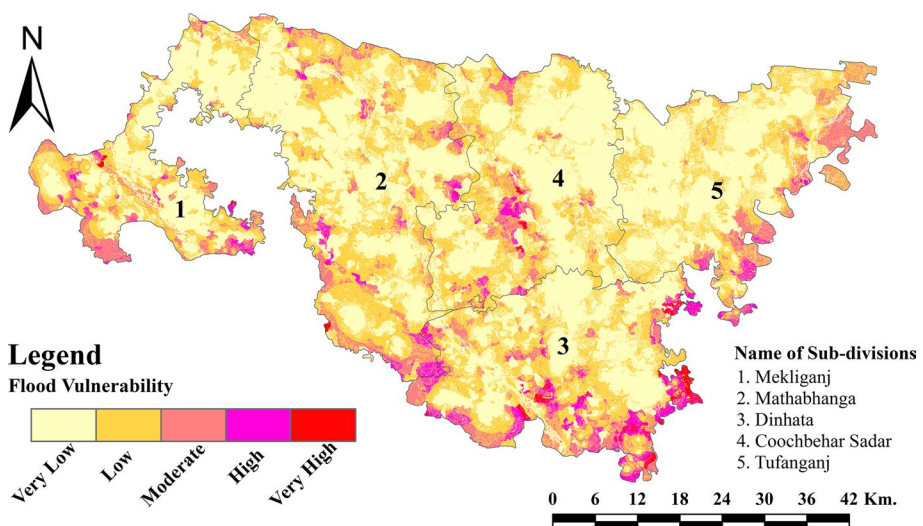


Fig. 7 Spatial character of flood vulnerability

high flood vulnerability levels. Unlike the FHI scores which considered predominantly the physical elements, this FVI analysis takes mostly demographic and socioeconomic criteria into consideration. The FVI scores are found at moderate to very high levels for the subdivisions of Dinhata (45.75%), Coochbehar Sadar (31.08%) and Mekliganj (31.05%) subdivisions. Unlike their significant FHI scores, the Tufanganj (29.68%) and Mathabhanga (29.59%) subdivision have recorded diminished FVI scores in terms of moderate to very high vulnerability classes. At block levels, there are at least 129 villages/towns (10.93%) with high to very high FVI scores and come from Dinhata-I (24), Dinhata-II (18), Coochbehar-I (17), Sitai (13), Mathabhanga-II (12), Mekliganj (11), Sitalkuchi (9), Haldibari (7), Coochbehar-II and Tufanganj-II (5 for each), Mathabhanga-I (4) and Tufanganj-I (4). All of the C.D. blocks have contributed significantly in a collective total of 279 villages/towns (23.64%) found to be associated with moderate flood vulnerability. However, highest numbers of such settlements have been observed at the C.D. blocks of Coochbehar-I (42), Dinhata-I (39), Dinhata-II (35), Mekliganj (35), Sitalkuchi (23), Mathabhanga-II and Coochbehar-II (19 for each) and Tufanganj-II (16). Villages/towns with low (367) to very low flood vulnerability (412) are scattered well over the entire district; however, their greater concentrations (collectively) were observed in the Mekliganj (110), Coochbehar-I and II (92 for each), Mathabhanga-I (87), Dinhata-I (71), Dinhata-II (66), Mathabhanga-II (63), Tufanganj-I (57) and Haldibari (41) C.D. blocks.

It is observed that majority of the most vulnerable settlements are situating along the Indo-Bangladesh international border. This category of settlements has mostly low to moderate population densities (Fig. 5a) but have greater shares of female population (Fig. 5b), an important demographic indicator that has been reported as quite important in increasing the vulnerability particularly for the patriarchal societies (such as in India) where women form an important part of the undisclosed vulnerable groups (UNISDR 2016; Sharma et al. 2018). Majority of these settlements are marked by families headed by females while working age males migrated to other cities and states to acquire better means of earnings and livelihood. In such circumstances, women who are deprived and disadvantaged socio-economically can be expected to be more vulnerable and is likely to be affected greatly by floods (Yumarni et al. 2014) The effect of agricultural landuse (Fig. 5c) is good but the prominent factor being the lack of proper infrastructural developments which is reflected by the lower existence of the resilient elements of road networks, flood shelters and hospitals (Fig. 5d–f). Moreover, the literacy and employment (Fig. 5g, h) rates which are prime issues in driving public awareness in emergencies and recovery after probable damages are also at their lower levels increasing the FVI scores for these frontier locations. Some random clusters are there at the central, north-central and northern parts of the district which have been found as highly vulnerable and this vulnerability is the collective result of moderate to very high population densities along with high to very high shares of female population. Additionally, the landuse is primarily agricultural with some settlement areas and wetlands. The road network density is not optimum (very low to moderate) as well as no nearby flood shelters and hospitals are available within assuring distances. Besides, both the literacy and employment rates at these villages/towns are moderate pushing them toward an increasing vulnerability. The moderately vulnerable settlements are well distributed over the district and are characterized by moderate to high population densities together with high to very high percentage of females within the village population, agricultural landuse and the partial absence of flood shelters within close neighborhoods and moderate employment rates. However, the FVI scores were brought down by the moderate to high literacy rates, optimum road networks and nearby hospitals demonstrating good degree of resilience. This is perhaps more true in case of the villages/towns with lower

levels of flood vulnerability where the efficacy of the resilient elements has overshadowed the exposed socioeconomic and demographic assets resulting into lesser FVI scores. However, it is true that these FVI scores are not rigid but may get altered with changes in its indicators as well as with time and space. Thus, the FVI scores observed here are rather exclusively space-time specific expressions. Since, vulnerability is a theoretical concept (Ciurean et al. 2013) the indicators here simply have transformed it into an operational one leading to the development of a predictive model, the outcomes of which are suggesting potential states that might or might not occur. The FVI outcome at a glance appeared dissimilar to the FHI profile of the district but can be justified by their subjective natures as hazard represents an actual and existing state carved out by the physical elements that alter steadily. Vulnerability, on the other hand, is a potential state that has been predicted based on some socioeconomic indicators. This potential state of vulnerability may alter with changes in its indicators and as these criteria are much more dynamic than the hazard criteria. Thus, the present FVI profile may look different with variation in space and progression of time.

4.3 Risk profiles of the Coochbehar district and its subdivisions

The FRI scores computed for the Coochbehar district suggest that both the hazard and the vulnerability elements have mutually carved out the flood risk patterns (Fig. 8) over the district; however, their influences have been varied, i.e., at places the influence is in union while at some areas this has been clearly unilateral. The villages/towns with higher scores of FHI but low to moderate FVI scores have been observed to record higher FRI outputs as in case of the settlements in the eastern and southeastern parts. These villages/towns mostly are situating along the banks of the Torsha, Kaljani, Raidak-I, Raidak-II and Sankosh rivers. Settlements at low to high flood risk categories have associations with low to high FHI scores and with mostly low to moderate flood vulnerabilities (with fewer villages/towns with very high FVI scores) and can be exemplified by the villages/towns aligned along either bank of the Jaldhaka river and its

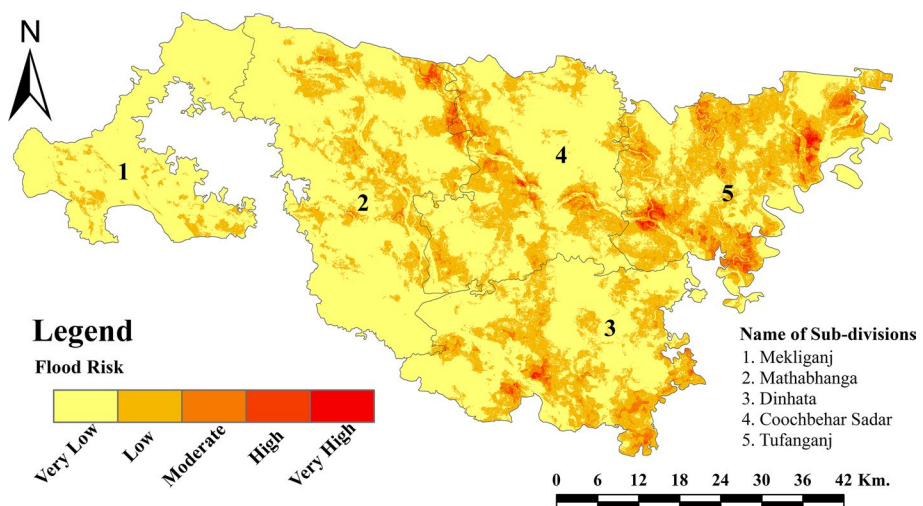


Fig. 8 Distribution of flood risk over the Coochbehar district

tributary Dharala (an earlier branch of the Torsha river) and Jarda rivers at the central and southern parts. West to the Jaldhaka river, the vulnerability elements (moderate to high FVI scores) have carved out nominal (low to very low) FRI scores instead of negligible FHI scores recorded at the villages/towns situating here. The district level flood risk map provided the information of 58 (4.91%) villages/towns with high to very high FRI scores followed by 145 (12.29%) settlements with moderate flooding risks and 456 (38.64%) locations with low FRI outputs. The rests (552) are characterized by very low flood risk scores and are spreading predominantly over the western, southwestern and in east-central parts of the district. Since, flood risk mapping is the most prioritized input in future flood mitigation and preparedness, the entire Coochbehar district has been divided into five administrative subdivisions (Fig. 9a–e) for comprehensive explanation and detailed micro-level coverage.

The Mekliganj subdivision (Fig. 9a) is identified to be the safest as the district-scale FRI distribution has demonstrated (26.48% villages/towns under low flood risk) in terms of flooding risks. However, the nominal FRI scores (low to very low) cannot overlook the potentialities of substantial flooding in regard to a micro-scale analysis. Although majority of the villages/towns in this subdivision are grouped under low to very low FHI scores some of them have moderate to very high levels of FVI indicating possibilities of significant flooding with changes in the hazard intensities (as occurred during the 1968’s flood). This would be more prominent in case of the villages/towns located at either bank of the Teesta (e.g., Uttar Bakshiganj, Bibiganj, Par Mekliganj, Dari Pattani,

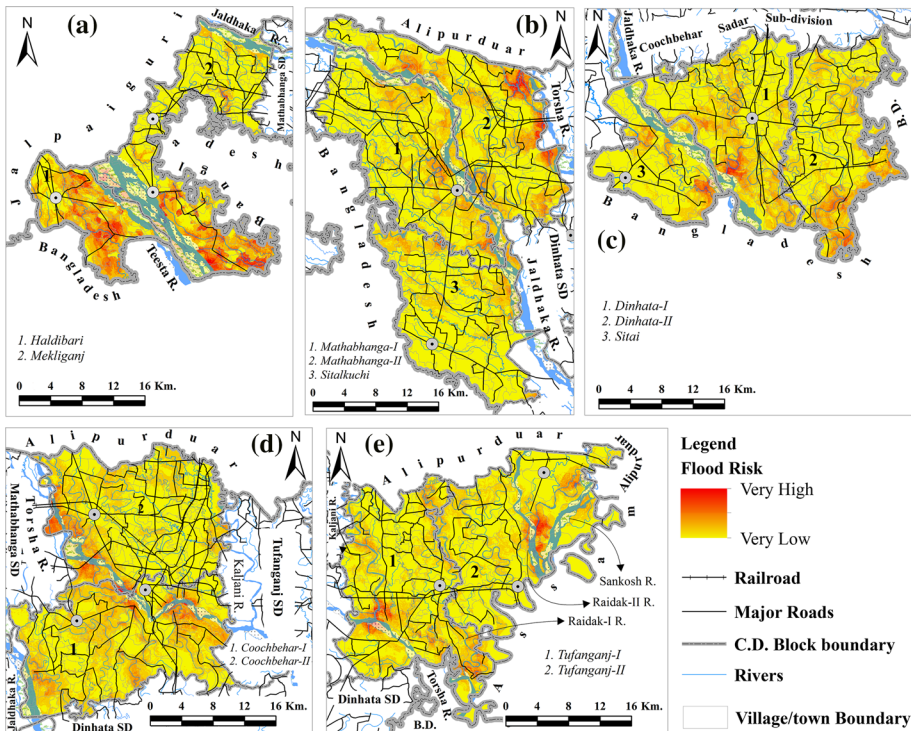


Fig. 9 Spatial distribution of flood risk in the administrative subdivisions of Coochbehar district: **a** Mekliganj, **b** Mathabhanga, **c** Dinhatata, **d** Coochbehar Sadar, **e** Tufanganj

Khasbas and Uttar Daribas in Haldibari C.D. block and Nijtaraf, Mekliganj municipality, Tista Nadir Payasti, Andaran Kuchlibari in Mekliganj C.D. block) and along the right side settlements of the Jaldhaka such as Sarohati, Bara Dhulia Khalisa, Paschim Dhulia Baldiahati, Purba Dhulia Baldiahati etc of Mekliganj C.D. block.

The Mathabhanga subdivision (Fig. 9b) constitutes an important hotspot for floods and thus, has contributed collectively 14 (5.26%) settlements with high to very high FRI scores along with 31 (11.65%) and 101 (37.97%) villages/towns with moderate and low FRI scores, respectively. The rest of the 120 (45.11%) settlements come under the very low flood risk category indicating safer locations. The Mathabhanga-II C.D. block recorded the maximum concentration (11) of settlement areas in high to very high FRI scores while the remaining C.D. blocks of Mathabhanga-I and Sitalkuchi have relatively safer positions in terms of high to very high flood risks (2 and 1 settlements, respectively). In case of the number of settlements prone to moderate-low FRI scores, Mathabhanga-I (53) is leading and is followed by Mathabhanga-II (49) and Sitalkuchi (31) C.D. blocks. This subdivision is predominantly drained by the Jaldhaka river itself and its plentiful tributary and distributaries while some rivers and streams meet the Torsha river flowing along the eastern fringe of the subdivision. The flood hazard intensities were found at moderate to very high levels along these two large rivers. Therefore, preparedness and mitigation priorities are needed for such high flood risk locations, e.g., Ksheti Phulbari, Phulbari Dewanbas, Singijani, Angarkata Pardubi, Baraibari, Baghmara Sukhandighi, Lafabari, Sauderbas, Dwarikamari, Dhalaguri, Unisha Bisha, Shalmara Dwitia Khanda (Mathabhanga-II), Jorpatki, Bhurungamari, Kurshamari, Mathabhanga municipality, Khaterbari, Indrerkuthi, Nityanandi, Bherbheri Manabari, Pachagarh, Daibhangi (Mathabhanga-I) and Shibpur, Panaguri, Bhogdabri, Bhaier Thana and Chhoto Salbari (Sitalkuchi).

The Dinhata subdivision (Fig. 9c) contains mostly settlements with low to moderate (56.86%) flood intensities but is found under moderate to very high FVI scores influencing the overall flood risk. Instead of its lesser to medium flooding intensities, this subdivision has got 9 settlements (2.91%) in high to very high flood risk classes while collectively there are 55 villages/towns that have moderate level of flood risk. 145 (47.38%) settlements with low flood risk have been identified ensuring the rest 97 villages/towns of the subdivision as safer locations in terms of flood hazard. At block levels, both Dinhata-I and II were found to be the riskier areas containing 8 (4 for each), 48 (25 for Dinhata-I and 23 for Dinhata-II) and 121 (65 and 56, respectively) settlements in a descending flood risk scale. Comparatively, the villages/towns of Sitai are safer as there is only 1 settlement (Andaran Singimari) found to be at high flood risk along the right bank of the Jaldhaka River. However, there are at least 7 and 24 locations recorded with moderate to low flood risk levels. The Dinhata subdivision is drained entirely by the Jaldhaka (known here as the Mansai or Singimari) and its tributary rivers such as the Giridhari, Dharala and Baniadaha. Majority of these rivers (except the Jaldhaka) are too heavily sinuous and thus are featured by sluggish flows for most part of the year. Besides, most of these rivers and their floodplain remnants in forms of various wetlands have been degenerated by widespread agricultural encroachment. Therefore, prolonged flood water stagnation is usual here worsening the flood impacts and resulting into increasing flood risk. This is particularly true for the settlements of Dinhata-I (e.g., Petla, Jaridharala, Borham Payasti, Bara Atiabari, Indra Narayan, Panchadhawaji, Dukha Bholar Kuthi, Chandra Narayan, Okrabari, Bara Soulmari, Putimari Phuleswari, Hari Bhanga etc.) and Sitai (Chamta, Brahmottar Chatra, Silduar, Bara Adabari, Andaran Singimari, etc.) that are aligned to the major rivers of Jaldhaka, Dharala and Giridhari. Contrastingly, the frontier areas of Dinhata-II (such as Dighaltari, Kumarganj, Kochabari, Kalamati, Badalgir, Nagarerbari, Shukarur Kuthi, etc.) face weeks long flood

stagnation mainly because of very poor runoff disposal owing to lesser slopes and small number of drainage units.

The Coochbehar Sadar (Fig. 9d) registered as the second most riskier subdivision in the district having 15 (5.70%) settlements under high to very high FRI levels along with 30 (11.40%) and 111 (42.20%) settlements featured under moderate to low FRI scales, respectively. Out of its two constituent blocks, the Coochbehar-II contains nine village/towns with higher flood risk scores. Contrastingly, in case of moderate and low flood risk scales, the Coochbehar-I C.D. block is leading significantly by having 17 and 75 settlements while the Coochbehar-II has 13 and 36 settlements falling in these classes. This subdivision although has registered only 12.54% of its villages/towns associated with moderate to very high flooding intensities, the vulnerability profile is relatively gloomy as 31.08% of its settlements have been found at moderate to very high levels on the FVI scale. Settlements that are positioned along the Torsha river were observed to be riskier ones than those situating along the Jaldhaka river in the southwestern edge or alongside the Kaljani river flowing in the eastern fringe. This is entirely due to the prominent influence of the hazard elements coupled with the concentration of moderate to highly vulnerable areas (Kamrangaguri, Haripur, Bara Atharakota, Kalabarighat, Dauaguri, Ghughumari, Lankabar, Bhojanpur etc in Coochbehar-I and Ghoramara, Kaminirghat, Madhupur, Karisal, Takagachh, Kalapani, Jatrapur, Shalmara Tritia Khanda, Basdaha Natibari, Sajherpar Ghoramara, Sajherpar Kathalbari in Coochbehar-II) in the vicinities of the Torsha that have shaped this kind of FRI distribution while this is partly true in case of the areas alongside of the Jaldhaka river. Exceptions are made by the isolated settlements situating along the western bank of the Kaljani and its tributaries like Ghargharia where instead of negligible flood vulnerabilities, moderate FHI scores have resulted in moderate to high flood risk levels that are associated with locations such as Soutlukri Barapak, Marichbari and Kaljani.

The Tufanganj subdivision (Fig. 9e) although performed well in the FVI analysis by registering only 29.58% of its settlements under moderate to very high FVI scores but is undeniably surpassed by its higher hazard proneness as mentioned earlier. There are at least 21 (16.93) settlements (13 in Tufanganj-I and 8 in Tufanganj-II) that have been found at high to very high flood risk levels, making it the least safe administrative subdivision in the Coochbehar district. Besides, there are 28 (22.58%) and 41 (33.06%) villages/towns that have got moderate and low flood risk scores demonstrating only 34 (27.42%) settlements as relatively safe localities in the entire subdivision. Five out of the seven large rivers that drain the entire district flow through this subdivision while some of them converge here. Besides, all of the hazard elements are present in abundance to germinate flooding by these rivers and their numerous tributaries. Majority of the area is consisting of younger active and meandering floodplains that are subjected to frequent flooding. Observed 3 days' rainfall suggests maximum rainfall intensity over this subdivision while higher drainage densities are quite of a concern here. Moreover, the drainage spacing is too low and it is usual to face a river only at distance of 3 km. In spite of this, the rivers cannot drain out the flood waters from the floodplains because of meager surface slopes. Avulsive movements during high flows are also common particularly for the Raidak-II and Sankosh rivers. Anthropogenic activities like indiscriminate encroachment toward the rivers and even to the riverbed for cultivation and illegal construction and waste disposal in the rivers (as happening to the Raidak-I river in the Tufanganj municipality) are further worsening the flood impacts and enhancing the flood risks. Location such as Balarampur, Deocharai, Chilakhana, Bhelakopa Pratham Khanda, Chhit Bhelakopa, Santoshpur, Krishnapur, Balabhut, Bhelapeta, Dhoghuri, Amlaguri Dwitia Khanda, Bilsil Dwitia Khanda, Dhalpal, Andaran Phulbari,

Sikdarekhata, Rajarkuthi, Dwiparpar (Tufanganj-I) and Mansai, Langalgram, Bhareya, Salbari, Basraja Pratham Khanda, Dorko, Bhanukumari, Palika, Mahishkuchi, Phersabari, Falimari, Rampur, Takoamari, Jaldhoa (Tufanganj-II), etc. thus need immense importance from the flood management authorities for appropriate mitigation.

4.4 Validity of the flood risk model

Efficiency assessments suggest that the presented flood risk model has accurately predicted 277 (89.64%) of the flood prone locations. This was found more efficient in demonstrating accuracy levels in case of Haldibari, Coochbehar-I and Tufanganj-I (100%), Tufanganj-II (95.24%), Dinhata-I (93.33%), Mathabhanga-II (90%) and Coochbehar-II (86.36%) while the minimum accuracy was recorded for the points falling in Dinhata-II (79.17%) followed by Sitalkuchi (80%) and Mathabhanga-I (81.82%) C.D. blocks. The overall efficiency of the flood risk model is found to be good with relatively lower errors acquired by the RME (RME = 0.395) and RMSE (RMSE = 0.223) methods signifying that the present model can be utilized for identifying the flood prone locations within the Coochbehar district and further for the early preparedness and mitigation.

Meanwhile, it was found that some of the areas predicted with low flood risks in this work remain unreported in the official reports and rather have been overlooked but their inundation incidents are confirmed by flood time field photographs (Fig. 10). A broad generalization yielded that about 1130.09 km² (irrespective of flood inundation extent, i.e., partial or whole) of the district is flood prone as per government report while our analysis suggested 1055.54 km² (93.40%) excluding the unreported areas. Besides this, 1181.88 km² of unreported area of the district is found under very high-low flood risk scales collectively defining 2311.97 km² (68.23%) area as under flooding threat. This can be partially validated by the reported damage of only standing croplands covering 1849.10 km² of the



Fig. 10 Glimpses of flood events of 2016 and 2017 in the Coochbehar district. *Source:* field surveys

district during the August, 2017 flood event (State Inter Agency Group 2017) excluding areas and lands devoted to other cover/use types.

5 Conclusions

The flood risk analysis in this work has focused on the basic elements of hazard intensity and flood vulnerability which ultimately have been found to shape the spatial flood risk distribution. Therefore, all three necessary inputs regarding flood management, i.e., flood risk, vulnerability and flood hazard have been comprehensively assessed and mapped, providing the decision making system some readily available tools to trace the disaster footprints. As it has gone through proper validation therefore it is reliable and can be utilized in identifying the key areas that need priorities during the framing of mitigation and coping policies. Additionally, this work has considered a large magnitude flood event (August, 2017) and the most important element of it, i.e., the hazard inducing rainfall concentration (at local scales); therefore, it can not only guide to the identification of the most flood prone areas in the Coochbehar district but also those areas that might get inundated after voluminous rainfall and its resultant large flood events.

This work is based on a wide variety of efficient criteria reported from numerous research works carried out in different parts of the world and hence can be attributed as the first hand documentation for this data-lacking region presented before larger scientific forums. The efficiency of the coupling of AHP and GIS is again found to be at good levels and can be suggested as a reliable tool for flood risk assessments particularly for such data-lacking regions. Undeniably, further researches are needed for this flood victimized region to understand the nature, timings and causative processes of flooding as well as also on the nature of the hydrological regimes of the large rivers flowing over this region. Priorities should also be given upon understanding the floodplain uses and implications of flooding upon the livelihoods of the local people. Flood defense system should emphasize more on non-structural options rather than simply constructing flood protection embankments that has spread a false sense of safety among the floodplain dwellers throughout the region. Measures such as prohibiting agricultural-settlement encroachments toward rivers, appropriate floodplain usage, constructing easily reachable flood shelters, flood insurance and most importantly public awareness raising should be considered at the very beginning. As prevention of flood is perhaps impossible, policy designs therefore, should be guided more and more toward preparedness and mitigation so that the implications can be adjusted at acceptable limits and people can recover the flood losses at the earliest.

References

- Balica S (2012a) Approaches of understanding developments of vulnerability indices for natural disasters. *Environ Eng Manag J* 11(5):1–13
- Balica SF (2012b) Applying the flood vulnerability index as a knowledge base for flood risk assessment. CRC Press/Balkema, Leiden
- Balica SF, Douben N, Wright NG (2009) Flood vulnerability indices at varying spatial scales. *Water Sci Technol* 60(10):2571–2580
- Balica SF, Wright NG, van der Meulen F (2012) A flood vulnerability index for coastal cities and its use in assessing climate change impacts. *Nat Hazards* 64(1):73–105. <https://doi.org/10.1007/s11069-012-0234-1>

- Balica SF, Popescu I, Beevers L, Wright NG (2013) Parametric and physically based modelling techniques for flood risk and vulnerability assessment: a comparison. *Environ Model Softw* 4:84–92. <https://doi.org/10.1016/j.envsoft.2012.11.002>
- Central Water Commission (2018) State wise flood damage statistics. Flood Forecast Monitoring Directorate, Central Water Commission, Government of India, New Delhi, No. 3/38/2012-FFM/1067-1165
- Chakraborty S (2017) Dynamics of hydro-geomorphological environment in Jaldhaka river basin of West Bengal and its impacts on landuse. Unpublished Ph.D. thesis, Visva-Bharati, Santiniketan
- Ciurean RL, Schröter D, Glade T (2013) Conceptual frameworks of vulnerability assessments for natural disasters reduction. InTech. <https://doi.org/10.5772/55538>
- Cutter SL, Boruff BJ, Shirley WL (2003) Social vulnerability to environmental hazards. *Soc Sci Q* 84:242–261
- de Brito MM, Evers M, Almoradie ADS (2018) Participatory flood vulnerability assessment: a multi criteria approach. *Hydrol Earth Syst Sci* 22:373–390. <https://doi.org/10.5194/hess-22-373-2018>
- Defossez S, Vinet F, Leone F (2017) 14-assessing vulnerability to flooding: progress and limitations. In: *Floods*. Elsevier, Amsterdam, pp 241–257. <https://doi.org/10.1016/b978-1-78548-268-7.50014-6>
- Dewan AM, Islam MM, Kumamoto T, Nishigaki M (2007) Evaluating flood hazard for land-use planning in greater Dhaka of Bangladesh using remote sensing and GIS techniques. *Water Resour Manage* 21:1601–1612. <https://doi.org/10.1007/s11269-006-9116-1>
- Dottori F, Martina MLV, Figueiredo R (2018) A methodology for flood susceptibility and vulnerability analysis in complex flood scenarios. *J Flood Risk Manag* 11:S632–S645. <https://doi.org/10.1111/jfr3.12234>
- Elkhrachy I (2015) Flash flood hazard mapping using satellite images and GIS tools: a case study of Najran City, Kingdom of Saudi Arabia (KSA). *Egypt J Remote Sens Space Sci* 18:261–278. <https://doi.org/10.1016/j.ejrs.2015.06.007>
- Fekete A (2009) Assessment of social vulnerability for river-floods in Germany. United Nations University, Bonn
- Fernandez DS, Lutz MA (2010) Urban flood hazard zoning in Tucumán Province, Argentina, using GIS and multicriteria decision analysis. *Eng Geol* 111:90–98
- Fernandez P, Mourato S, Moreira M, Pereira L (2016a) A new approach for computing a flood vulnerability index using cluster analysis. *Phys Chem Earth* 94:47–55
- Fernandez P, Mourato S, Moreira M (2016b) Social vulnerability assessment of flood risk using GIS-based multicriteria decision analysis. A case study of Vila Nova de Gaia (Portugal). *Geomat Nat Hazards Risk* 7(4):1367–1389. <https://doi.org/10.1080/19475705.2015.1052021>
- Ghosh A, Kar SK (2018) Application of analytical hierarchy process (AHP) for flood risk assessment: a case study in Malda district of West Bengal. *Nat Hazards, India*. <https://doi.org/10.1007/s11069-018-3392-y>
- Gupta S, Javed A, Datt D (2003) Economics of flood protection in India. *Nat Hazards* 28:199–210
- Hazarika N, Barman D, Das AK, Sarma AK, Borah SB (2018) Assessing and mapping flood hazard, vulnerability and risk in the Upper Brahmaputra River valley using stakeholders' knowledge and multicriteria evaluation (MCE). *J Flood Risk Manag* 11(52):S700–S716. <https://doi.org/10.1111/jfr3.12237>
- Hinkel J (2011) Indicators of vulnerability and adaptive capacity: towards a clarification of the science-policy interface. *Global Environ Change* 21:198–208. <https://doi.org/10.1016/j.gloenvcha.2010.08.002>
- Hu S, Cheng X, Zhou D, Zhang H (2017) GIS-based flood risk assessment in suburban areas: a case study of the Fangshan District, Beijing. *Nat Hazards* 87:1525–1543. <https://doi.org/10.1007/s11069-017-2828-0>
- Jana MM (1997) Management and development of River Basins in North Bengal using remote sensing techniques. *J Indian Soc Remote Sens* 25(2):105–111
- Jana MM (2002) Application of remote sensing in the study of geomorphic processes and landforms in piedmont zone of Darjeeling sub-himalaya. *J Indian Soc Remote Sens* 30(1–2):61–72
- Kale VS (2004) Floods in India: their frequency and pattern. In: Valdiya KS (ed) *Coping with natural hazards: Indian context*. Orient Blackswan, Hyderabad, pp 91–103
- Kazakis N, Kougias I, Patsialis T (2015) Assessment of flood hazard areas at a regional scale using an index-based approach and analytical hierarchy process: application in Rhodope-Evros region, Greece. *Sci Total Environ* 538:555–563
- Khosravi K, Nohani E, Maroufian E, Pourghasemi HR (2016) A GIS-based flood susceptibility assessment and its mapping in Iran: a comparison between frequency ratio and weights-of-evidence bivariate statistical models with multi-criteria decision-making technique. *Nat Hazards* 83(2):947–987
- Kia M, Pirasteh S, Pradhan B, Mahmud AR, Sulaiman WNA, Moradi A (2012) An artificial neural network model for flood simulation using GIS: Johor River Basin, Malaysia. *Environ Earth Sci* 67:251–264

- Kourgialas NN, Karatzas GP (2011) Flood management and a GIS modelling method to assess flood-hazard areas- a case study. *Hydrol Sci J* 56(2):212–225
- Masood M, Takeuchi K (2012) Assessment of flood hazard, vulnerability and risk of mid-eastern Dhaka using DEM and 1D hydrodynamic model. *Nat Hazards* 61:757–770. <https://doi.org/10.1007/s11069-011-0060-x>
- Meeraj G, Romshoo SA, Yousuf AR, Altaf S, Altaf F (2015) Assessing the influence of watershed characteristics on the flood vulnerability of Jhelum basin in Kashmir Himalaya. *Nat Hazards* 77(1):153–175. <https://doi.org/10.1007/s11069-015-1605-1>
- Merz B, Kreibich H, Schwarze R, Thieken A (2010) Assessment of flood economic damage. *Nat Hazards Earth Syst Sci* 10:1697–1724
- Mohapatra PK, Singh RD (2003) Flood management in India. *Nat Hazards* 28:131–143
- Mollah S (2016) Assessment of flood vulnerability at village level for Kandi block of Murshidabad district, West Bengal. *Curr Sci* 110(1):81–86
- Nath SK, Roy D, Singh Thingbaijam KK (2008) Disaster mitigation and management for West Bengal, India—an appraisal. *Curr Sci* 94(7):858–866
- Paul S, Ghosh S, Oglesby R, Pathak A, Chandrasekharan A, Ramsankaran R (2016) Weakening of Indian summer monsoon rainfall due to changes in land use land cover. *Sci Rep* 6:32177. <https://doi.org/10.1038/srep32177>
- Qi H, Altinakar MS (2011) A GIS-based decision support system for integrated flood management under uncertainty with two dimensional numerical simulations. *Environ Model Softw* 26:817–821. <https://doi.org/10.1016/j.envsoft.2010.11.006>
- Qi S, Brown DG, Tian Q, Jiang L, Zhao T, Bergen KM (2009) Inundation extent and flood frequency mapping using LANDSAT imagery and digital elevation models. *GISci Remote Sens* 46(1):101–127. <https://doi.org/10.2747/1548-1603.46.1.101>
- Rahmati O, Pourghasemi HR, Zeinivand H (2016a) Flood susceptibility mapping using frequency ratio and weights-of-evidence models in the Golastan Province, Iran. *Geocarto Int* 31(1):42–70. <https://doi.org/10.1080/10106049.2015.1041559>
- Rahmati O, Zeinivand H, Besharat M (2016b) Flood hazard zoning in Yasooj region, Iran, using GIS and multi criteria decision analysis. *Geomat Nat Hazards Risk* 7(3):1000–1017. <https://doi.org/10.1080/19475705.2015.1045043>
- Saaty TL (1977) A scaling method for priorities in hierarchical structures. *J Math Psychol* 15:234–281
- Saaty TL (2008) Decision making with the analytic hierarchy process. *Int J Serv Sci* 1(1):83–98
- Samuels PG (2006) Risk and uncertainty in flooding. In: Knight DW, Shamseldin AY (eds) *River basin modelling for flood risk mitigation*. Taylor and Francis/Balkema, London, pp 481–518
- Sanyal J, Lu XX (2006) GIS-based flood hazard mapping at different administrative scales: a case study in Gangetic West Bengal, India. *Singap J Trop Geogr* 27:207–220. <https://doi.org/10.1111/j.1467-9493.2006.00254.x>
- Sarkar S (2008) Flood hazard in the sub-himalayan North Bengal, India. In: Singh S, Starkel L, Syiemlieh HJ (eds) *Environmental changes and geomorphic hazards*. Bookwell, New Delhi, pp 247–262
- Schanze J, Zeman E, Marsale J (2006) Flood risk management: hazards, vulnerability and mitigation measures. Springer, Dordrecht. <https://doi.org/10.1007/978-1-4020-4598-1>
- Sharma SVS, Roy PS, Chakravarthi V, Srinivasa Rao G (2018) Flood risk assessment using multi-criteria analysis: a case study from Kopili river basin, Assam, India. *Geomat Nat Hazards Risk* 9(1):79–93. <https://doi.org/10.1080/19475705.2017.1408705>
- Sinha R, Bapalu GV, Singh LK, Rath B (2008) Flood risk analysis in the Kosi river basin, using multi-parametric approach of analytical hierarchy process (AHP). *J Indian Soc Remote Sens* 36:335–349
- Starkel L, Sarkar S, Soja R, Prokop P (2008) Present-day evolution of the Sikkimese-Bhutanese Himalayan Piedmont, vol 219. *Polska Akademia Naukinstytut Geografii I Przestrzennego Zagospodarowania, Prace Geograficzne*, Warsaw, pp 62–70
- State Inter Agency Group (2017) North Bengal flood report, situation report 2, Kolkata, p 4
- Subrahmanyam VP (1986) Hazards of floods and droughts in India. In: El-Sabh MI, Murty TS (eds) *Natural and man-made hazards*. D. Reidel Publishing Company, Dordrecht, pp 337–356
- Tang Z, Zhang H, Yi S, Xiao Y (2018) Assessment of flood susceptible areas using spatially explicit, probabilistic multi-criteria decision analysis. *J Hydrol*. <https://doi.org/10.1016/j.jhydrol.2018.01.033>
- Tehrany MS, Pradhan B, Jebur MN (2013) Spatial prediction of flood susceptible areas using rule based decision tree (DT) and a novel ensemble bivariate and multivariate statistical models in GIS. *J Hydrol* 504:69–79. <https://doi.org/10.1016/j.jhydrol.2013.09.034>

- Tehrany MS, Pradhan B, Jebur MN (2014) Flood susceptibility mapping using a novel ensemble weights-of-evidence and support vector machine models in GIS. *J Hydrol* 512:332–343. <https://doi.org/10.1016/j.jhydrol.2014.03.008>
- Tehrany MS, Shabani F, Jebur MN, Hong H, Chen W, Xie X (2017) GIS-based spatial prediction of flood prone areas using standalone frequency ratio, logistic regression, weight of evidence and their ensemble techniques. *Geomat Nat Hazards Risk* 8(2):1538–1561. <https://doi.org/10.1080/19475705.2017.1362038>
- UNISDR (2009) Terminology on disaster risk reduction. Geneva, Switzerland. http://www.unisdr.org/files/7817_UNISDRTerminologyEnglish.pdf. Accessed 15 April 2018
- UNISDR (2016) Issues of vulnerability with specific reference to gender in the Asia-Pacific. UNISDR Secretariat, Asia and the Pacific, Bangkok, p 20
- Wisner B, Blaikie P, Cannon T, Davis I (2004) *At risk, natural hazard, people's vulnerability and disasters*, 2nd edn. Routledge, London, pp 49–52
- Yumarni T, Amaratunga D, Haigh D (2014) Assessing gender vulnerability within post-earthquake reconstruction: case study from Indonesia. *Proc Econ Financ* 18:763–771

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.