



# Riverbank erosion induced vulnerability in India: a review for future research framework

Nirsobha Bhuyan<sup>1</sup> · Haroon Sajjad<sup>1</sup> · Md. Hibjur Rahaman<sup>1</sup> · Raihan Ahmed<sup>2</sup>

Received: 22 November 2023 / Accepted: 8 July 2024

© The Author(s), under exclusive licence to Springer Nature B.V. 2024

## Abstract

Riverbank erosion is a significant risk that results in damages and economic losses. India is severely vulnerable to riverbank erosion due to its demographic profile, socio-economic conditions, and physiographic setting. This paper attempts to analyze the studies on vulnerability to riverbank erosion in India through a systematic literature review from 2007 to 2023. A total of 68 articles were chosen for this study using keyword search. The findings revealed that studies on political as well as physical and psychological health vulnerability were underrepresented. Ecological vulnerability studies based on site-specific indicators were also found to be limited. The maximum number of studies were concentrated in West Bengal and Assam. Studies based on the use of machine learning and other automated techniques were scant in the existing literature. Most of the reviewed articles relied on a qualitative and descriptive approach. Though a substantial body of work has been carried out on riverbank erosion, the vulnerability posed by riverbank erosion requires adequate representation. The study calls for carrying out more research on specific target groups based on gender, age, and other socio-cultural parameters. Hydrodynamic models and machine learning algorithms for analyzing vulnerability to riverbank erosion are suggested for the future progression of the research.

**Keywords** Literature review · Riverbank erosion · Ecological and socio-economic vulnerability · Research gaps · Future research

---

✉ Haroon Sajjad  
haroon.geog@gmail.com

Nirsobha Bhuyan  
nirsobhabhuyan08@gmail.com

Md. Hibjur Rahaman  
hibjuronline@gmail.com

Raihan Ahmed  
raihan.geog@gmail.com

<sup>1</sup> Department of Geography, Faculty of Natural Sciences, Jamia Millia Islamia, New Delhi, India

<sup>2</sup> Department of Geography, Nowgong College, Nagaon, Assam, India

# 1 Introduction

Riverbank erosion is a major natural hazard that has been causing heavy loss of life and property for centuries (Das et al. 2014). Climate change and the increasing pressure exerted by anthropogenic activities have increased the magnitude and intensity of the hazard (Bhuyan et al. 2024). Rivers have been identified as active agents of erosion. Bank erosion is the process that occurs when the force of running water in rivers exceeds the resistance capacity of the bank materials (Klausmeyer 2016). Riverbank erosion is a natural hazard that is recurring in nature (Debnath et al. 2017). It is considered to be more devastating and dangerous than floods due to its long-lasting impact (Biswas and Anwaruzzaman 2019). Bank erosion leaves a permanent trace of loss and economic distress since the lands lost to rivers cannot be replaced and it takes years to recover from it (Das et al. 2014; Ferdous and Mallick 2019). It is a constantly occurring process and it is usually difficult to observe its impacts over a short length of time which makes it different from other natural hazards (Arobi et al. 2019). Various factors like soft alluvial soil, substantial runoff, perpetual rainfall, stream power, high sediment load, seismic events and deforestation have been recognized as controlling factors of bank erosion (Biswas and Anwaruzzaman 2019; Debnath et al. 2017; Khan 2012). Additionally, anthropogenic activities like bridges, dams and barrage construction have also impacted erosion rates (Debnath et al. 2023). Apart from this wide range of factors, floods and bank erosion have been found to be closely interrelated (Das and Samanta 2023). Floods are natural processes that play a vital role in sustaining the fluvial system and ecological habitats (Kotoky et al. 2015). Bank erosion is initiated during floods and mass failures continue to occur in the flood recession phase (Kotoky et al. 2005). This exposure to floods causes riverbank erosion which leads to significant risks and damages (Pareta et al. 2019).

With an increase in population and scarcity of resources, specifically, land, vulnerability to riverbank erosion has increased over the years (Das et al. 2014; Rahman and Gain 2020). Countries all around the world like India, Bangladesh, Pakistan, Nepal, the USA, the UK, Greece, Serbia, Vietnam, etc. are vulnerable to riverbank erosion. Bank erosion in Bangladesh is mostly driven by the braided nature of its rivers, a condition worsened by heavy rainfall and heightened water flow (Billah et al. 2023). It has been predicted that riverbank erosion will rise considerably in the Jamuna, Ganges and Padma rivers in Bangladesh with an increase in flood discharge by 20% by the next century (Hasan et al. 2018). The Indus River in Pakistan shifted its course between 2000 and 2022 owing to floods and bank erosion (Ahmad et al. 2024). According to a report by the Asian Development Bank (2019), the Terai region of Nepal also witnessed significant bank erosion caused by floods that led to the devastation of settlements and agricultural land. One such major flood event occurred in 2017 which affected almost 1.7 million people in Nepal. The tropical storm Irene, resulted in severe flooding that led to substantial bank erosion in the United States' Mad River valley (Ross et al. 2019). Ho Chi Minh City in Vietnam gets inundated every year and bank erosion has become a persistent issue as a consequence of flooding (Olson 2022). Likewise, Dragicevic et al. (2017) established that flood events in Serbia's Kolubara Basin caused bank erosion.

Hundreds of rivers drain the Indian soil and heavily erode the riverbanks. It is estimated that more than 12% of the total geographical area of the country is affected by riverbank erosion and floods (Ministry of Home Affairs, Govt of India 2011). On average, the coun-

try experiences an economic loss of approximately \$450 million every year and the Ganges-Brahmaputra-Meghna River basins extending over Assam, Bihar, West Bengal, Uttar Pradesh, and other northeastern states are the most vulnerable areas in the Indian territory (ADB 2010). Erosion along the Ganga and Brahmaputra rivers is reported to be the worst (Das et al. 2017). In Assam alone, the Brahmaputra and its tributaries eroded over 4.27 lakh ha. land in the last 60 years (Water Resources, Government of Assam, 2024). The state lost about 7% of the land to riverbank erosion between 1954 and 2011 and suffered an economic loss of around \$20 million (Pradhan et al. 2021).

Though hazards occur across the world, the people of developing countries are the most vulnerable due to their large population bases, high population density, poverty, and relatively backward levels of technology (Zorn 2018). Due to India's geographical setting and socio-economic conditions, riverbank erosion has emerged as one of the major risks in the country (Das and Samanta 2023; Ministry of Home Affairs, Govt of India 2011). Bank erosion leads to huge losses in terms of ecological, social, economic, and health aspects (Rinaldi et al. 2013). Vulnerability resulting from riverbank erosion is catastrophic, yet it has not received enough recognition among social, political, and scientific communities and has not been acknowledged as a natural disaster under Indian disaster management laws (Sahay et al. 2020). Along with humans, riparian vegetation and faunal life are also threatened by bank erosion. Numerous streams flow through India and the rivers like the Ganga and Brahmaputra are some of the most erosive rivers in the world (Das et al. 2014). For instance, in comparison to other rivers of the world, the Brahmaputra is known to carry very large amounts of sediment that transitions the river to a highly braided channel, thereby increasing the potential of bank erosion (Bhuyan et al. 2023). The Brahmaputra alone eroded over 1500 sq. km. of land in the state of Assam between 1974 and 2014 (Saikia et al. 2019). Similarly, the Bhagirathi-Hugli River erodes 8 sq. km. of land in West Bengal every year on average (Islam 2016; Mukhopadhyay et al. 2023). Bank erosion in India is one of the most detrimental hazards that has caused profound impacts on humans (Das et al. 2017; Das and Samanta 2023). ). These grounds make studying vulnerability to riverbank erosion of utmost importance in India for safeguarding the people and protecting the environment. One of the important steps towards this is the analysis of the existing literature on vulnerability to riverbank erosion in India. A review helps in tracing the timeline of a particular topic underlining its nature, scope, and evolution. It is vital in academic research for gathering existing knowledge and assessing the current state of any research domain (Linnenluecke et al. 2020). Though a large body of research has presented reviews on various hazards, a comprehensive review on vulnerability to riverbank erosion is lacking in the existing literature. Thus, the novelty of this paper lies in its attempt to carry out a detailed review on the vulnerability to riverbank erosion in India. The integration of a bibliometric approach adds further value to this research. This would give researchers an insight into the works undertaken, the research gaps, and possible future frameworks for further studies.

## 2 Materials and methods

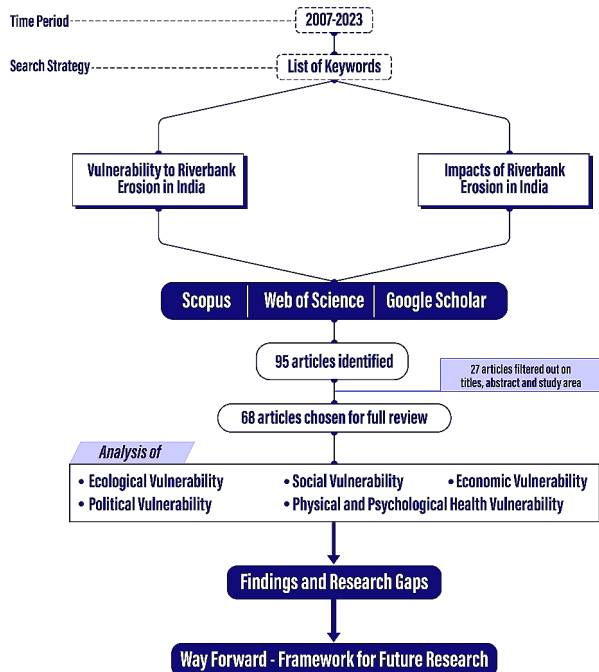
The present study is based on a systematic literature review of the research conducted on vulnerability to riverbank erosion in India. The time frame chosen for the study was 2007–2023 spanning over 17 years. The study aimed at assessing the literature on riverbank ero-

sion vulnerability in recent times spanning the last 20 years from 2004 to 2023. However, studies explicitly on vulnerability to riverbank erosion were available from 2007 onwards. Hence, the time frame was considered from 2007 to 2023. Literature mining was carried out using the keyword search criterion. Two keywords were used for the literature survey- ‘vulnerability to riverbank erosion in India’ and ‘impacts of riverbank erosion in India’. Articles were downloaded from authentic databases like Web of Science, Google Scholar, and Scopus. A total of 95 articles were downloaded along with reports published by various international and national agencies and organizations like Intergovernmental Panel on Climate Change (IPCC), Asian Development Bank (ADB), and United Nations Development Programme (UNDP). Of these, 68 articles were filtered out based on titles, abstracts, and study area. These articles were thoroughly studied to present a detailed review of vulnerability to riverbank erosion in India. For better handling of the articles, a master table was constructed in Microsoft Excel for recording the studies along with attributes like authors, study area, keywords, indicators, and methods. The methodological framework of the review is represented in Fig. 1.

### 3 Results and discussion

Vulnerability entails a substantial scientific perspective aimed at delineating the condition of possible harm, lack of defense and both physical and social marginalization (Adger 2006). It suggests a certain level of risk intertwined with the degree of social and economic liability along with the capacity to manage the ensuing circumstances (Proag 2014). Vulnerability pertains to the extent to which a system is susceptible to experiencing harm as a result of exposure to a hazard (Turner et al. 2003). Therefore, poor socio-economic condi-

**Fig. 1** Methodological framework



tions and the inaccessibility to resources to recover from hazards render an individual or community vulnerable. This understanding guides the implementation of suitable measures to promote the well-being of the affected population (Singha and Pal 2022). One of the most widely accepted definitions of vulnerability is provided by the IPCC. IPCC (2007) defines vulnerability as “the degree to which a system is susceptible to and unable to cope with, adverse effects of climate change, including climate variability and extremes”. In other words, “vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, the sensitivity and adaptive capacity of that system”. Hence, vulnerability is the function of exposure, sensitivity, and adaptive capacity. According to the 6th Assessment Report of the IPCC (2022), vulnerability is the propensity or predisposition to be negatively impacted. It includes various concepts and components of sensitivity or susceptibility to harm and the inability to cope and adapt. Vulnerability to riverbank erosion is the impact caused by exposure to riverbank erosion which individuals and communities cannot cope with. The degree of vulnerability differs across communities, age, gender, or any other social identity (Kuran et al. 2020). The concept of vulnerability has evolved over the years and has shaped up as multidimensional in nature (Biswas and Nautiyal 2023). Vulnerability varies spatially and temporally and carries diverse meanings. Most of the disciplines today accommodate the concept of vulnerability which helps in evaluating the conditions of people when exposed to hazards (Sarker et al. 2019). The research articles reviewed in this study on vulnerability to riverbank erosion were categorized into five themes- ecological, social, economic, political, and physical and psychological health. Research articles associated with the impact on natural assets and the assessment of vulnerability using physical and ecological parameters were utilized to investigate ecological vulnerability (Table 1). Similarly, articles on parameters related to social (demography, education, gender, age, social institutions, social bonding, culture and migration) and economic (livelihood and income) domains were examined to study social and economic vulnerabilities respectively. The research papers which focused on factors linked to legal rights and nationality were used for political vulnerability analysis whereas physical and psychological health vulnerability analysis included factors related to diseases, psychological stress and healthcare infrastructure. To present a comprehensive review, this paper tries to accommodate the various approaches to vulnerability as analyzed in the reviewed articles. Thus, the paper considers vulnerability based on the components of exposure, sensitivity and adaptive capacity, adverse impacts of bank erosion on different components and parameter-driven vulnerability analysis.

### 3.1 Ecological vulnerability

Riverbank erosion creates ecological vulnerability<sup>1</sup> by disturbing the fragile balance of nature. Erosion is a primary driver of channel widening, channel migration, and various channel changes. The concave banks of the rivers usually cave in due to erosion and lead to a severe loss of land. Nearly 704 hectares of land of Gosaba Island was highly vulnerable to bank erosion. The island has already lost more than 33 hectares of land in the past 45 years (Ghosh and Mistri 2021). The sinuosity of the Ganga River in West Bengal increased

<sup>1</sup> Ecological vulnerability is the extent of disturbance caused to an ecosystem, the damage it undergoes and the system's capacity to revive itself (Hou et al. 2022). It results from an ecosystem being unable to endure stress (Cao et al. 2022).

**Table 1** Definitions and typologies of vulnerability and its types

Vulnerability and its types	Definition/Typology	References
Vulnerability	“Vulnerability represents the interface between exposure to physical threats and the capacity of people and communities to cope with those threats. Threats may arise from a combination of social and physical processes. The most conspicuous and widely-reported manifestation of this vulnerability is when people are affected- suddenly and violently- by natural hazards.”	Lahiri-Dutt and Samanta (2007)
	“Vulnerability reflects the sum of the risks (hazards) to which a society or community is exposed, mitigated by its adaptive or coping capacity (its ability to respond effectively to risk) and compensated by the available alternative economic opportunities.”	Sharma et al. (2010)
	“Vulnerability is indirectly proportional to resilience (i.e. vulnerability= 1/resilience) and vulnerability is directly proportional to susceptibility (vulnerability=susceptibility).”	Mukherjee (2011)
	“Vulnerability is the degree of loss to an element or set of elements from any natural or man-made phenomena. The concept of vulnerability implies some risk associated with the physical, social and economic liability and the ability to cope up with the resulting event.”	Biswas and Anwaruzaman (2019)
Ecological Vulnerability	Negative impact on the natural assets leading to their degradation and shrinkage	Das and Gogoi (2022)
	Vulnerability resulting due to channel migration/erosion and its impact on land use land cover observed based on changes in:	Guite and Bora (2016); Ghosh and Sahu (2019)
	Agricultural land, water body, marshy land, sandy land and sparse vegetation	Debnath et al. (2017)
	Dense forest, open forest, cultivated land, water body, barren land	Mondal and Mandal (2018)
	Water body, vegetation, agricultural land and fallow land	Saikia et al. (2019)
River, sandbars, agricultural land and vegetation		
Mapping vulnerability zones based on physical and geo-technical factors	Bandyopadhyay et al. (2014); Bandyopadhyay and De (2017); Pareta et al. (2019); Sarkar and Bera (2022); Dutta et al. (2023)	

**Table 1** (continued)

Vulnerability and its types	Definition/Typology	References
Social Vulnerability	Impacts on demography, social institutions like family, social bonding, culture, education	Biswas and Anwaruz-zaman (2019); Debnath et al. (2017); Islam and Guchhait (2018); Sahay and Roy (2017); Das and Gogoi (2022)
	Vulnerability studied based on migration and displacement	Das et al. (2017); Dekaraja and Mahanta (2018, 2021, 2022); Das et al. (2023); Islam and Guchhait (2017)
	Adverse impacts on women	Dutta (2011); Krishnan (2022)
	Adopted IPCC's approach of integrating sensitivity and adaptive capacity based on socio-economic indicators. Vulnerability=f(Sensitivity, Adaptive Capacity)	Sharma et al. (2010)
Economic Vulnerability	Income levels and livelihood represent the domain of economic vulnerability	Das et al. (2022); Majumdar et al. (2023); Singha et al. (2020); Singha and Pal (2022)
	Vulnerability based on change in occupation	Das and Gogoi (2022); Saikia and Mahanta (2023)
	Livelihood vulnerability assessment based on IPCC's concept of exposure, sensitivity and adaptive capacity	Ahmed et al. (2018); Das et al. (2017); Dutta et al. (2020)
Political Vulnerability	Livelihood vulnerability assessment based on IPCC's concept of exposure, sensitivity and adaptive capacity	Das et al. (2022); Majumdar et al. (2023); Singha et al. (2020); Singha and Pal (2022)
	Political vulnerability resulted from: Loss of identity (nationality or statehood) Loss of legal and citizenship rights Being victims of border disputes and hostilities	Biswas and Anwaruz-zaman (2019) Rudra (2020) Mukherjee (2011); Islam and Guchhait (2017)
Physical and Psychological Health Vulnerability	Physical and psychological health vulnerability was evaluated based on:	Biswas and Anwaruz-zaman (2019)
	Disease outbreak and lack of proper medical facilities	Das et al. (2014); Das et al. (2017)
	Degrading health conditions of women and children Increase in psychological stress and trauma	Islam and Guchhait (2018)

considerably from 1955 to 2010 which enabled the river to erode large plots of land, rendering many villages vulnerable (Laha and Bandyapadhyay 2013). About 90 villages were vulnerable to bank erosion caused by the shifting of the Ganga River in the Diara region of Eastern India (Mukherjee and Pal 2018). A similar situation was noted in Eastern India wherein the migration of the Kaljani River affected the resources of the Buxa reserved forest (Dutta and Mandal 2022). A meandering pattern and lateral migration were also observed for the Bhagirathi River (Ghosh et al. 2022). The Teesta River also experienced lateral migration in North Bengal between 1980 and 2021 with an average shift of 642.72 m and 1605.05 m along the left and right banks respectively (Das et al. 2022). Channel migration

led to riverbank failure which had severe consequences on land use land cover (Ghosh and Sahu 2019; Mondal and Mandal 2018; Saikia et al. 2019). The area under cultivated land, open forests, and vegetation decreased in Assam's Brahmaputra Valley and the catchment area of the Khowai River in Tripura (Debnath et al. 2017; Saikia et al. 2019). The Duar and Tal regions in the foothills of the Himalayas experienced heavy erosion by the Torsa River which resulted in a high volume of sediment load in the river leading to modification of the channel and land use land cover changes. Shoal areas were formed and expanded which obstructed the flow of water leading to further erosion (Dey and Mandal 2018). An increase in sediment load also raised the riverbed causing floods. A decrease in area under agriculture and an increase in wastelands were observed along the lower Balasan River due to the river eroding its banks (Das et al. 2021).

The agroecosystem suffered an adverse impact due to the loss of agricultural land and crop biodiversity induced by riverbank erosion. The eroded lands often emerged as sandy char lands which aided the growth of unwanted weeds and grasses. Such grasses and weeds have affected the growth of crops. Excessive deposition of sand also compelled the erosion-affected people to put their croplands to other land use. This was observed by Biswas and Anwaruzzaman (2019) in the Malda district where large tracts of agricultural lands were eroded by riverbank erosion giving way to the creation of sand bars. Such events of sand deposition rendered the soil unfit for agricultural activities. Erosion also led to an increase in soil salinity which reduced soil fertility and productivity (Khan 2012). The tidal waters of the Saptamukhi and Muriganga rivers entered the island of Namkhana in West Bengal and caused massive erosion. The waters also brought with them sediments and salts which decreased the channel depth and increased salinity. A rise in salinity level led to a decline in soil fertility thereby reducing crop production. Contamination of groundwater also occurred due to the seepage of saline waters into the soils (Dhara and Mondal 2019). Sand casting caused by riverine erosion along the Subansiri River also made lands infertile reducing productivity and diversity of crops, especially downstream where siltation was heavy (Guite and Bora 2016).

Riverbank erosion and channel migration caused siltation and endangered the fauna in the Brahmaputra River System (Sarkar 2017). Sarma (2014) also arrived at similar results about erosion caused by the river Brahmaputra. The author found that heavy siltation and diminishing areas of the swamps and water bodies endangered the flora and fauna of the island of Majuli. Aquatic life and both resident and migratory birds' habitats were threatened by riverine erosion thereby reducing their numbers and creating an imbalance in the ecosystem. Heavy siltation has lowered the productivity of the croplands (Dekaraja and Mahanta 2022). Riparian erosion also eroded the forest lands which were habitats of the animals and cut off the corridors for animal passage. This was evident in states like Assam and West Bengal (Dutta and Chakroborty 2013). Due to erosion by the Brahmaputra, many people were displaced from their native places. This relocation urged the displaced population to occupy reserve forests leading to deforestation, scarcity of wood, fodder, and environmental degradation (Das et al. 2014). Guite and Bora (2016) found that the shifting course of the Subansiri River in Assam eroded forests, bamboo cultivation, and swamps which in turn negatively affected the ecological balance of the area. Agricultural lands were also lost due to the erosive activity of the river Khowai in Tripura, India, and the reduction in swamps disturbed the ecological equilibrium around the area (Debnath et al. 2017).

### 3.2 Social vulnerability

Riverbank erosion has directly impacted people and disrupted their socio-cultural setup (Singha and Pal 2022). Breakage in social bonds, familial relations, and networks, lowering of social esteem and status, destitution, increase in illegal activities, and impact on social dignity occurred because of riverine erosion (Das et al. 2017). Most villages located along the erosive rivers were vulnerable to bank erosion especially because the rural communities relied on agricultural activities (Das and Samanta 2023). With large territories of croplands lost to the rivers, the villagers, usually poor and unskilled, were left highly vulnerable (Das and Gogoi 2022). One of the issues associated with bank erosion is migration. Migration was not just a stand-alone affair but led to a chain of events that accelerated vulnerability (Ghosh and Sahu 2018). Das et al. (2014) identified the pattern of “continuous forced migration” which indicated a brutish cycle of displacement, migration, and resettlement. The authors implied that the erosion-affected population was compelled to relocate to other areas due to erosion and this was repeated every few years making it a tedious cycle of relocation. Displacement of people due to the erosive activities of rivers was observed in the Shantipur block of West Bengal where the erosion-affected people were displaced about 4 times in 20 years (Chatterjee and Mistri 2013). In West Bengal’s Nadia district, 26% of households were displaced 5 times followed by 4 times (14%), 3 times (12%), 2 times (20%), and once (14%) (Paul and Bhattacharji 2022). Huge chunks of the population along the Bhagirathi, Dhansiri, and Himalayan rivers in North Bengal were left homeless and forced to migrate after the risk of erosion struck (Das et al. 2022; Islam and Guchhait 2017; Karmakar 2016; Mili et al. 2013). The people living along the Lower Gumti River and Khowai River in Tripura, India, were displaced many times due to channel migration and some people migrated permanently out of the area to comparatively safer places (Ahmed et al. 2018; Debnath et al. 2017).

After migrating, people faced a change in their way of life for the worse. The people at their places of origin led happy and peaceful lives with stable incomes, low expenditures, and strong socio-cultural ties. Life in the newly settled lands was never easy for the erosion-affected people. Migrating to other places meant that people had to live in slums that were cramped, unplanned, and unhygienic (Ghosh and Sahu 2018). This also led to a change in family structure from joint to nuclear and a reduction in the overall income (Mondal and Tripathy 2022). Sharma (2018) found that moving to a different region resulted in the breakage of social bonding that people earlier shared with the members of their society. A study on the Khowai River in Tripura by Debnath et al. (2016) also revealed that the social fabric of the erosion-vulnerable people was torn apart. The authors noted that relationships broke and anti-social activities rose as people were displaced.

As the social fabric and relationships loosened with displacement, the cultural tapestry also started waning out. Celebrating festivals and engaging in various folk practices was impossible which not only made the cultural aspect vulnerable but also led to social isolation and anxiety. Moreover, the new settlers were often ostracized by society as they were considered illegal migrants which increased their sense of isolation (Dutta et al. 2020). Furthermore, riverbank erosion changed the demography of eroded areas. The riverine island of Majuli in Assam, known to be home to the Mishing tribe, saw gradual depletion in its population since many of its original inhabitants migrated out of the island to other areas as the island was highly vulnerable to riverbank erosion. The others who stayed back on the island

were forced to change their way of life (Sarma 2014). Sahay (2022) has also highlighted the plight of the Mishing community resulting from riverbank erosion. More than half of the total villages in Majuli were washed away by erosion (Sahay et al. 2020). The satras which are cultural institutions in Assam were washed away due to erosion. The erosion of these satras not only meant mere physical destruction of property but also weakened the culture of neo-Vaishnavism in Assam, particularly Majuli (Kalita 2016; Sahay and Roy 2017). Change in the demographic domain along the Bhagirathi River was identified by Islam and Guchhait (2018). They found that family sizes among the poor in the erosion-prone areas were larger. This was because the family earnings were low and having more family members meant having a higher cumulative income which served as a survival strategy. Therefore, people lived together to share the available resources and support the households. The authors also observed that since the primary objective of the erosion-affected people was to arrange for their basic needs, there were often no concerns about ingraining ideologies and values which degraded their cultural milieu.

Riverbank erosion negatively impacted the levels of education of the victims since the schools and associated infrastructure were destroyed by the process of erosion. The victims of riverbank erosion had lower educational attainments leading to a cascading effect of unskillfulness, unemployment, lower levels of understanding, and poor decision-making. The educational crisis was further deepened by displacement (Khan 2012). Biswas and Anwaruzzaman (2019) carried out a study in the Malda district which found a decrease in literacy rate and an increase in the number of school drop-outs among erosion victims. Another study on Malda showed that the displaced population with low levels of educational attainment found it difficult to secure a decent living (Das et al. 2017); Das et al. (2023) arrived at similar results regarding an increase in school dropouts induced by bank erosion in Assam.

Women-run households were socially more susceptible to risks (Dutta 2011). The history of oppression against women is serious and with the physical destruction of infrastructures like schools, health care, and sanitation facilities due to riverbank erosion, the situation of vulnerability is exacerbated. Women suffered in terms of access to and lack of education and other basic amenities, financial instability, increase in laborious tasks, and the threat of harassment. They suffered from severe physical and mental torture due to the infelicitous situations created by hazards. Riverbank erosion forced men to migrate to urban areas to secure their livelihoods and left the women behind to shoulder all household responsibilities (Krishnan 2022). Mukherjee (2011) unveiled that in Malda and Murshidabad districts, the women had to provide financial support to their families after incurring losses due to bank erosion. This compelled the young girls to join deleterious jobs by leaving their education behind and the women had to join the smuggling nexus as couriers which made them susceptible to sexual abuse. Women also constituted a major chunk of the displaced population in Malda (O'Neil 2010). Another study in Malda revealed that food insecurity was high among displaced females since they used to eat whatever little remained after all the other family members finished their meals (Dutta 2011). The families could not afford much due to riverbank erosion-induced losses and patriarchy-conditioned lives made women more vulnerable. Women faced several threats not only during the hazards but also during the post-hazard phase. These sacrifices and adjustments that women in particular had to make to keep the family running, became a part and parcel for the rest of their lives.

### 3.3 Economic vulnerability

Riverbank erosion devastated personal assets and state-owned resources and infrastructure. This promptly put the erosion-hit people in a taxing situation by inflicting the loss of land and livelihood on them which reduced their income. Their income exhaustion led to a low intake of food resulting in poor health conditions. Due to ill health, many people were unable to engage in work which increased their level of poverty and degree of vulnerability. With the rivers eroding lands and properties, loss of livelihood and the resultant depletion in income was a familiar sight in Assam along the Brahmaputra (Sharma et al. 2010). Debnath et al. (2016) identified a relationship between a reduction in financial ability incurred due to riverbank erosion and family status among the villagers along the Khowai River. The authors observed that loss in income and resources led to the lowering of the socio-economic status of families.

Occupational change was a major impact of riverbank erosion on the people. People living in Malda, West Bengal, and along the Khowai River in Tripura were victims of livelihood pattern change due to riparian erosion (Das et al. 2017; Debnath et al. 2016, 2017). Loss of lands, assets, and means of living compelled people to search for newer livelihood options and alter their occupations by migrating to other areas (Ahmed et al. 2018; Dekaraja and Mahanta 2021; Dutta 2011; Dutta et al. 2020; Majumdar 2018; Mondal and Tripathy 2022; Sahay and Roy 2017; Sharma 2018). In the case of Dhubri and Dhemaji districts of Assam, though the short-term migration rate was higher, long-term migration was also found in the severely eroded areas since the loss of crops and livestock shrunk the income of the people leading to a reduction in expenditure (Dekaraja and Mahanta 2018). Some erosion victims of Shantipur, West Bengal were weavers and they lost all their weaving set-ups to the erosive rivers. Resetting the entire arrangement, especially after migrating to other places made it difficult for them to continue with their traditional occupation (Das et al. 2014). Though people sought new professions, the alternate livelihood options were less due to a lack of expertise and skill which even made people take up hazardous jobs just to earn a meagre amount (Dutta and Chakraborty 2013).

Unemployed people and landless labourers increased since people were mostly engaged in agriculture in the erosion-affected areas (Khan 2012). Islam and Guchhait (2017) concluded that as the effects of erosion built up over the years by washing away huge expanses of cultivable lands, there was a fall in the number of people engaged in agriculture and a rise in the number of non-agricultural labourers, generation after generation along the Bhagirathi River in West Bengal. Change in livelihood patterns was observed in Malda and Nadia, India, wherein the number of main workers engaged in agricultural activities decreased after large tracts of cultivable lands were lost to the erosive rivers (Biswas and Anwaruzzaman 2019; Paul and Bhattacharji 2022). Similarly, a decline in the agricultural workforce from 63 to 21% was seen along the Teesta in North Bengal which testified to the hazardous erosion scenario (Das et al. 2021). Around 74% of the population of the villages in Assam's Dhubri and Dhemaji districts along the Brahmaputra was compelled to switch from agrarian to non-agrarian activities (Dekaraja and Mahanta 2022). Diversifying livelihood options by force, however, had negative implications for the victims. Getting involved in three or more occupations on a diurnal or seasonal basis due to unstable economic conditions exhausted the workers (Islam and Guchhait 2018). Erosion of cultivable lands also led to an oversupply of agricultural labourers which resulted in the employment of these

workers at a wage way below the minimum amount fixed by the government (Mukherjee 2011). Such instances which generated surplus labour compelled many people to migrate to the cities as well to take up menial jobs (Chatterjee and Mistri 2013). Thus, displaced people due to erosion have formed a major part of the rural-to-urban migration stream (Adhikary 2022). This led to an increase in the population of the urban areas where people often lived impoverished lives (Rudra 2020). The Mishings community of Majuli was also found to be economically vulnerable owing to riverbank erosion. The Mishings are referred to as the 'river people' who have been residing along the riverbanks historically (Thakur 2021). They depend on the river and livestock rearing, especially piggery, for their livelihood (Saikia and Mahanta 2023). The wetlands also provided them with certain benefits like fishing grounds, medicinal herbs and reed for mat-making (Das 2014; Sahay 2022). The community was vulnerable to bank erosion due to living in the proximity of the erosive Brahmaputra. Majuli is a riverine island in the Brahmaputra River and wetlands are an integral part of the island (Social Forestry Division, Government of Assam 2022). However, these wetlands are considered wastelands or barren lands in Majuli. Thus, when this vulnerable community was displaced from their lands, they did not receive due compensation from the government since compensation was given only for agricultural lands. This led to the community being economically marginalized and landless (Sahay 2022).

### 3.4 Political vulnerability

The feeling of 'not belonging' to any political territory and loss of legal rights essentially takes up the form of political vulnerability (Biswas and Anwaruzzaman 2019; Das et al. 2014). The people affected by erosion lost their lands and resettled on newly emerged char lands whose jurisdiction remained questionable, hence no state readily accepted these environmental refugees. Many erosion victims had legal identity proofs yet they could not reap the benefits of government services as they were not acknowledged as citizens by any country or state. Moreover, the shifting river channels disrupted the political boundaries between places which created situations of mayhem. This vulnerability was experienced at both international and intra-national levels. Boundary disputes were common between India and Bangladesh which affected the erosion victims (Das et al. 2014). The rivers eroded the border posts between the two countries which created confusion and made the borders porous (Mukherjee 2011). Similar vulnerabilities also existed within India. For example, the shifting nature of the Damodar River raised questions over the security of its char dwellers. The Damodar delineated the border between the Burdwan and Bankura districts and most of the chars were administered by the latter district. However, with the river migrating towards Burdwan, the char dwellers were distanced from the administrative centre and were marginalized (Lahiri-Dutt and Samanta 2007). The citizenship rights of the char dwellers of India's Malda district were neither recognized by West Bengal nor Jharkhand (Mukherjee 2011; Rudra 2020). Therefore, identity crisis, border dispute, cross-border conflicts, and eviction in Malda were major challenges for the erosion-affected people (Biswas and Anwaruzzaman 2019). The victims also lost the right to civic amenities and the benefits of government programmes since they were not granted citizenship rights by any state. In the Brahmaputra Valley in Assam, the riverbank erosion migrants faced an identity crisis as they were doubted to be illegal immigrants (Das et al. 2014). Debnath et al. (2016) remarked that the newly emerged lands in the area drained by the Khowai River in Tripura often became

the bone of contention among the people of different villages who wanted to claim these lands. This led to enmity and rivalry among villages. These confrontations, at times, were so violent that people were severely injured and even lost their lives. Such conflicts, though they have not gained much momentum along the Bhagirathi in West Bengal, India, have the potential to escalate into bigger disputes (Islam and Guchhait 2017). The possibility of such conflicts is apparent in Majuli between the Mishing and non-Mishing Assamese communities (Sahay 2022).

### 3.5 Physical and psychological health vulnerability

Riverbank erosion led to a serious deterioration in health conditions which were worsened by various implications of bank erosion like poverty, loss of assets, lack of infrastructural facilities, poor transportation and communication, and migration. People were infected with many diseases because of poor sanitation facilities, lack of hygienic environments, and living in congested places due to the series of onslaughts by riverine erosion (Islam and Guchhait 2017; Sharma et al. 2010). The outbreak of diseases like malaria and typhoid was observed to be common in the bank erosion-hit places and the situation was aggravated because of the lack of proper medical facilities (Biswas and Anwaruzzaman 2019).

Women were found to be extremely vulnerable to riverbank erosion. Women often had to manage their families and it became a real challenge after experiencing heavy losses due to riverbank erosion. Overworking to manage households and substituting the losses incurred from erosion deteriorated their physical health conditions. Due to the patriarchal set-up of the societies, women were conditioned to adhere to certain norms which worked against their favour. For instance, women generally ate after all the other family members had eaten. This made women usually eat only leftovers and sometimes retire for the day with an empty stomach. Such circumstances made them very weak and feeble. Das et al. (2017) calculated the Body mass index (BMI) of the mothers in Malda and found that the women suffered from malnourishment. The children of these malnourished mothers were also born undernourished. Das et al. (2014) and Mukherjee (2011) concluded that many malnourished children, unfortunately, faced death and immunization was out of scope. The authors also highlighted the helpless condition of the pregnant mothers who died due to infrastructural lag. People were highly vulnerable health-wise since most people had low food or calorie intake, did not have access to proper healthcare facilities and qualified doctors were unavailable.

Vulnerability induced by riverbank erosion was not only distinct in terms of degrading physical health but also affected people mentally. The erosion victims suffered from mental shock due to the loss of land and other assets to riverbank erosion (Mondal and Tripathy 2022). Psychological distress varied between males and females. The stress was observed more in males in the pre-erosion phase since the males usually experienced the wrath of erosion first-hand, on-site. The males, who worked outside of their homes in fields as bread earners of the family, encountered the impacts of the risk first as it directly hit their livelihoods. The post-erosion phase put women under severe psychological trauma as the females had to bear all the burden of managing the households (Islam and Guchhait 2018). The pressure to manage and feed the families weighed down on women and made them succumb to these biased gender roles. This took a toll on the health and psychology of women.

### 3.6 Adaptation strategies adopted

Some studies provided certain adaptation measures to cope with riverbank erosion-induced vulnerability. Das et al. (2023) suggested that people in Assam chose to migrate to safer areas as a coping mechanism for both long and short terms. Migration was also observed in the districts of Dhubri and Dhemaji in Assam, though it was often seen as the last resort (Dekaraja and Mahanta 2021). Other coping strategies like the sale of land and livestock and engagement in small-scale businesses were adopted in the relatively less eroded areas in these districts of the Brahmaputra valley (Dekaraja and Mahanta 2018). Many erosion victims also chose to change their professions, especially shifting from farming to non-farming activities in Malda, West Bengal (Sharma 2018). The non-agricultural occupations included masonry, daily wage labour, small enterprises and working in the handloom and tobacco industries. Krishnan (2022) provided a detailed note on the adaptation strategies adopted by women in particular in the riverbank erosion vulnerable areas in Assam. The author stated that women built temporary dwellings instead of permanent facilities since this helped them move to other safer areas quicker, once their homes were eroded. Women were also dependent upon their social capital and relations like relatives and neighbours so as to share the available means and resources. Women, who headed households in Malda, chose migration as an adaptive strategy (Dutta 2011). This saved the families from imminent starvation that resulted from the loss of land and other assets due to bank erosion. Ghosh and Mistri (2021) recommended the use of techniques like the construction of porcupines, bamboo barriers, and cultivating mangroves to tackle erosion. Kalita (2016) also proposed some remedies to reduce vulnerability to riparian erosion namely renovating embankments, practicing social forestry, conserving the cultural heritage, and provision of monetary support from the government. Sarkar and Bera (2022) recommended the use of rock-filled gabion boxes, bio-engineering, geotextiling, and the construction of gravity, retaining, cantilever and sheet piling walls. Rudra (2020) suggested the need for government intervention, strengthening of early warning systems and disaster preparedness to combat the perils of hydrological hazards. Saikia and Mahanta (2023) suggested the organization of training programmes and workshops, the use of traditional knowledge and the installation of porcupines to reduce the negative impacts of erosion.

### 3.7 Drivers of erosion

Riverbank erosion has caused substantial damage to different parts of India. The studies indicated that large proportions of areas were eroded by various rivers owing to a wide range of factors. Pareta et al. (2019) presented a detailed description of the factors that drive the mechanism of riverbank erosion. The authors recognized an increase in hydraulic forces, configuration, and properties of the bank as the causes of riverbank erosion. Hydraulic forces became active as a result of steep slopes, higher flood discharge, channel migration, and change in flow direction. Bank characteristics that affected erosion include particle size, soil moisture, and cohesion between particles. In terms of bank configuration, parameters like bank height, vegetal cover, presence of hard points like resistant rocks, and cross slope of banks determined riverine erosion. The study also found that heavy precipitation increased the velocity and water flow of the rivers which caused massive erosion along the riverbanks. Non-cohesive soils and asymmetrical channel form also contributed to bank

erosion (Ahmed et al. 2018). The rivers eroded the soft alluvial soil particles and caused undercutting of the banks resulting in shear bank failure (Laskar and Phukon 2012). Toe erosion and slumping were also observed to be associated with bank failure (Biswas et al. 2020; Ghosh and Mistri 2021). In the valley regions, high rainfall, steeper slopes, and the presence of unconsolidated soil generated large quantities of sediments in the rivers (Chakraborty and Saha 2022; Ghosh and Saha 2022). Thus, high sediment load, high velocity of the river, and high discharge increased river bank erosion (Debnath et al. 2017). Similarly, Khan (2012) and Biswas and Anwaruzzaman (2019) identified factors such as flood, incessant rainfall, deforestation, powerful river currents, and high sediment load of rivers as the drivers of bank erosion. Guite and Bora (2016) also considered the geological and topographical parameters as the factors of bank erosion. Likewise, Bandyopadhyay et al. (2014) and Bandyopadhyay and De (2017) argued that heavy rainfall led to a higher runoff which aided erosion. Also, a higher bank slope and steeper riverbed indicated higher erosion whereas the presence of vegetation deterred erosion. Sarkar (2017) found steep gradients, alluvial banks and the occurrence of earthquakes caused severe erosion along the river’s banks. Debnath et al. (2023) arrived at similar conclusions regarding the drivers of erosion. The braided nature of the river channel, flood, discharge, bed load, flow direction, river confluence, presence of channel bars, topography, seismic activities, and human activities were identified as the factors leading to bank erosion. Moreover, banks experienced erosion in the form of slumping and subaqueous failure. The authors also found that anthropogenic activities like building road and rail bridges and changes in land use land cover practices accelerated the process of erosion. Similar observations were also made by Das et al. (2014) that the construction of bridges, dams, and barrages intensified the process of erosion.

### 3.8 Assessment of methodologies used

Several approaches and methods were employed to analyze vulnerability (Fig. 2). Indices were constructed by some studies to assess riverbank erosion vulnerability. The conditioning factors observed in the reviewed articles for examining vulnerability are listed in



Fig. 2 Techniques adopted by the reviewed articles

Table 2. The livelihood vulnerability index (LVI) developed by Hahn et al. (2009) based on the IPCC approach was adapted by Majumdar et al. (2023) and Singha and Pal (2022) to assess vulnerability in parts of West Bengal. A similar livelihood vulnerability approach was used by Das et al. (2022) based on the components of exposure, sensitivity, and adaptation. Bandyopadhyay et al. (2014) and Bandyopadhyay and De (2017) employed a new remote sensing and geographic information system-based method to prepare bank erosion vulnerability zones which included eight parameters encompassing both natural and anthropogenic factors. The results were then compared with the bank erosion hazard index and near bank stress (BEHI-NBS) method. BEHI was utilized by Chakraborty and Saha (2022) to delineate areas vulnerable to riparian erosion. BEHI and river embankment breaching vulnerability index (REBVI) were employed by Hasanuzzaman et al. (2021) to study channel migration and vulnerability of the areas along the lower reach of the Ganga in West Bengal. Dey and Mandal (2022) used BEHI, NBS and analytical hierarchy process (AHP) to generate riverbank erosion vulnerability zones to map suitable sites for human habitation. Sarkar and Bera (2022) adopted the bank erosion susceptibility index (BESI), a modified form of BEHI to evaluate bank erosion susceptibility. Sharma et al. (2010) formulated the plan form index proved useful in assessing vulnerability caused by riverbank erosion. In addition, the authors also constructed a socio-economic vulnerability index based on sensitivity and adaptive capacity. The infrastructural index computed by Ghosh and Sahu (2018) was calculated by incorporating the per-capita small savings index, toilet facility index, household having electric facility index, drinking water facility index, and health facility index which revealed low levels of infrastructural development owing to riverbank erosion. The natural growth index (NGI) and the migrational growth index (MGI) were constructed

**Table 2** Factors influencing riverbank erosion vulnerability

Vulnerability	Factors
Ecological	Hydraulic forces Bank properties Bank configuration Geo-tectonic aspects Rainfall Soil type Flood level Land use land cover changes Distance from river Presence of vegetation
Socio-economic	Gender Age Differently-abled people Income Profession Loss of land and other assets Infrastructure availability in health-care Education sector and daily needs
Health	Prevalence of diseases Unavailability of healthcare facilities and Doctors Improper sanitation facilities Mental stress
Political	Identity crisis No citizenship No legal rights Conflicts

by Dekaraja and Mahanta (2021) which depicted population growth and rural-urban migration. The authors further created a factor correlation matrix developed on the indicators related to demography, riverbank erosion, and livestock to study the association between riverbank erosion and migration. Dekaraja and Mahanta (2022) applied head count ratio (HCR) and poverty gap index (PGI) to estimate the severity and incidence of poverty among the people of Dhubri and Dhemaji affected by bank erosion in Assam. The authors further conducted focus group discussions (FDG) to get an in-depth idea regarding the impacts of bank erosion.

Field surveys were conducted through structured questionnaires to collect primary data on different vulnerability indicators (Das et al. 2022; Singha et al. 2020; Singha and Pal 2022). The statistical techniques were used to identify patterns, and trends, compare datasets, test significance levels, and establish relationships among the variables. T-test, Pearson's product moment correlation analysis, comparative index, coefficient of variation, etc. were used. Apart from these, advanced approaches like principal component analysis, categorical principal component analysis, and tajfel matrix were also utilized (Islam and Guchhait 2018). However, studies that incorporated models, indices, and advanced statistical tools were limited in number.

The most common technique applied to demarcate the areas of erosion and accretion was by delineating the bank lines from satellite imageries through remote sensing and GIS tools. The bank lines were overlaid to ascertain their migration based on which polygons were digitized for areas of erosion and accretion (Ahmed et al. 2018; Chakraborty and Saha 2022; Saikia et al. 2019). Biswas et al. (2020) computed average erosion rates by dividing the mean channel shifting by time denoted by the number of years. For calculating bank line shifting, the automated technique of digital shoreline analysis system (DSAS) was used by Hasanuzzaman et al. (2021) and Debnath et al. (2023) which provided accurate results as per the accuracy assessments carried out by the authors. Hasanuzzaman et al. (2021) also predicted the rates of erosion to be 0.164 km/y and 0.031 km/y along the left and right banks of the Lower Ganga respectively between 2020 and 2045. Ghosh et al. (2022) utilized the logarithmic regression technique to predict mean erosion rates for the Bhagirathi in West Bengal and found that the river would migrate 174 m/y from 2018 to 2030. This would make 17 villages along the river vulnerable to riverbank erosion. The modifications along the riverbanks were studied mostly through the changes in LULC. The changes were studied by analyzing LULC maps for different time periods and calculating changes in area under various LULC classes by constructing confusion matrix or change matrix (Das et al. 2021; Debnath et al. 2017; Saikia et al. 2019). Conversion of LULC maps was also prepared to assess the alterations in LULC classes (Chakraborty and Saha 2022; Mondal and Mandal 2018).

In recent times, modelling and machine learning algorithms have come to play a crucial role in studying vulnerability to riverbank erosion. In light of this, a livelihood vulnerability state (LVS) was modelled using advanced machine learning algorithms like artificial neural network (ANN), random forest (RF), random subspace (RS), and support vector machine (SVM) by Singha et al. (2020). The models were validated using the area under the receiver operating characteristic (ROC) curve. The accuracy assessment showed that the AUC-ROC values ranged between 0.80 and 1.00 which demonstrated excellent to good accuracy (Rasyid et al. 2016). Thus, vulnerability assessment carried out using machine learning algorithms provided reliable results. In addition to the ROC curve, model validation could

be undertaken using other techniques like accuracy, recall, precision and F-1 score. Machine learning techniques also enable the identification of parameters that influence vulnerability through sensitivity analysis (Bhuyan et al. 2024). Dutta et al. (2023) prepared riverbank erosion vulnerability zones for Majuli Island using geotechnical parameters. The information on the geotechnical parameters were obtained through laboratory tests conducted on the soil samples collected on-site. This study provided a well-grounded methodology for vulnerability assessment and sensitivity analysis based on in-situ data. The binary logistic regression model was used by Ghosh and Saha (2022) to analyze the parameters that caused high bank erosion along the Ganga River in Malda district in India. The pressure and release model used by Biswas and Anwaruzzaman (2019) studied the progression of vulnerability to riverbank erosion based on social components (root causes, dynamic pressure, and unsafe conditions) and a natural component (the disaster itself). Saikia and Mahanta (2023) employed both quantitative and qualitative techniques to assess the vulnerability of char residents of Assam. They used the participatory rural appraisal method (qualitative) and vulnerability as uninsured exposure to risk econometric model (quantitative) for which data was gathered from the target group through a schedule-based survey.

### 3.9 Findings and research gaps

Though a sizeable number of studies are available on the concept of riverbank erosion, the processes associated with it, and its causes, research conducted particularly on vulnerability to the hazard, is limited. Of the total articles referenced from 50 journals, 2 journals published 3 articles each, and 1 journal published 2 articles on vulnerability to riverbank erosion. The remaining 47 journals published 1 article each on riverbank erosion vulnerability. It was found that more studies were conducted on vulnerability to riverbank erosion in India after 2014 (Fig. 3). The highest number of studies was recorded in the year 2022. In the existing literature on vulnerability to riverbank erosion, the majority of studies focused on socio-economic vulnerability. The most common keywords identified were riverbank erosion, vulnerability, channel migration, land use land cover and GIS and remote sensing

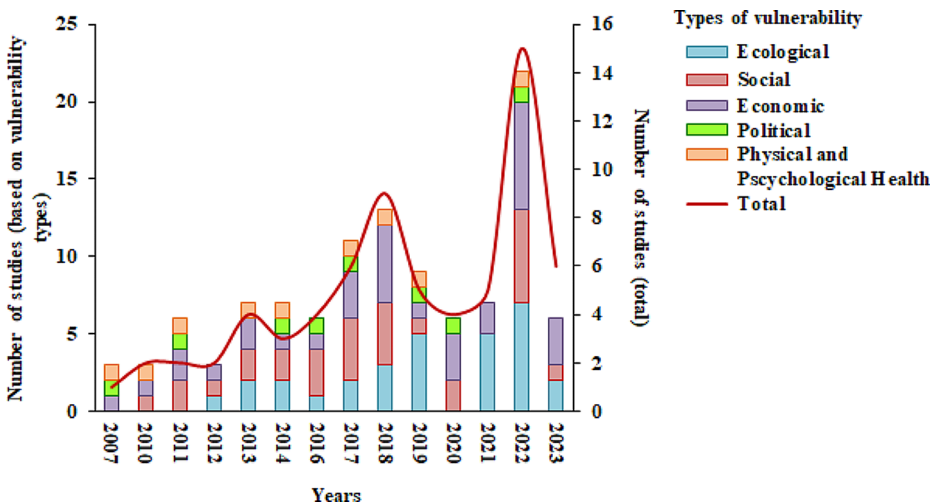


Fig. 3 Trend of publications

(Fig. 4). The frequency of keywords like channel, land use land cover and GIS and remote sensing sharply increased post-2014. The keyword analysis also revealed that the focus on livelihood, migration and bank protection increased 2014 onwards.

Das et al. (2014) had found that the issue of riverbank erosion was not very pronounced in India’s northwest, central and, Deccan regions. The present literature survey also revealed that riverbank erosion was prominent in the eastern and northeastern parts of India. The studies primarily covered the states of West Bengal, Assam, and Tripura, which are situated in the eastern and northeastern parts of the country. The char lands (sandbars and riverine islands) in these states which are always in direct contact with the rivers were the most vulnerable areas. Most of the studies were conducted along the river Ganga (21) followed by the Brahmaputra (19) (Fig. 5). These rivers flowed down the hilly terrains, carried a huge amount of silt, and frequently altered their courses, thereby causing severe bank erosion. The construction of the Farakka Barrage has also increased erosion along the Ganges (Das et al. 2014). The Ganga and the Brahmaputra were found to be the most destructive rivers. These sinuous rivers formed braiding patterns which gave rise to riverine islands or chars. These chars were extremely vulnerable to bank erosion since they were located within the river channel and were composed of easily erodible loose sediments. These rivers drained some of the most densely populated regions of India. They flowed through diverse terrains that were very rich in biodiversity. Their erosive nature rendered the population and the riverbanks vulnerable ecologically as well as socio-economically. Moreover, these were international rivers that flowed through different countries. Hence, certain political tensions associated with these rivers also rose and created a politically vulnerable situation for certain groups of people. The author distribution analysis showed that bank erosion vulnerability studies were carried out primarily by scholars of West Bengal and Assam. Scholars from the states of Tripura and Meghalaya also made significant contributions to vulnerability assessment studies (Fig. 6). Though vulnerability studies were lacking for the western, and southern Indian states, authors’ collaboration from the states of Maharashtra and Rajasthan (western India) and Karnataka (southern India) was observed. A few international collaborations were also noted which included countries like Japan, Austria, Australia, Belgium and the United Kingdom.

The findings of the study identified some crucial research gaps. It was found that detailed descriptions of vulnerabilities related to political, physical and psychological health induced by bank erosion were insufficient. Most studies expressed ecological vulnerability through channel oscillation, land use land cover changes and morphometric analysis. However, they failed to provide a satisfactory and plausible analysis of the vulnerability it induces. Few

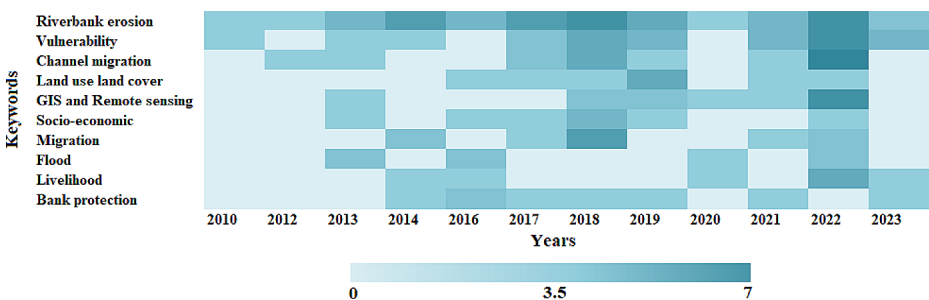
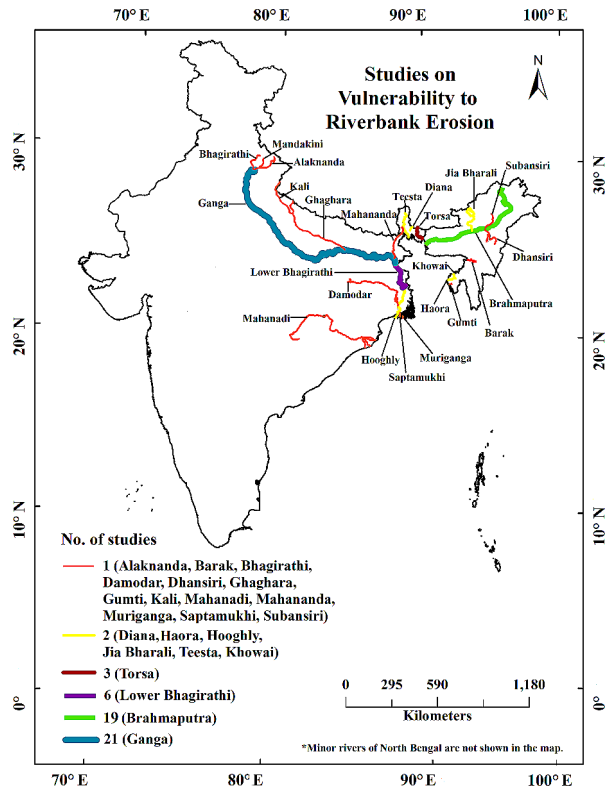


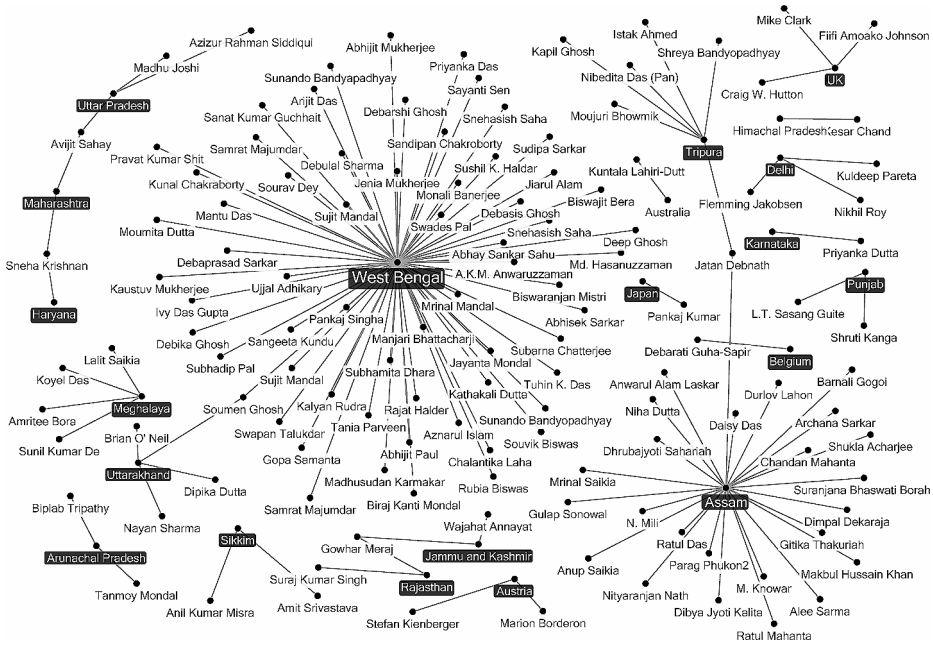
Fig. 4 Heatmap for keyword analysis

**Fig. 5** River-wise bank erosion vulnerability studies



studies emphasized vulnerabilities specific to particular communities based on factors such as age, gender or other social identities. For instance, only 3 studies were explicitly based on women, and vulnerability faced by children and the elderly was not assessed adequately. Studies concentrating on vegetation, the animal kingdom, and the ecosystem were restricted to just a handful. The reviewed articles also acknowledged the loss of agricultural lands as one of the most vulnerable land use category, however, the vulnerability of farmers to riparian erosion did not receive due consideration. The spatial extent of riverbank vulnerability studies is also limited. Apart from the eastern, northeastern and parts of northern India, relevant articles on vulnerability to bank erosion could not be identified for the rest of the country.

Since vulnerability varies with space and time, it is important to focus on site-specific factors to assess the various aspects of vulnerability. The selection of site-specific indicators helps in formulating indices. Studies based on indices present an excellent means to analyze vulnerability by incorporating different parameters (Sahana et al. 2019). Another notable approach to assess vulnerability is based on the components of exposure, sensitivity, and adaptation (IPCC 2007). A comprehensive approach representing these three components would give a complete picture of the concept of vulnerability. However, such an approach was inadequate in representation and most studies depicted vulnerability only in terms of destruction caused by bank erosion. The studies were mostly qualitative and descriptive in nature. Very few studies enriched their research through the quantitative or semi-quantitative approach. Agriculture, for instance, was highly affected by bank erosion



**Fig. 6** Distribution of author collaboration

but indices relating to crop yield, food pricing, etc. were not used to augment the concept of vulnerability. Similarly, detailed accounts of vulnerability faced by the educational and health sectors, two of the most important socio-economic components, were scant. Thus, a gap was seen in transforming the various parameters into meaningful indices and employing them in models. The application of machine learning was deficient in the existing literature. Other issues that persisted were the paucity of techniques like sensitivity analysis to identify the most influential factors of vulnerability and parameter estimation. The shortage of field-based studies, especially for ecological vulnerability and prediction models further adds to the research gaps.

Riverbank erosion is a continuous process that some part of the world experiences every now and then (Das and Samanta 2023). Therefore, real-time data on bank erosion is not recorded and the lack of hydrological data poses limitations for vulnerability assessment (Bhuyan et al. 2024). The Government of Assam has launched an online portal called the Flood Reporting and Information Management System (FRIMS) which provides timely information on floods at local levels (National Institute of Disaster Management 2022). However, such provisions of periodic data are unavailable for bank erosion. Also, the extent of areas vulnerable to river erosion, loss of property and possibly life, economic loss, and projections of impacts in the coming times are not well documented. This unavailability of a reliable dataset is a major hindrance as many of the losses go undetected. Thus, there is a dire need to work on more studies reflecting different outlooks on vulnerability to riverbank erosion.

## 4 Way forward: a framework for future research

Though some studies have been conducted on vulnerability to bank erosion in India, there exist certain research gaps that are required to be bridged. Designing indices for assessing vulnerability to riverbank erosion is crucial. The indices should be capable of accommodating context-specific indicators for different areas and time periods since vulnerability would not be similar throughout. Apart from this, studies have to be supported with other indices related to particular aspects like climate, livelihood vulnerability, etc. Since riverbank erosion can be viewed from different perspectives, an interdisciplinary approach would be a much-welcomed step. Riverbank erosion occurs due to natural as well as human-made causes and impacts both the biotic and abiotic environments. Therefore, research needs to be aided with more composite indices with an amalgamation of physical and socio-economic indicators.

More studies need to be conducted concerning ecological vulnerability to riverbank erosion. Riverine erosion directly impacts the ecological balance of a place and with climate change being one of the principal topics of research, it is very crucial to study the environmental consequences of riparian erosion. According to the global climate risk index report, India is ranked 7th which indicates a high level of risk for the country (Eckstein et al. 2021). Therefore, keeping in mind the climate risk India faces and the fragile ecosystems it hosts, attention needs to be paid to studies concerning the physical environment and biodiversity of the country. The IPCC approach, which provides a holistic view on vulnerability, could be employed for assessing different types of vulnerabilities by considering site-specific indicators and categorizing those into exposure, sensitivity, and adaptive capacity parameters.

Further, more studies on the prediction of riverbank erosion are required to project the upcoming dangers and help mitigate them so that vulnerabilities are reduced in the future. For example, erosion risk assessment can be undertaken using risk assessment indices to show the linkage between riverbank erosion and soil composition which would come in handy to predict erosion risks. One of the many arenas which are directly impacted by riverbank erosion is the agricultural sector. Topics like the impact of riverbank erosion on cropping patterns, cropping intensity, etc. need to be studied more. The population of India shows an increasing trend and with various environmental and cultural challenges, it is evident that food insecurity would increase further. Moreover, agriculture is the primary activity of a major part of the population in India, hence agricultural losses have an immediate impact on the people, especially the rural population and the country as a whole. Riverbank erosion is a hindrance to development and economic losses. Therefore, more research should be undertaken on the economic vulnerabilities to bank erosion which shows how the different economic sectors are affected by erosion.

The spectrum of target groups needs to be increased. The Indian population represents a heterogeneous composition and different groups of people are affected by riverbank erosion in different ways. The behaviour and response showcased by different groups vary. Thus, it is necessary to conduct more studies on specific groups of people rather than only focusing on the population in general. These variations could be documented with studies dedicated to diverse sections of the population based on gender, age, religion, caste, race, etc. to find out the reactions of different groups when exposed to riverbank erosion and their adaptive strategies to cope with and mitigate the risks. Studies on such aspects would be very meaningful in the Indian context since the country exhibits a diverse population. The vulnerabili-

ties faced by women, the elderly, and the disabled need to be brought under the purview of research since they are highly susceptible to the ills of riverbank erosion. This would also ensure inclusivity. Furthermore, studies in India fairly represented the eastern and northeastern regions of the country. Thus, studies covering other parts of India are required to assess the vulnerability to riverbank erosion induced by different rivers across the country.

There is a pressing need for a riverbank erosion database that provides data and answers questions on ‘how much/many and where’ loss of land, life, assets, property, etc. occurred. It should also represent the loss in monetary terms covering different geographic and political units. An operational system similar to the functioning of the global flood awareness system (GloFAS) or FRIMS could be designed. Therefore, methods and models are required for the generation of real-time erosion and accretion data. There is a necessity to undertake more research using hydrodynamic models, geotechnical parameters, and geospatial tools like remote sensing and GIS for more concrete and refined assessments. Vulnerability needs to be modelled more in terms of machine learning algorithms to deliver an in-depth understanding of the different components of susceptibility and risk. For example, models such as MIKE-SHE and MIKE-11 could be used to simulate hydrologic processes and MaxEnt to ascertain the probability of the presence of erosion. Machine learning techniques provide higher accuracy. Ensembles generated by integrating different models can overcome the drawbacks of single models and provide higher accuracy (Ado et al. 2022). Moreover, these techniques use site-specific indicators and the dominant factors controlling the risk could be ascertained using machine learning algorithms. This would aid the government, policymakers, and local stakeholders to focus on the factors that induce high vulnerability. Vulnerability to risks like landslides and floods has been assessed using machine learning techniques in India (Chowdhuri et al. 2020; Harshasimha and Bhatt 2023; Solanki et al. 2022). However, machine learning techniques have not been harnessed well in analyzing vulnerability to riverbank erosion. Many other machine learning models like random forest, multi-layer perceptron (MLP) and their ensembles could be used to map vulnerability. There is a requirement to augment the qualitative and descriptive approach with a quantitative approach which would make the vulnerability assessment more effective. This would also help in preparedness and thereby reduce vulnerability. The driver-pressure-state-impact-response (DPSIR) framework could also be used for analyzing the interactions between the society and environment.

Various policy implications, mitigation strategies, and adaptation techniques must be employed to protect the lands from further erosion. The concept of increasing the area under forests based on the model of ‘Molai Kathoni’ could be implemented to protect lands from bank erosion (Guha 2021). Molai Kathoni is a riverine island in the Brahmaputra River wherein the planation of mixed tree species, especially in the floodplains, could control riparian erosion (Gogoi et al. 2021). These trees include the likes of *Bombax ceiba*, *Gmelina arborea*, *Samanea saman*, *Dalbergia sissoo* and *Tetrameles nudiflora*. Cultivating indigenous tree species like bamboo, and mangroves, the use of geobags, and the construction of embankments and porcupines could help in controlling riverbank erosion (Bhuyan et al. 2024). The use of geobags could help reduce the rate of bank erosion (Thompson et al. 2020). The stability of the geobags could be further enhanced by using wire mesh gabion boxes (Maurya et al. 2022). Settlement plans could be drafted to identify safe areas for the construction of homes and other land use purposes (Dutta and Chakroborty 2013). Traditional knowledge needs to be acknowledged more in the domain of research. For instance,

the use of Bamboo in the Char regions of Assam could immensely help in reducing the impacts of bank erosion (Saikia and Mahanta 2023). It is also important to consider the views of the people as to how they perceive riverbank erosion to understand bank erosion-induced vulnerability better. The local communities must also be engaged in managing and mitigating the risks.

## 5 Conclusion

Riverbank erosion is a disastrous event that has pushed millions of people to the brink of vulnerability in India, yet it has not been focused on enough compared to other hazards like floods, cyclones, or storm surges. Therefore, it is of utmost necessity for this issue to be studied further since it causes great losses. Though vulnerability to riverbank erosion has received limited attention compared to other hazards, it has gradually made its way to scientific circles in recent times. This article is a contribution toward providing a timeline of the various works conducted on vulnerability to riverbank erosion in India from 2007 to 2023. The existing literature in this duration showed that the vulnerabilities inflicted by riverbank erosion intensified over the years, new dimensions of vulnerability were explored and new parameters of vulnerability assessment were introduced. This has led to the development of a deeper understanding of vulnerability to riverbank erosion in India. The degree of vulnerability increased as time rolled by with a boom in population in India and the degeneration of the environment. Migration, dislocation of families, loss of assets and properties, loss of livelihood, change in occupation, and negative impact on the environment remained the noteworthy points of vulnerability. With machine learning, GIS, and remote sensing revolutionizing the methodologies of vulnerability assessment, a more scientific approach came to be adopted for understanding vulnerability to riverbank erosion. However, there are still certain issues associated with the study of riverbank erosion that needs to be addressed in the near future for a holistic view of the phenomenon. It is equally important to share the fruits and knowledge of the research with the erosion-affected population helping them step out of their vulnerable circumstances to build a safer and sustainable future.

**Acknowledgements** The authors are grateful to the anonymous reviewers and Associate Editor for their insightful comments and meaningful suggestions to improve the overall quality of our work.

**Author contributions** The authors contributed to the article in the following ways: Idea for the article: Nirsobha Bhuyan, Haroon Sajjad. Literature search and data analysis: Nirsobha Bhuyan, Md. Hibjur Rahaman. Article drafting and critical revision of the work: Nirsobha Bhuyan, Md. Hibjur Rahaman, Haroon Sajjad, Raihan Ahmed.

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

## Declarations

**Competing interests** The authors have no competing interests to declare that are relevant to the content of this article.

## References

- ADB (2019) Consultant Report: Nepal: Flood Risk Sector Assessment. Project Number: TA 9634-REG: Strengthening Integrated Flood Risk Management. <https://www.adb.org/sites/default/files/project-documents/52014/52014-001-dpta-en.pdf>. Accessed 20th April 2024
- ADB (2010) Subsector Assessment (Summary): Flood Protection. Project Number: 38412-013, India: Assam Integrated Flood and Riverbank Erosion Risk Management Investment Program. <https://www.adb.org/projects/documents/assam-integrated-flood-and-riverbank-erosion-risk-management-investment-program-rrp>. Accessed 20th July 2021
- ADB (2011) Environmental Assessment Report. Summary Environmental Impact Assessment. Project Number: 38412, India: Assam Integrated Flood and Riverbank Erosion Risk Management Investment Program. <https://www.adb.org/sites/default/files/project-document/76484/38412-01-ind-seia.pdf>. Accessed 20th July 2021
- Adger WN (2006) Vulnerability. *Glob Environ Change* 16(3):268–281. <https://doi.org/10.1016/j.gloenvcha.2006.02.006>
- Adhikary U (2022) Riverbank (Bidya River) erosion and its impacts on rural stakeholder's livelihoods of Rangabelia village under Rangabelia Panchayat of Gosaba CD Block, South 24 Parganas, WB. *Int J Multidiscip Educ Res* 11(6):65–79
- Ado M, Amitab K, Maji AK, Jasinska E, Gono R, Leonowicz Z, Jasinski M (2022) Landslide susceptibility mapping using machine learning: a literature survey. *Remote Sens* 14:3029. <https://doi.org/10.3390/rs14133029>
- Ahmad D, Afzal M, Ishaq M (2024) Impacts of riverbank erosion and flooding on communities along the Indus River, Pakistan. *Nat Hazards* 120:131–152. <https://doi.org/10.1007/s11069-023-06216-2>
- Ahmed I, Das N, Debnath J, Bhowmik M (2018) Erosion induced channel migration and its impact on dwellers in the Lower Gumti River, Tripura, India. *Spat Inf Res*. <https://doi.org/10.1007/s41324-018-0196-9>
- Arobi S, Naher J, Soron TR (2019) Impact of river bank erosion on mental health and coping capacity in Bangladesh. *Global Psychiatry* 2(2):195–200
- Bandyopadhyay S, De SK (2017) Estimation of bank erosion of the Haora River and proposition of bank erosion vulnerability zonation model. *Human Interference on River Health. Advances in Asian Human-Environmental Research*. Springer International Publishing Switzerland, pp 141–167. [https://doi.org/10.1007/978-3-319-41018-0\\_9](https://doi.org/10.1007/978-3-319-41018-0_9)
- Bandyopadhyay S, Ghosh K, De SK (2014) A proposed method of bank erosion vulnerability zonation and its application on the River Haora, Tripura, India. *Geomorphology* 224:111–121. <https://doi.org/10.1016/j.geomorph.2014.07.018>
- Bhuyan N, Sharma Y, Sajjad H, Ahmed R (2023) Estimating bankline migration of the Brahmaputra River in the Middle Brahmaputra floodplains of Assam, India using Digital Shoreline Analysis System. *Environ Earth Sci* 82:385. <https://doi.org/10.1007/s12665-023-11061-4>
- Bhuyan N, Sajjad H, Saha TK, Roshani, Sharma Y, Masroor M, Rahaman H, Ahmed R (2024) Assessing landscape ecological vulnerability to riverbank erosion in the Middle Brahmaputra floodplains of Assam, India using machine learning algorithms. *CATENA* 234:107581. <https://doi.org/10.1016/j.catena.2023.107581>
- Billah MM, Majumdar A, Rahman SMA, Alam MS, Hossain MJ, Talukder J, Islam MM, Khanam T (2023) Riverbank erosion and rural food security in Bangladesh. *World* 4(3):528–544. <https://doi.org/10.3390/world4030033>
- Biswas R, Anwaruzzaman AKM (2019) Measuring hazard vulnerability by bank erosion of the Ganga River in Malda district using PAR model. *J Geogr Environ Earth Sci Int* 22(1):1–15. <https://doi.org/10.9734/JGEESI/2019/v22i130136>
- Biswas S, Nautiyal S (2023) A review of socio-economic vulnerability: the emergence of its theoretical concepts, models and methodologies. *Nat Hazards Res* 3:563–571. <https://doi.org/10.1016/j.nhres.2023.05.005>
- Biswas S, Ghosh S, Halder R (2020) Impact of human intervention on assessing downstream channel behaviour of Ichamati River on the lower Gangetic Plain of West Bengal, India. *Model Earth Syst Environ* 7:1651–1665. <https://doi.org/10.1007/s40808-020-00895-7>
- Cao JS, Yang YQ, Deng ZY, Hu YD (2022) Spatial and temporal evolution of ecological vulnerability based on vulnerability scoring diagram model in Shennongjia, China. *Sci Rep* 12:5168. <https://doi.org/10.1038/s41598-022-09205-w>
- Chakraborty K, Saha S (2022) Assessment of bank erosion and its impact on land use and land cover dynamics of Mahananda River basin (Upper) in the SubHimalayan North Bengal, India. *SN Appl Sci* 4:20. <https://doi.org/10.1007/s42452-021-04904-x>

- Chatterjee S, Mistri B (2013) Impact of river bank erosion on human life: a case study in Shantipur block, Nadia district, West Bengal. *Int J Humanit Soc Sci Invent* 2(8):108–111
- Chowdhuri I, Pal SC, Arabameri A, Ngo PTT, Chakraborty R, Malik S, Das B, Roy P (2020) Ensemble approach to develop landslide susceptibility map in landslide dominated Sikkim Himalayan region, India. *Environ Earth Sci* 79:476. <https://doi.org/10.1007/s12665-020-09227-5>
- Das D (2014) Majuli in Peril': challenging the received wisdom on flood control in Brahmaputra River Basin, Assam (1940–2000). *Water History* 6(2):167–185
- Das R, Gogoi B (2022) Analyzing river bank erosion vulnerability of Sadiya region, Assam, India. *Eco Env Cons* 28:452–458. <https://doi.org/10.53550/EEC.2022.v28i02s.069>
- Das R, Samanta G (2023) Impact of floods and river-bank erosion on the riverine people in Manikchak Block of Malda District, West Bengal. *Environ Dev Sustain* 25:13595–13617. <https://doi.org/10.1007/s10668-022-02648-1>
- Das TK, Haldar SK, Gupta ID, Sen S (2014) River bank erosion induced human displacement and its consequences. *Living Rev Landsc Res* 8(3):1–35. <https://doi.org/10.12942/lrllr-2014-3>
- Das TK, Haldar SK, Sarkar D, Borderon M, Kienberger S, Gupta ID, Kundu S, Guha-Sapir D (2017) Impact of riverbank erosion: a case study. *Australas J Disaster Trauma Stud* 21(2):73–81
- Das K, Bandyopadhyay S, De SK (2021) Assessing the impact of riverbank erosion on land use/land cover along the lower reach of Balasan River, West Bengal. *J Indian Geomorphol* 9:1 ISSN 2320–0731
- Das M, Parveen MT, Ghosh D, Sarkar A, Alam J, Saha S (2022) Unstable behavioural pattern of Teesta River and its impact on riverine dwellers: a case study of confluence area of Teesta and Dharala River, India. <https://doi.org/10.20944/preprints202212.0510.v1>
- Das D, Dekaraja D, Mahanta R (2023) The dynamics of deforestation, riverbank erosion and migration in India with special reference to Assam. In: Ranjan A, Khara R, Deka P (eds) *Environment, Climate Change and Migration in South Asia*, 1st edn. Routledge, London, pp 109–126. <https://doi.org/10.4324/9781003367802>
- Debnath J, Das N, Ahmed I, Bhowmik M (2016) Vulnerability Assessment of socio-economic condition due to river bank erosion: a case study on River, Tripura, India. *IOSR J Humanit Soc Sci* 21(5):37–42
- Debnath J, Das N, Ahmed I, Bhowmik M (2017) Channel migration and its impact on land use/land cover using RS and GIS: a case study on Khowai River of Tripura, North-East India. *Egypt J Remote Sens Space Sci* 20:197–210. <https://doi.org/10.1016/j.ejrs.2017.01.009>
- Debnath J, Sahariah D, Saikia A, Mera G, Nath N, Lahon D, Annayat W, Kumar P, Chand K, Singh SK, Kanga S (2023) Shifting sands: Assessing bankline shift using an automated approach in the Jia Bharali River, India. *Land* 12:703. <https://doi.org/10.3390/land12030703>
- Dekaraja D, Mahanta R (2018) Extent of population migration from riverbed eroded areas and its rationales: a case study of Dhubri and Dhemaji districts of Assam. *Indian J Econ Dev* 6(1):1–12
- Dekaraja D, Mahanta R (2021) Riverbank erosion and migration inter-linkage: with special focus on Assam, India. *Environ Syst Res* 10:6. <https://doi.org/10.1186/s40068-020-00214-0>
- Dekaraja D, Mahanta R (2022) Exploring the socioeconomic impact of riverbank erosion in the Brahmaputra Valley of Assam, India: a case study of two districts. *Landsc Online* 97:1105. <https://doi.org/10.3097/LO.2022.1105>
- Dey S, Mandal S (2018) Assessing channel migration dynamics and vulnerability (1977–2018) of the Torsa River of the duars and Tal region of eastern himalayan foothills, West Bengal, India. <https://doi.org/10.1007/s41324-018-0213-z>. *Spat Inf Res*
- Dey S, Mandal S (2022) Assessing channel migration, bank erosion vulnerability and suitable human habitation sites in the Torsa River Basin of eastern India using AHP model and geospatial technology. In: Mandal S, Maiti R, Nones M, Beckedahl HR (eds) *Applied Geomorphology and Contemporary issues. Geography of the physical environment*. Springer, Cham. [https://doi.org/10.1007/978-3-031-04532-5\\_33](https://doi.org/10.1007/978-3-031-04532-5_33)
- Dhara S, Mondal BK (2019) River bank erosion and changing course of river Saptamukhi and Muriganga of Namkhana Island. In: *West Bengal: Geoinformatics for Sustainable Environment Management, II*: pp161–170
- Dragicevic S, Stojanovic Z, Manic E, Roksandic M, Stepic M, Zivkovic N, Zlatic M, Kostadinov S (2017) Economic consequences of bank erosion in the lower part of the Kolubara river basin, Serbia. *Environ Eng Manag J* 16(2):381–390
- Dutta P (2011) Migration as source of risk-aversion among the environmental refugees: the case of women displaced by erosion of the river Ganga in the Malda district of West Bengal. In: ESF-UniBi-ZiF research conference on 'Environmental Change and Migration: From Vulnerabilities to Capabilities, Bad Salzufflen, Germany, December 5–9, 2010 COMCAD pp 4–28
- Dutta K, Chakraborty S (2013) Human aspects of river bank erosion: a case study Khairkata village, Diana river basin, Jalpaiguri, West Bengal. *Geo-Analyst* 82–93

- Dutta M, Mandal S (2022) Channel migration vulnerability in the Kaljani River Basin of eastern India. In: Mandal S, Maiti R, Nones M, Beckedahl HR (eds) Applied Geomorphology and Contemporary issues. Geography of the physical environment. Springer, Cham. [https://doi.org/10.1007/978-3-031-04532-5\\_3](https://doi.org/10.1007/978-3-031-04532-5_3)
- Dutta N, Sonowal G, Thakuria G (2020) A study on the bank erosion by the river Jia Bharali and its impact on the Panchmile area of Tezpur Town, Assam (India). *Int J Adv Res Eng Technol* 11(12):2359–2367
- Dutta D, Misra AK, Srivastava A (2023) River bank erosion vulnerability demarcation based on the sensitivity analysis of geotechnical parameters: Majuli Island, India. *J Appl Water Eng Res* 12:224–243. <https://doi.org/10.1080/23249676.2023.2256223>
- Eckstein D, Kunzel V, Schafer L (2021) Global climate risk index 2021. Who suffers most from extreme weather events? Weather related loss events in 2019 and 2000–2019. [www.germanwatch.org](http://www.germanwatch.org). Accessed 29th August 2021
- Ferdous J, Mallick D (2019) Norms, practices, and gendered vulnerabilities in the Lower Teesta basin, Bangladesh. *Environ Dev* 31:88–96. <https://doi.org/10.1016/j.envdev.2018.10.003>
- Ghosh S, Mistri B (2021) Delineating the influence of erosion and accretion to identify the vulnerable zone of embankment breaching in Gosaba Island, South 24 Parganas, West Bengal, India. <https://doi.org/10.1007/s12524-021-01409-3>. *Indian Soc Remote Sens*
- Ghosh D, Saha S (2022) Predicting vulnerable sites and causative factors of bank erosion in river Ganga (Malda, India) using remote sensing and statistical modeling approach. *Res Square*. <https://doi.org/10.21203/rs.3.rs-1636807/v1>
- Ghosh D, Sahu AS (2018) Problem of river bank failure and the condition of the erosion victims: a case study in Dhulian, West Bengal, India. *Reg Sci Inq X* (2):205–214
- Ghosh D, Sahu AS (2019) Bank line Migration and its impact on land use and land cover change: a case study in Jangipur subdivision of Murshidabad district, West Bengal. *J Indian Soc Remote Sens*. <https://doi.org/10.1007/s12524-019-01043-0>
- Ghosh D, Banerjee M, Pal S, Mandal M (2022) Spatio-temporal variation of channel migration and vulnerability assessment: a case study of Bhagirathi River within Bardhaman District, West Bengal, India. In: Shit PK, Bera B, Islam A, Ghosh S, Bhunia GS (eds) Drainage Basin Dynamics. Geography of the physical environment. Springer, Cham. [https://doi.org/10.1007/978-3-030-79634-1\\_14](https://doi.org/10.1007/978-3-030-79634-1_14)
- Gogoi A, Ahirwal J, Sahoo UK (2021) Plant biodiversity and carbon sequestration potential of the planted forest in Brahmaputra flood plains. *J Environ Manag* 280:111671. <https://doi.org/10.1016/j.jenvman.2020.111671>
- Guha N (2021) Planted forests can tackle flood and erosion impacts along the Brahmaputra. <https://india.mongabay.com/2021/11/planted-forests-can-tackle-flood-and-erosion-impacts-along-the-brahmaputra/>. Accessed 27 May 2023
- Guite LTS, Bora A (2016) Impact of riverbank erosion on land cover in Lower Subansiri River flood plain. *Int J Sci Res Publ* 6(5):480–486
- Hahn MB, Riederer AM, Foster SO (2009) The livelihood vulnerability index: a pragmatic approach to assessing risks from climate variability and change—A case study in Mozambique. *Glob Environ Change* 19(1):74–88. <https://doi.org/10.1016/j.gloenvcha.2008.11.002>
- Harshasimha AC, Bhatt CM (2023) Flood Vulnerability Mapping using MaxEnt Machine Learning and Analytical Hierarchy process (AHP) of Kamrup Metropolitan District, Assam. *Environ Sci Proc* 25(1):73. <https://doi.org/10.3390/ECWS-7-14301>
- Hasan M, Quamruzzaman C, Rahim A, Hasan I, Methela NJ, Imran SA (2018) Determination of riverbank erosion probability: vulnerability and risk in southern shoreline of Bangladesh. *Int J Energy Sustain Dev* 3(3):44–51
- Hasanuzzaman M, Bera B, Islam A, Shit PK (2021) Estimation and prediction of riverbank erosion susceptibility and shifting rate using DSAS, BEHI, and REBVI models: evidence from the Lower Ganga River in India. *Res Square*. <https://doi.org/10.21203/rs.3.rs-1097959/v1>
- Hou K, Tao W, He D, Li X (2022) A new perspective on ecological vulnerability and its transformation mechanisms. *Ecocyst Health Sustain* 8(1):2115403. <https://doi.org/10.1080/20964129.2022.2115403>
- IPCC (2022) Climate Change 2022: Impacts, adaptation, and vulnerability. Final draft of the forthcoming 6th Assessment Report (AR6) of the Second Working Group (WG2) for the Intergovernmental Panel on Climate Change. <https://www.ipcc.ch/report/ar6/wg2/>. Accessed 15th April 2024
- IPCC (2007) Climate change 2007: impacts, adaptation, and vulnerability. Contribution of Working Group II to the Fourth Assessment Report (Ch. 9). Cambridge University Press, Cambridge. [https://www.ipcc.ch/site/assets/uploads/2018/03/ar4\\_wg2\\_full\\_report.pdf](https://www.ipcc.ch/site/assets/uploads/2018/03/ar4_wg2_full_report.pdf). Accessed 15th May 2021
- Islam SN (2016) Deltaic floodplains development and wetland ecosystems management in the Ganges–Brahmaputra–Meghna Rivers Delta in Bangladesh. *Sustain Water Resour Manag* 2:237–256. <https://doi.org/10.1007/s40899-016-0047-6>

- Islam A, Guchhait SK (2017) Search for social justice for the victims of erosion hazard along the banks of river Bhagirathi by hydraulic control: a case study West Bengal, India. *Environ Dev Sustain* 19:433–459. <https://doi.org/10.1007/s10668-015-9739-6>
- Islam A, Guchhait SK (2018) Analysis of social and psychological terrain of bank erosion victims: a study along the Bhagirathi River, West Bengal, India. <https://doi.org/10.1007/s11769-018-0937-7>. *Chin Geogr Sci*
- Kalita DJ (2016) Impact of flood and riverbank erosion in Majuli, Assam (India) and its restoration measures. *Dimorian Rev* 3(5):21–30
- Karmakar M (2016) Impact of river bank erosion on human life: a study of sub-himalayan north Bengal region in India from geographical perspective. *Int J Multidisciplinary Approach Stud* 3(2):195–205
- Khan MH (2012) River erosion and its socio-economic impact in Barpeta district with special reference to Mandia development block of Assam. *Int J Eng Sci* 1(2):177–183
- Klausmeyer KJ (2016) Stream bank erosion. USDA, Natural Resources Conservation Service, Kansas. <http://www.ks.nrcs.usda.gov>
- Kotoky P, Bezbaruah D, Baruah J, Sarma JN (2005) Nature of bank erosion along the Brahmaputra River Channel, Assam, India. *Curr Sci* 88(4):634–640. <http://www.jstor.org/stable/24110266>
- Kotoky P, Bezbaruah D, Sarma JN (2015) Spatio-temporal variations of erosion-deposition in the Brahmaputra river, Majuli-Kaziranga sector, Assam: implications on flood management and flow mitigation. In: Ramkumar M, Kumaraswamy K, Mohanraj R (ed) *Environmental management of river basin ecosystems*, Springer Earth System Sciences, pp 227–251. [https://doi.org/10.1007/9783-319-13425-3\\_12](https://doi.org/10.1007/9783-319-13425-3_12)
- Krishnan S (2022) Adaptive capacities for women's mobility during displacement after floods and riverbank erosion in Assam, India. *Clim Dev*. <https://doi.org/10.1080/17565529.2022.2092052>
- Kuran CHA, Morsut C, Kruke BI, Kruger M, Segnestam L, Orru K, Naevestad TO, JaanaKeranen MA, Gabel F, Hansson S, Torpan S (2020) Vulnerability and vulnerable groups from an intersectionality perspective. *Int J Disaster Risk Reduct* 50:101826. <https://doi.org/10.1016/j.ijdrr.2020.101826>
- Laha C, Bandyopadhyay S (2013) Analysis of the changing morphology of river Ganga, shift monitoring and vulnerability analysis using space-borne techniques: a statistical approach. *Int J Sci Res Publ* 3(7):118–127
- Lahiri-Dutt K, Samanta G (2007) Like the drifting grains of sand: vulnerability, security and adjustment by communities in the charlands of the Damodar River, India. *South Asia: J South Asia Stud* 30(2):327–350. <https://doi.org/10.1080/00856400701499268>
- Laskar AL, Phukon P (2012) Erosional vulnerability and spatio-temporal variability of the Barak River, NE India. *Curr Sci* 103(1):80–86
- Linnenluecke MK, Marrone M, Singh AK (2020) Conducting systematic literature reviews and bibliometric analyses. *Aust J Manag* 45(2):175–194. <https://doi.org/10.1177/0312896219877678>
- Majumdar S (2018) Impact of flood and bank erosion on human life: a case study of Panchanandapur at Malda, West Bengal, India. *Int J Basic Appl Res* 8(9):1038–1056
- Majumdar S, Das A, Mandal S (2023) Riverbank erosion and livelihood vulnerability of the local population at Manikchak block in West Bengal, India. *Environ Dev Sustain* 25:138–175. <https://doi.org/10.1007/s10668-021-02046-z>
- Maurya S, Gupta M, Chitra R (2022) Use of geosynthetics as a soft structural measure to mitigate flood hazard and bank erosion problem. In: Reddy CNVS, Saride S, Krishna AM (eds) *Ground improvement and reinforced soil structures*. Lecture notes in civil engineering. Springer, Singapore, pp 751–763. [https://doi.org/10.1007/978-981-16-1831-4\\_67](https://doi.org/10.1007/978-981-16-1831-4_67)
- Mili N, Acharjee S, Konwar M (2013) Impact of flood and river bank erosion on socio-economy: a case study of Golaghat revenue circle of Golaghat district, Assam. *Int J Geol Earth Environ Sci* 3(3):180–185
- Ministry of Home Affairs, Govt of India (2011) Report on disaster management in India. [https://www.india-portal.org/sites/default/files/iwp2/Disaster\\_management\\_in\\_India\\_Ministry\\_of\\_Home\\_Affairs\\_UNDP\\_2011.pdf](https://www.india-portal.org/sites/default/files/iwp2/Disaster_management_in_India_Ministry_of_Home_Affairs_UNDP_2011.pdf)
- Mondal J, Mandal S (2018) Monitoring changing course of the river Ganga and land-use dynamicity in Manikchak Diara of Malda district, West Bengal, India, using geospatial tools. *Spat Inf Res*. <https://doi.org/10.1007/s41324-018-0210-2>
- Mondal T, Tripathy B (2022) A study on impact of bank erosion on socio-economic sectors of sundarban region, West Bengal. *Madhya Bharti* 82(20):178–189
- Mukherjee J (2011) No voice, no choice: riverine changes and human vulnerability in the chars of Malda and Murshidabad. Occasional paper 28, Kolkata: Institute of Development Studies, pp 1–16
- Mukherjee K, Pal S (2018) Channel migration zone mapping of the river Ganga in the Diara surrounding region of eastern India. *Environ Dev Sustain* 20:2181–2203. <https://doi.org/10.1007/s10668-017-9984-y>
- Mukhopadhyay A, Acharyya R, Habel M, Pal I, Pramanick N, Hati JP, Sanyal MK, Ghosh T (2023) Upstream river erosion vis-a-vis sediments variability in Hugli Estuary, India: a geospatial approach. *Water* 15(7):1285. <https://doi.org/10.3390/w15071285>

- National Institute of Disaster Management (2022) Webinar report: flood monitoring and management using remote sensing. [https://nidm.gov.in/pdf/trgReports/2022/July/Report\\_13July2022sp.pdf](https://nidm.gov.in/pdf/trgReports/2022/July/Report_13July2022sp.pdf). Accessed 20th April 2024
- O'Neil B (2010) Women and displacement: a case study of women displaced by Ganga erosion in Malda district of West Bengal in India. In: European Population Conference (EPC 2010), Vienna, Austria, 1–4 September, <http://epc2010.princeton.edu/papers/100534>. Accessed 8th July 2021
- Olson KR (2022) The Mekong Delta in Vietnam and Cambodia is subsiding and in need of remediation. *Open J Soil Sci* 12:171–192
- Pareta K, Jakobsen F, Joshi M (2019) Morphological characteristics and vulnerability assessment of Alaknanda, Bhagirathi, Mandakini and Kali rivers, Uttarakhand (India). *Am J Geophys Geochem Geosyst* 5(2):49–68. <http://www.aiscience.org/journal/aj3g>
- Paul A, Bhattacharji M (2022) Assessing the impacts and livelihood vulnerability of river bank erosion: a case study in Chakdah C. D. Block of Nadia District, West Bengal. *Indian J Geogr Environ* 19:82–97
- Pradhan NS, Das PJ, Gupta N, Shrestha AB (2021) Sustainable management options for healthy rivers in South Asia: the case of Brahmaputra. *Sustainability* 13(3):1087. <https://doi.org/10.3390/su13031087>
- Proag V (2014) The concept of vulnerability and resilience. *Procedia Econ Financ* 18:369–376. [https://doi.org/10.1016/S2212-5671\(14\)00952-6](https://doi.org/10.1016/S2212-5671(14)00952-6)
- Rahman MS, Gain A (2020) Adaptation to riverbank erosion induced displacement in Koyra Upazila of Bangladesh. *Progress in Disaster Science* 5:1–8. <https://doi.org/10.1016/j.pdisas.2019.100055>
- Rasyid AR, Bhandary NP, Yatabe R (2016) Performance of frequency ratio and logistic regression model in creating GIS based landslides susceptibility map at Lompobattang Mountain, Indonesia. *Geoenvironmental Disasters* 3(1):19. <https://doi.org/10.1186/s40677-016-0053-x>
- Rinaldi M, Wyzga B, Dufour S, Bertoldi W, Gurnell A (2013) River processes and implications for fluvial ecogeomorphology: a European perspective. In: Shroder J, Butler DR, Hupp CR (eds) *Treatise on Geomorphology*. Academic, San Diego, CA, 12, Ecogeomorphology, 37–52
- Ross DS, Wemple BC, Willson LJ, Balling CM, Underwood KL, Hamshaw SD (2019) Impact of an extreme storm event on river corridor bank erosion and phosphorus mobilization in a mountainous watershed in the Northeastern United States. *J Geophys Res: Biogeosciences* 124:18–32. <https://doi.org/10.1029/2018JG004497>
- Rudra K (2020) Combating flood and erosion in the Lower Ganga Plain in India: some unexplored issues. In: Andharia J (ed) *Disaster Studies*. Disaster Studies and Management Springer Nature Singapore Private Limited, pp 173–186. [https://doi.org/10.1007/978-981-32-9339-7\\_9](https://doi.org/10.1007/978-981-32-9339-7_9)
- Sahana M, Rehman S, Paul AK, Sajjad H (2019) Assessing socio-economic vulnerability to climate change-induced disasters: evidence from Sundarban Biosphere Reserve, India. *Geol Ecol Landsc* 5(1):40–52. <https://doi.org/10.1080/24749508.2019.1700670>
- Sahay A (2022) Riverbank erosion and inter-community relationships in Majuli Political implications of a changing landscape in Assam. In: Pattanaik S, Sen A (eds) *Regional Political ecologies and environmental conflicts in India*, 1st edn. Routledge, pp 49–64. <https://doi.org/10.4324/9780367486433-4>
- Sahay A, Roy N (2017) Shrinking space and expanding population: socioeconomic impacts of Majuli's changing geography. *Focus Geogr* 60:1–24
- Sahay A, Roy N, Siddiqui AR (2020) Understanding riverbank erosion in Majuli Island of India: geomorphological process and policy implications. *Focus Geogr* 1–2. <https://doi.org/10.21690/foqe/2020.63.7f>
- Saikia M, Mahanta R (2023) Riverbank erosion and vulnerability – a study on the char dwellers of Assam, India. *Nat Hazards Res*. <https://doi.org/10.1016/j.nhres.2023.10.007>
- Saikia L, Mahanta C, Mukherjee A, Borah SB (2019) Erosion-deposition and land use/land cover of the Brahmaputra River in Assam, India. *J Earth Syst Sci* 128(211):1–12. <https://doi.org/10.1007/s12040-019-1233-3>
- Sarkar A (2017) Brahmaputra river bank failures-causes and impacts on river dynamics. In: Mikos M, Vilimek V, Yin Y, Sassa K (eds) *Advancing culture of living with landslides*. WLF 2017. Springer, Cham. [https://doi.org/10.1007/978-3-319-53483-1\\_32](https://doi.org/10.1007/978-3-319-53483-1_32)
- Sarkar S, Bera B (2022) Around seven decades river course shifting and bank erosion susceptibility of river Mujnai. *River* 1:221–239. <https://doi.org/10.1002/rvr2.19>
- Sarker MNI, Wu M, Alam GMM, Shouse RC (2019) Livelihood vulnerability of riverine-island dwellers in the face of natural disasters in Bangladesh. *Sustainability* 11(6):1–23. <https://doi.org/10.3390/su11061623>
- Sarma A (2014) Landscape degradation of river island Majuli, Assam (India) due to flood and erosion by river Brahmaputra and its restoration. *J Med Bioeng* 3(4):272–276. <https://doi.org/10.12720/jomb.3.4.272-276>
- Sharma D (2018) Bank erosion induced socio-economic vulnerability in Kaliachak-III block of Malda district, West Bengal. *Res Rev Int J Multidisciplinary* 3(8):683–697

- Sharma N, Johnson FA, Hutton CW, Clark M (2010) Hazard, vulnerability and risk on the Brahmaputra basin: a case study of river bank erosion. *Open Hydrology J* 4:211–226. <https://doi.org/10.2174/1874378101004010211>
- Singha P, Pal S (2022) Livelihood vulnerability assessment of the Island (Char) dwellers in the Ganges riparian corridor, India. *GeoJournal* 87:3701–3717. <https://doi.org/10.1007/s10708-021-10461-y>
- Singha P, Das P, Talukdar S, Pal S (2020) Modeling livelihood vulnerability in erosion and flooding induced river island in Ganges riparian corridor, India. *Ecol Indic* 119:1–15. <https://doi.org/10.1016/j.ecolind.2020.106825>
- Social Forestry Division, Government of Assam (2022) Majuli (T) Forest Division. <https://majuli.assam.gov.in/departments/social-forestry-division#:~:text=A%20Forest%20Range%20Office%20under,Division%20of%20Social%20Forestry%20wing>. Accessed 14th April 2024
- Solanki A, Gupta V, Joshi M (2022) Application of machine learning algorithms in landslide susceptibility mapping, Kali Valley, Kumaun Himalaya, India. *Geocarto Int* 37(27):16846–16871. <https://doi.org/10.1080/10106049.2022.2120546>
- Thakur N (2021) The struggles of a River people in Assam. <https://www.sapiens.org/all-articles/>. Accessed 14th April 2024
- Thompson A, Oberhagemann K, She Y (2020) Geobag stability for riverbank erosion protection structures: physical model study. *Geotext Geomembranes* 48:110–119. <https://doi.org/10.1016/j.geotextmem.2019.103526>
- Turner BLII, Roger EK, Matson PA, Mccarthy J, Corell RW, Christensen L, Selin NE, Kasperson JX, Luers AL, Martello ML, Polsky CD, Pulsipher A, Schiller A (2003) A framework for vulnerability analysis in sustainability science. *Proc Natl Acad Sci USA* 100(14):8074–8079
- Water, Resources, Government of Assam (2024) Flood and erosion problems. <https://waterresources.assam.gov.in/portlets/flood-erosion-problems>. Accessed 14th April 2024
- Zorn M (2018) Natural disasters and less developed countries. In: Pelc S, Koderman M (eds) *Nature, tourism and ethnicity as drivers of (De)Marginalization. Perspectives on Geographical Marginality*, vol 3. Springer, Cham. [https://doi.org/10.1007/978-3-319-59002-8\\_4](https://doi.org/10.1007/978-3-319-59002-8_4)

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

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.