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AG prepared the maps

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Social Vulnerability to Environmental Hazards in the Ganges-Brahmaputra-Meghna Delta, India and Bangladesh

Abstract

The coastal areas of the Ganges-Brahmaputra-Meghna delta are acknowledged hotspots of environmental and social concerns. This reflects a large, mainly rural population of 56.7 million, which is exposed to a range of natural hazards exacerbated by climate change, sea-level rise and subsidence. There are high levels of poverty and limited social well-being, including poor access to education, health, drinking water, and sanitation facilities. A spatial assessment of social vulnerability can indicate which communities are more susceptible to environmental hazards, while a temporal assessment may indicate how such vulnerability is changing due to development and other drivers. This study provides the first analysis of social vulnerability across the entire coastal delta within Bangladesh and India. It uses consistent and common secondary data at the sub-district level for two time periods: 2001 and 2011. These are used to construct a socio-economic vulnerability index across the region using Principal Component Analysis. Three main conclusions emerge. Firstly, there is a cross-shore social vulnerability gradient across the whole delta, with more vulnerable people living near the coast. Here, the benefits of access to marine fisheries are not apparent. Secondly, non-agricultural development and economic expansion have reduced the vulnerability significantly, showing its benefits. Lastly, despite general positive development trends, shocks due to major cyclone landfall appear to have enhanced vulnerability in the impacted areas. Further comprehensive analysis across the whole delta is recommended to improve our understanding of the common threats and possible solutions.

Keywords

Environmental hazards; Social vulnerability; Ganges-Brahmaputra-Meghna delta; Census; Principal component analysis

1. Introduction

1.1 Deltas and vulnerability

Globally, deltas are vital socio-ecological systems, which support more than 500 million people on just one per cent of the total land area (Ericson et al. 2006; Foufoula-Georgiou et al. 2011; Renaud et al. 2014). The majority of these people are in the global south with significant development needs (de Souza et al. 2015). For at least 30 years, deltas have been recognised as a highly vulnerable coastal setting (Milliman et al. 1989; Tsyban et al. 1990) threatened by multiple factors of sea-level rise and climate change, upstream changes such as sediment starvation due to dams, and changes within the delta such as subsidence (Milliman et al. 1989; Ericson et al. 2006; Syvitski et al. 2009; Nicholls et al.2020). At the same time, deltas are widely developing and experiencing significant demographic and economic change, which also impact delta areas in terms of intensified agriculture, expansion of aquaculture, and urbanisation (Woodroffe et al. 2006; Beondizio et al. 2016; Renaud et al. 2016; Szabo et al. 2016; Nicholls et al. 2020). As such, there is a strong nexus between the development of delta areas and managing these growing risks to ensure the well-being of delta residents.

Extreme environmental events (Meyers 2011), both climatic and non-climatic, with the potential to adversely affect the community and their surrounding environment are perceived as 'hazards' by the community. While hazards like cyclones and surges are rapid onset type in nature, sea level rise and coastal erosion, drought or salinisation in the deltas are of slow onset nature. Be it slow onset or fast, environmental hazards pose serious threats to human life and livelihoods, such as losses in crop yields, food insecurity, damaged homes, and loss of sense of place (Olsson et al. 2014). Environmental hazards disproportionately affect the rural, poor, child, female, elderly, and marginalised communities (Kasperson and Kasperson 2001; Vincent 2004; Dasgupta et al. 2014).This situation contributes to poverty, hunger, inequality, and displacement of inhabitants that create social destabilisation and affect the local economy in deltaic regions (Addo 2015; Adger et al. 2014; Ayeb-Karlsson et al. 2016). To what extent a community or human society will be affected by environmental hazards is determined not only by the magnitude and frequency of such events, but also by the inherent vulnerability of the community residing in the hazard impact areas.

1.2 Social vulnerability

Vulnerability of deltaic communities therefore, reflects the socio-economic status of the community before the occurrence of such events (Žurovec et al. 2017). Social vulnerability is defined as the inability of people, organisations, and societies to withstand adverse impacts from multiple stressors to which they are exposed (Adger 1999; Adger and Kelly 1999; Vincent 2004). It is an important concept, especially in the arena of sustainability science, and viewed as an inherent property of a system arising from its internal characteristics (Cutter et al. 2003; Adger et al. 2005). Social vulnerability is determined by socio-economic factors, such as economic status - wealth, income, and poverty, education level, housing quality, tenure type, built environment, family structure, age, gender, marginalisation, food insecurity, and access to insurance (Adger and Kelly 1999; Mileti 1999; Buckle et al. 2000; Cross 2001; Cutter et al. 2003, 2008; Brooks and Adger 2003; Dwyer et al. 2004; Blaikie et al. 2005; Burton and Cutter 2008). It is one of the major determinants of vulnerability, and plays an equivalent role of sensitivity in the IPCC vulnerability framework where human systems are concerned (Brooks 2003; Adger et al. 2005).

In Asian deltas, previous studies (Woodroffe 2010; Terry et al. 2015; Nguyen et al. 2019) have highlighted general vulnerability to natural hazards of populations living in deltas, but social vulnerability studies (Adger 1999; Tran et al. 2017) are limited, and there is no consistent assessment, particularly across the whole GBM delta, the most populous and second largest delta of the world, which covers parts of India and Bangladesh. Mallick et al. (2011), Ahsan and Warner (2014), and Rabby et al. (2019) have assessed the social vulnerability for the Bangladeshi part of the GBM delta, while Mondal (2013) and Sahana et al. (2019) have assessed the social vulnerability for the Indian part of the GBM delta. In addition, previous studies mainly focused on the spatial distribution of socially vulnerable communities in the delta, but not on the temporal assessment of changing nature of social vulnerability with development/adaptation or successive hazard event.

1.3 Aims

This paper has a twofold aim: to construct a social vulnerability index consistent for the whole GBM delta in a decadal time frame at the sub-district level (community development block in India and upazila in Bangladesh), taking consistent and common secondary data from both national censuses for the years 2001 and 2011, and to observe the temporal variability in social vulnerability with further impact of hazards and adaption/development activities.

The assessment of social vulnerability across deltas or other areas of interest improves understanding of how, where and which communities are exposed to slow onset environmental hazards like sea level rise and coastal erosion and fast onset hazards like cyclones and surges, as well as communities' ability to withstand and recover from the damages sustained. The spatio-temporal assessment of social vulnerability at a higher resolution identifies possible impact hotspots where adaptation measures are urgently required. This is a prerequisite for any delta level intervention to reduce vulnerability to environmental hazards adhering to the principles of the Sendai framework of disaster risk reduction (2015-30).

The manuscript is organised as follows. Section 1 introduces the delta and vulnerability, and identifies the gaps in literature that are addressed by this study. Section 2 provides the detailed administrative, demographic and socio-economic characteristics of the study area. Section 3 describes the data and methods. Section 4 presents the results, while Section 5 discusses them, and Section 6 concludes the study.

2. Study Area

2.1 The physical context of the delta

The GBM delta is one of the world's most dynamic and significant deltas (Nicholls et al. 2020). It is the second largest by area, and the most populous delta in the world (Ericson et al. 2006; Woodroffe et al. 2006). It covers most of Bangladesh and parts of West Bengal in India, with a total population exceeding 100 million, depending on how the delta extent is defined (Ericson et al. 2006; Woodroffe et al. 2006). The tide dominated macro tidal delta front is about 380 km long (Allison 1998). With a tidal amplitude exceeding 5 m, tidal influence extends up to 100 km inland, and the general land elevation here, of less than 3 m above mean sea level, has formed one of the world's largest coastal lowlands (Kausher et al. 1996). The delta extends up to 450 km inland and reaches elevations of more than 20 m above sea level (Woodroffe et al. 2006).

The region has a humid, tropical climate with an annual rainfall of about 1,650–1,800 mm in central and northern areas, and as much as 2,790 mm on the outer coast. The mean maximum temperature is 29°C (during June-July), whereas mean minimum temperature is 20°C. Recent reports suggest that the air temperature over the delta and adjacent parts of the Bay of Bengal are increasing (Huq et al. 1999; Agrawala et al. 2003). 70 – 80 % of annual rainfall occurs during the summer monsoon (southwest monsoon), resulting in high river discharge which declines steadily during non-monsoonal months. The monsoon however, has been showing increased variability in the time of onset and amount of rainfall in the delta.

Due to its climatic and tidal conditions, the delta is bestowed with the world's largest mangrove forest of 10,000 km^2 areal extent, the Sundarbans, shared by Bangladesh (60%) and India (40%). It is a unique biodiversity hotspot (Gopal and Chouhan, 2006) with 35 true mangroves, 28 mangrove associates and 7 obligate mangroves (Naskar,1988), estuarine crocodile , river terrapin, water monitor lizard ,gangetic dolphin, olive ridley turtle ,260 bird species and a sizable population of the Royal Bengal Tiger. The communities inhabiting the margins of the delta are dependent on various ecosystem services of this mangrove forest like fish, crab, honey, fuel wood, shore and storm protection, and of recent, nature tourism.

Large scale land conversion from mangroves to agriculture, and human settlement initiated under the colonial regime, in the late 19th century, have made the study area one of the most populous parts of the two countries in the present century.

2.2 The socio-economic context of the delta

The study area comprises 19 administrative districts in Bangladesh (the official government-defined Coastal Zone of Bangladesh) and two administrative districts in West Bengal, India. All these regions contain extensive areas below 5 m elevation (note that such low areas extend further inland in Bangladesh, as far as towns like Sylhet, 250 km from the open coast). According to the 2011 census, the study area covers 61,204 km^2 (77% in Bangladesh and 23% in India). The study area has been divided into five distinct zones from west to east–1) Ganges Tidal Plane West (GTP-W), 2) Ganges Tidal Plane Central (GTP-C), 3) Ganges Tidal Plane East (GTP-E), 4) Meghna Deltaic Plane (MDP) and 5) Chittagong Coastal Plane (CCP) (**Fig. 1**).

Figure 1 here

According to the 2011 census, the total population of the study area is 56.7 million, of which males and females are 28.3 million (49.9%) and 28.4 million (50.1%), respectively (**Fig. 2**).In total, 18.2 million of the inhabitants live in India and 38.5 million live in Bangladesh, with population densities of 1293 and 817 persons/km^2, respectively. North 24 Parganas is the most populated district with a population of 10.0 million, whereas Jhalokati district has the lowest population (0.7 million) in the study area.

Figure 2 here

The overall population in the study area is growing at an estimated rate of 1.1% per year (Census 2011; BBS 2017). The annual growth rate is high in several districts like Cox's Bazar (2.9 %), Noakhali (2.1%) and South 24 Parganas (1.8 %), and low or negative in Bagerhat (-0.5%), Khulna (-0.3%), Jhalokati (-0.2%) and Barisal (-0.1 %). This suggests high in and out migration, which plays an important role in population dynamics in this delta (De Campos et al. 2020). Sex ratios indicate more females in almost all the districts, with the highest sex ratio of 1109 in Chandpur, and the lowest of 955in North 24 Parganas. The literacy rate is high in North 24 Parganas (73.5%), Jhalokati (66.7%) and Pirojpur (64.9%), and low in Cox's Bazar (39.3%) and Bhola (43.2 %). Female literacy is lower than male literacy in all districts, except in Chandpur (1.2% higher than males). The proportion of dependents (or non-working population) per 100 working-age people is high in most of the districts, being highest in Noakhali (93.3) and lowest in North 24 Parganas (49.3).

Almost 80 percent of the total population lives in rural areas (Census 2011a; BBS 2011). The dominant land use is for agriculture, representing 60% and 48% of the landholdings in Bangladesh and India, respectively (Lazar et al. 2015). According to the 2011 census, more than 60 percent of the total working population comprises cultivators and agricultural labourers who are basically subsistence farmers growing food crops to feed themselves and their families (Clarke et al. 2018).The major crop is rice, with *aman* rice being the staple food as it requires minimal irrigation, thanks to the monsoon rains (Clarke et al. 2018). Overall soil conditions are favourable for agricultural activities, but salinity is a major concern to farmers in these coastal regions (Baten et al. 2015). Along with agriculture, the GBM delta residents practice multiple livelihood activities related to the sea and forest e.g. fishing, aquaculture, honey collection, boat maintenance, net making, etc. and there are growing service, construction, and trade-transport sectors (Arto et al. 2020).Increasingly, tourism is playing an important role in the local economy, with visits to the Sundarbans mangrove forest being an important element (Danda et al. 2011; Arto et al. 2020). Local participants in tourism were observed to spend 19% of the total expenditure on food items and 38% on non-food items (Guha et al. 2007), indicating a significant economic activity, which has large growth prospects with the burgeoning megacities of the neighbouring Kolkata and Dhaka.

35% of the total population in the GBM delta is poor[1] (BBS2010; GoWB2009, 2010). The poverty head-count ratio is high in several districts like Barisal (54.8%), Shariatpur (52.6%), Chandpur (51.0%) and Satkhira (46.3%), and low in Noakhali (9.6%), Chittagong (11.5%) and Barguna (19.0%). This adverse economic situation is exacerbating migration out of the study area (De Campos et al. 2020).

2.3 Natural hazards and long-term environmental change experienced in the delta

The high rate of sea level rise over 7 mm/year (Rahman et al. 2020; Pethick and Orford 2013) over the last two decades, reduction of sediment supply (Gupta et al. 2012; Rahman et al. 2018) due to several natural and anthropogenic reasons, and the variable rate of subsidence 2.5-3.9 mm/year (Brown and Nicholls 2015) has made the delta, susceptible to coastal erosion, inundation and land loss. Two inhabited estuarine islands Lohachara and Suparibhanga (Hazra et al. 2001), and one uninhabited island New Moore (Hazra et al. 2016a) were completely lost to the sea inthe western part of the delta in the last 40 years. High rates of coastal and river erosion are also observed in several districts like Chandpur, Laksmipur, Bhola, Shariatpur and Barisal, and South 24 Parganas (BBS 2015; GoWB 2009). Historically, cyclones and storm surges have been regarded as major environmental hazard in the delta. However, during the last century, there has been around 26% rise (Singh 2007) in the number of very severe cyclonic storms over northern Bay of Bengal. In 2007 and 2009, Cyclones Sidr and Aila, respectively, severely affected the districts of Khulna, Satkhira, Bagerhat, Barguna, Patuakhali, Barisal, Jhalokati and South 24 Parganas, with impacts linked to saline flooding, and intense wind and rain (Roy et al. 2009; GoWB 2009; Mallick et al. 2017). On 20th May, 2020, Cyclone Amphan barrelled through the GBM delta, destroying the river embankments across the Sundarbans and leading to salt water intrusion into the land (Das et al. 2020). Home dwellings and infrastructure rebuilt after Cyclone Sidr and Cyclone Aila have been lost due to the most recent Cyclone Amphan. Fluvial flooding during the monsoon can be observed in Gopalganj, Barisal, Chandpur, Sariatpur, Narail and Jessor, during and after the monsoon (BBS 2015). Salinization is a major environmetal stress

[1] The population living below the poverty line (see Table 1).

in the GBM delta, mostly found in Khulna, Bagerhat, Satkhira, Cox's Bazar, North 24 Parganas and South 24 Parganas (BBS 2015; GoWB 2009, 2010; Baten et al. 2015; Rahman et al. 2020). Similarly, freshwater scarcity during the dry season is also a major problem (Chowdhury 2005; Lazar et al. 2015; Hazra et al. 2016b).

3. Methodology and Materials

3.1 Developing the Social Vulnerability Index

A range of different methods and approaches have been used to quantitatively assess social vulnerability at different scales (Cutter et al. 2003; Vincent 2004; Nguyen 2015; Armas and Gavris 2016). For this study, a social vulnerability index (SVI) has been constructed at the sub-district level using the data reduction technique – 'Principal Component Analysis' (PCA) using the SPSS software (version 22) (**Fig. 3**). Several researchers have used PCA in the field of vulnerability assessment (Cutter et al. 2008; Antony and Rao 2007; Krishnan 2010; Holand et al. 2011; Dunning and Durden 2013; Armas and Gavris 2016; Žurovec et al. 2017).PCA is a statistical method used to extract a smaller and more coherent set of uncorrelated (orthogonal) components from a large number of variables, where the first component accounts for the maximum amount of variation in the original variables, and each succeeding component accounts for as much of the remaining variability as possible (Dunteman 1989; OCED 2008; Field 2009; Krishnan 2010).

Figure 3 here

3. 2 Selection of variables

Great care was taken to ensure consistency of analysis in both Bangladesh and India. A comprehensive review of the literature and the availability of consistent and common secondary data sets from both national censuses (Census of India and Bangladesh Bureau of Statistics) for the years 2001 and 2011 was made. It was found that only 13 common socio-economic variables could be selected for the present analysis (**Table 1**) at the sub-district level for the years 2001 and 2011. Analysis at spatial scales finer than sub-district level is not possible due to the unavailability of all the required data sets for 2001 and 2011. All the aspects for determining the social vulnerability – household structure, gender, education, occupation, socio-economic status, housing, access to basic services and rural/urban proportion were considered during this selection. The selected variables are important to identify the socio-economically vulnerable communities exposed to multiple hazards (**Fig. 4**). All variables can be measured at the interval level. The description of the variables used in the present study is provided in **Table 1**.

Table 1 here

Table 2 here

Figure 4 here

3.3 Testing the appropriateness of a principal component analysis

A total of 14 sub-districts, which are urban areas (City district or Thana in Bangladesh) have been excluded from this analysis, as demographic and socio-economic variables in these areas are considerably higher and lower compared to the other sub-districts in the GBM delta. Their inclusion in this study could have had a negative effect on the results, as they are outliers. In this study, the sample size (cases) is 183 sub-districts (132 in Bangladesh and 51 in India). **Table 2** shows the descriptive statistics for the 183 sub-districts. According to Comfrey and Lee (1992), the sample size (close to 200) is fair for PCA. Hutcheson and Sofroniou (1999) recommend at least 150-300 cases, and Field (2009) suggests at least 10-15 cases per variable. The subjects-to-variables (STV) ratio is 14:1; therefore it satisfies the 'Rule of 10', 'Rule of 100', and 'Rule of 150' (OECD 2008). Histogram, normal Q-Q plot, box plot and descriptive statistics have been used to identify the outliers in the SPSS platform (**Table 2**). The test of normality has been done by inspecting the Kolmogorov-Smirnov statistic and the result (sig. = 0.00) suggests no violation of the assumption of normality (**Table 3**).

Table 3 here

In the present study, the Kaiser-Meyer-Olkin (KMO) test (Kaiser 1970) has also been used to measure the sampling adequacy and to detect multi-collinearity in the data, so that the appropriateness of carrying out the analysis can be identified. Multi-collinearity can also be detected by looking at the determinant of the R-matrix (|R|), which should be greater than 0.00001 (Field 2009). Another test of the strength of the relationship among variables has been done using the Bartlett's (1954) Test of Sphericity, which tells us whether correlation matrix is significantly different from an identity matrix (Krishnan 2010).All of the tests indicate that principal component analysis is appropriate for the data (**Table 3**).

3.4 Principal component analysis and final calculation

The correlation matrix has been used as an input to PCA to extract the principal components, as the variables are not standardized. Only those components with an eigenvalue more than 1.0 have been retained using the "eigenvalue-greater-than-one" rule proposed by Kaiser (1960). The varimax (orthogonal) rotation has been opted for to improve the interpretability of components.

The principal components account for much of the variance among the set of original variables, and first component explains most of the variance, then second component, and so on (Field 2009; Krishnan 2010).Therefore, the importance of the principal components in measuring overall socio-economic condition is not the same (Krishnan 2010).

To calculate the *Social Vulnerability Index (SVI)* for all the sub-districts of GBM delta, component scores are multiplied by the proportion of the variance (weights) and are summed up in SPSS platform (Krishnan 2010). This index can be expressed with the following mathematical equation:

$$SVI = \sum \left(\frac{Fi}{TV}\right) * FSi \ldots\ldots\ldots\ldots.(1)$$

Where, F_i is the percentage of variance explained by each component (i), TV is the total variance explained by all the retained components, and FSi is the component scores on each component (i).

The SVI value indicates that the higher the value, the higher is the social vulnerability, and the lower the value, the lower is the social vulnerability. Finally, the entire range has been divided into five equal categories, and each is assigned to a qualitative indicator of social vulnerability (from very low to very high). In order to visualise and analyse the results in a geographic context, two separate choropleth maps for the years 2001 and 2011 have been prepared using QGIS software (3.4.4 "Madeira").

4. Results

4.1 Results of principal component analysis

The results of the PCA using varimax rotation are presented in **Table 4**. Four components account for 71.1 % of the total variation in the data in 2011 and for 74.4 % in 2001. For the first component in 2011 (22.6%) and 2001 (28%), *rural population*, *agricultural dependency*, and *no electricity connection* have shown markedly higher positive loadings[2], while variables such as *no home ownership* and *population density* have shown strong negative loadings. This component is a reasonable representation of the economic system. It means that poor economic circumstances are associated with higher percentages of *rural population*, *agricultural dependency* and *no electricity connection*, and lower values of *population density* and *no home ownership*. For the second component in 2011(19.6 %), female *population*, and *illiteracy rate* have shown markedly higher positive loadings. This component can be interpreted as a measure of the social system. The third component explains the variations in *kutcha house*, *unsafe drinking water* (housing/access to basic services) in 2001, and the fourth component *household size* (household structure) in both the years. It is observed that the variables in the first, second and third components explain the majority of the total variation of social vulnerability.

Table 4 here

4.2 Social vulnerability mapping

Based on the results of the PCA, the index value of social vulnerability has been estimated and mapped for all the sub-districts to examine the spatial dimension, while two maps for the years 2001 and 2011 indicate temporal change (**Fig. 5a & 5b**).The top five most vulnerable sub-districts are Tazumuddin, Manpura, Galachipa, Maheshkhali and Ramgati in 2001, and Manpura, Maheshkhali, Hizla, Koyra and Mehendiganj in 2011.The most socially vulnerable sub-districts are concentrated in the eastern part of GBM delta (GTP-E and CCP) (**Fig. 5a &5b**). In the western part of GBM delta (GTP-W), Patharpratima, and Kultali in 2001, and Basanti in 2001 and 2011 are among the top 20 most vulnerable sub-districts.

Figure 5a here

[2]Loadings refer to the correlations between the variables and the components, ranging from -1 to +1.

Figure 5b here

There is a consistent declining landward vulnerability gradient throughout the delta. Both on the eastern and western parts, the sub-districts along the coastal fringe like Patharpratima, Basanti, Kultali, Shyamnagar, Koyra, Dacope, Mathbaria, Manpura, Hatiya, Maheshkhali, and Teknaf have a very high social vulnerability, while the inland sub-districts close to the cities of Kolkata, Dhaka or Chittagong have a very low social vulnerability. People on the delta margin (Bay of Bengal) are more exposed to environmental hazards, have limited economic opportunities and less access to services such as grid electricity, tap water and road transport.

On the basis of the temporal analysis of the social vulnerability of the period between 2001 and 2011, out of total 183 sub-districts, 31 sub-districts showed significant increase in social vulnerability, mainly in the eastern part of the GBM delta (GTP-E and MDP), while 34 sub-districts had significant reduction in social vulnerability.

5. Discussion

5.1 Drivers of social vulnerability

The identification of socially vulnerable sub-districts and the components contributing to social vulnerability is an important element for the preparation of the location based hazard specific plans and development strategies for the vulnerable areas of GBM delta. This study reveals that the more socially marginalised and vulnerable communities are living on the delta margin in both the Indian and Bangladeshi parts of the GBM delta, and that components such as strong dependency on agriculture and natural resources, high illiteracy, living in kutcha house, and lack of access to safe drinking water, poor sanitation facility and other services make them more sensitive to hazard events and climate variability. Apart from agriculture, marine fishing is the other important livelihood of delta margin communities. While the economic return from agriculture is becoming increasingly low from the delta margin, due mostly to higher price of labour, fertiliser and equipment costs, repeated salinity ingress, and market failures, the declining commercial marine fish catch in the northern Bay of Bengal (Das I. et al.2020) appeared to be insufficient to alleviate the poverty of the delta population, particularly for those living in the delta margin. The profit of the capital intensive mechanised fishing is shared mostly by the trawler owners, businessmen, and exporters in the urban centres far away from the coast.

5.2 Spatial analysis of social vulnerability

The discussion on comparatively more and less socio-economically vulnerable sub-districts (local level) provides an understanding of those sub-districts that are exposed to hazards and experience significant changes in their social vulnerability status. Manpura (MDP) and Maheshkhali (CCP) sub-districts are among the top 5 most vulnerable sub-districts of GBM delta for both years **(Fig. 5a & 5b)**. Higher percentages of *rural population*, *kutcha house*, *illiteracy*, *agricultural dependency*, *non-workers*, *no electricity connection* and *no sanitation facility* all make Manpura one of the most socio-economically vulnerable sub-districts in GBM delta. Bio-physical vulnerability of Manpura sub-district is also very high due to its geographic location (Mallick et al. 2013). Manpura is now more vulnerable to cyclone and associated hazards than at any time before (Siddiqui 2014). Maheshkhali is also extremely vulnerable to cyclone and coastal erosion (Ahmed et al. 2009; Tanim and Roy 2013). Environmental hazards directly caused livelihood shocks for which communities in these areas slide in the vulnerability scale. More than 40 percent of the total population in Maheshkhali are living below the upper poverty line (BBS 2010), indicating the poor socio-economic status of this sub-district.

In the western part of GBM delta (GTP-W), Patharpratima and Kultali in 2001, and Basanti in 2001 and 2011 are among the top 20 most vulnerable sub-districts. Basanti has a large *rural population*, high incidence of *poverty*, and *non-workers* (Census 2011a; GoWB 2009). It was the last among all the 29 sub-districts (South 24 Parganas) in terms of standard of living, and the second most vulnerable sub-district in the composite vulnerability index (GoWB 2009). People in Basanti are living in chronic poverty with poor physical and socio-economic resilience and are exposed to repeated coastal flooding and storm surges (Dasgupta et al. 2016). Kultali, ranked 25th in standard of living, last in infrastructure development, and third most vulnerable sub-district in the composite vulnerability index in South 24 Parganas (GoWB 2009). This sub-district was inundated by surge during Cyclone Aila, is exposed to frequent coastal flooding, and has an issue of arsenic contamination (Dasgupta et al. 2016). Patharpratima is also exposed to coastal flooding and erosion. G-plot and other marginal areas are highly inaccessible (Dasgupta et al. 2016). All of these factors have led to increasing poverty and inequality.

Shyamnagar and Koyra sub-districts in Ganges Tidal Plane –Central (GTP-C) are also socio-economically vulnerable. Sub-districts like Hizla, Koyra, Mehendiganj, Shyamnagar, Gosairhat, Haim Char, Ukhia, Teknaf, and Basanti show an increasing trend in relative ranking of social vulnerability between 2001 and 2011. These coastal sub-districts with maximum social vulnerability have the potential to be adversely affected by environmental hazards, where focussed adaptation measures are immediately required. The least vulnerable sub-districts in both the years are more urbanised ones, within the Khulna Metropolitan Area (GTP-C), and Kolkata Metropolitan Area (GTP-W). These sub-districts that are closer and better connected to the city and the district headquarters get greater advantages in terms of livelihood opportunities and access to services such as grid electricity and tap water.

From the above analysis, it can be observed that the eastern part of GBM delta (GTP-E, MDP and CCP) is socio-economically more vulnerable than the western and central parts, and that the population that is exposed and sensitive to climate extremes of the vulnerable sub-districts are not in a position to recover from the impacts of hazards like Sidr, Aila, or Amphan, unless pre and post disaster adaptation measures are undertaken within the disaster risk reduction framework of 'build back better' (**Fig. 6**).

Figure 6 here

5.3 Temporal analysis of social vulnerability

Social vulnerability can vary temporarily depending upon hazard incidence and the adaptation and development measures that are undertaken. For Sagar and Namkhana sub-districts (GTP-W), reduction in social vulnerability resulted from the growth of tourism facilities, post Aila recovery assistance and connection to grid electricity. Additionally, the plan to build a deep-water port in Sagar (GoWB 2009) might have some positive impact on the local economy albeit with implications for *in-situ* adaptation of local communities (Mortreux et al. 2018). Similarly reduction of social vulnerability could be achieved in Kuakata (GTP-E), a popular tourist destination in Kala Para sub-district, as in Bauphal sub-district (GTP-E). In many such places social vulnerability reduced in 2011 compared to that in 2001, reflecting improvement in access to basic services like safe drinking water, sanitation, electricity connection, and the development of alternative livelihood options. A negative change has been observed in 31 sub-districts (17%)

within the reference period of 2001-11. Most of these areas are in the eastern part of the GBM delta (GTP-E and MDP). Due to the continuous degradation of natural resources and unsustainable pattern of economic activity, many coastal sub-districts are in a worse economic situation. Low intensity cyclonic disturbances originating in the Bay of Bengal strike the GBM delta almost every year (Quader et al. 2017), and damages due to severe cyclonic storms like Sidr (2007) and Aila (2009) might be responsible for increase in social vulnerability in parts of the delta. Coastal districts with negative change are Chandpur, Lakshmipur, Bagerhat, and Shariatpur. The spatio-temporal change matrix indicates that social vulnerability status however, remained unchanged in 118 (64.5%) sub-districts of GBM delta during the period between 2001 to 2011. While it is understood that major changes in socio-economic vulnerability cannot be achieved in one decade, this study emphasises the need to develop location based emergency plans and hazard preparedness (as warranted in the case of Cyclone Amphan, 2020), by identifying the chronically vulnerable population and specific socio-economic aspects of their life (e.g. poverty, water, sanitation, housing etc.), which perpetuate such vulnerability.

6. Conclusions

This is the first spatial and temporal analysis of social vulnerability across the coastal region of the Ganges-Brahmaputra-Meghna (GBM) delta, including both India and Bangladesh. It shows that social vulnerability varies similarly on both sides of the border. This suggests that similar issues are present on both sides, and similar approaches to reduce this vulnerability are appropriate. It also suggests that concerted efforts for adaptation and development can systematically reduce social vulnerability, but the shocks of natural hazard events (e.g. major cyclones or major monsoon flooding) are also apparent and require assessment.

This analysis indicates that socially marginalised and vulnerable communities are mainly concentrated along the seaward margin of the delta. In addition, the eastern part of the GBM delta appears to be more socio-economically vulnerable than the western and central parts. Negative changes in socialvulnerability in parts of the delta, from 2001 to 2011, are consistent with a significant residual impact of cyclones Sidr in 2007 and Aila in 2009, particularly in the eastern region. Hence, flooding and espcially cyclone landfall remain major concernsfor the delta as they can cause major loss and hinder development. The study helps to inform the design of location-based hazard specific plans and development strategies for these vulnerable areas. Due to on-going climate change and other trends such as subsidence, adaptation measures in this area need to go beyond normal development activities (Tompkins et al. 2017; Suckall et al. 2018).This can be achieved through a multi-faceted approach, including multiple livelihood development programmes, skill enhancement projects, eco-tourism, hazard preparedness and capacity building programmes, along with ensuring access to essential services such as safe drinking water, sanitation facilities, safe housing, primary health services, and education. Scaling up the existing government schemes (for example, promoting the adaptation of sustainable agricultural practices, diversification to off-farm activities, seasonal employment schemes in agriculture), to provide support to farmers and create alternative and sustainable livelihood options in rural areas, with a special focus on women and youth, can also be fundamental to reduce the present social vulnerability. In doing so, the root cause of distress migration (no livelihood options to survive) can also be addressed. Together, these measures have the potential to reduce the overall vulnerability and social distress and improve the standard of living of residents in spite of climate shocks and changing climate conditions. Addressing these issues will involve a wide range of reinforcing actions.

Building on this foundation, further and more detailed assessment of risk, and adaptation and development needs would be useful. The authors recommend a social-ecological approach, linking the biophysical environment and its recent changes to human well-being and development.

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Figure Captions

Figure 1. The study area of the coastal GBM delta, showing the zones, districts and sub-districts.

Figure 2. Decadal Variation in Population since 1901

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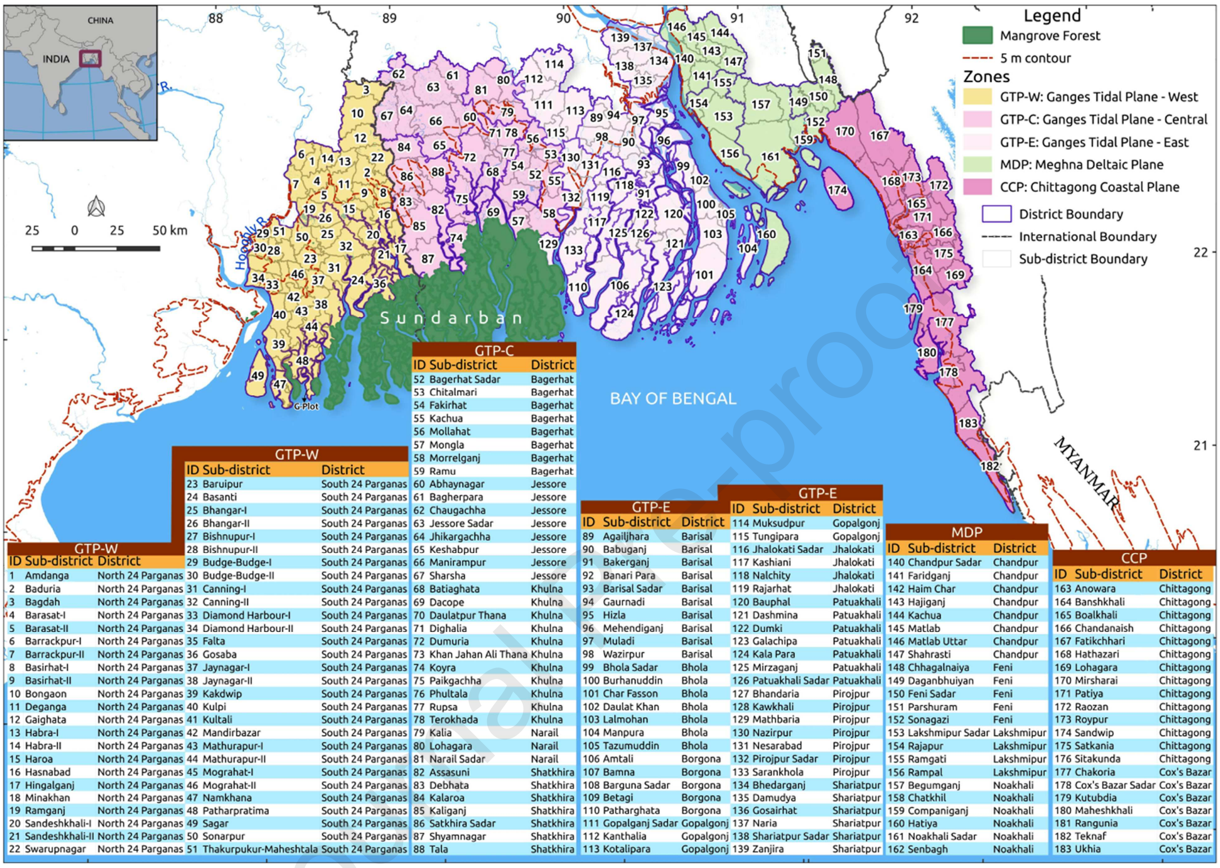
Figure 6. Spatio-temporal dynamics of Social Vulnerability of GBM delta (2001 – 2011).The red and blue lines demarcate the paths of Cyclone Sidr of 2007 and Aila of 2009 with 25 Km buffer denoted by dotted lines

Figures



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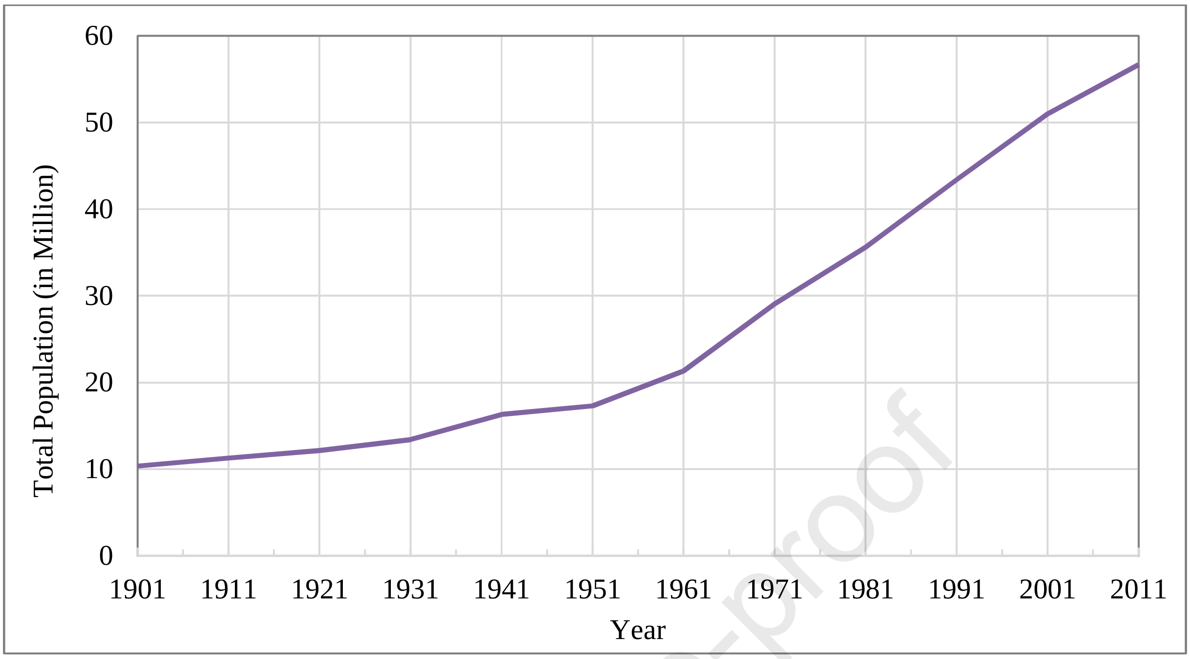

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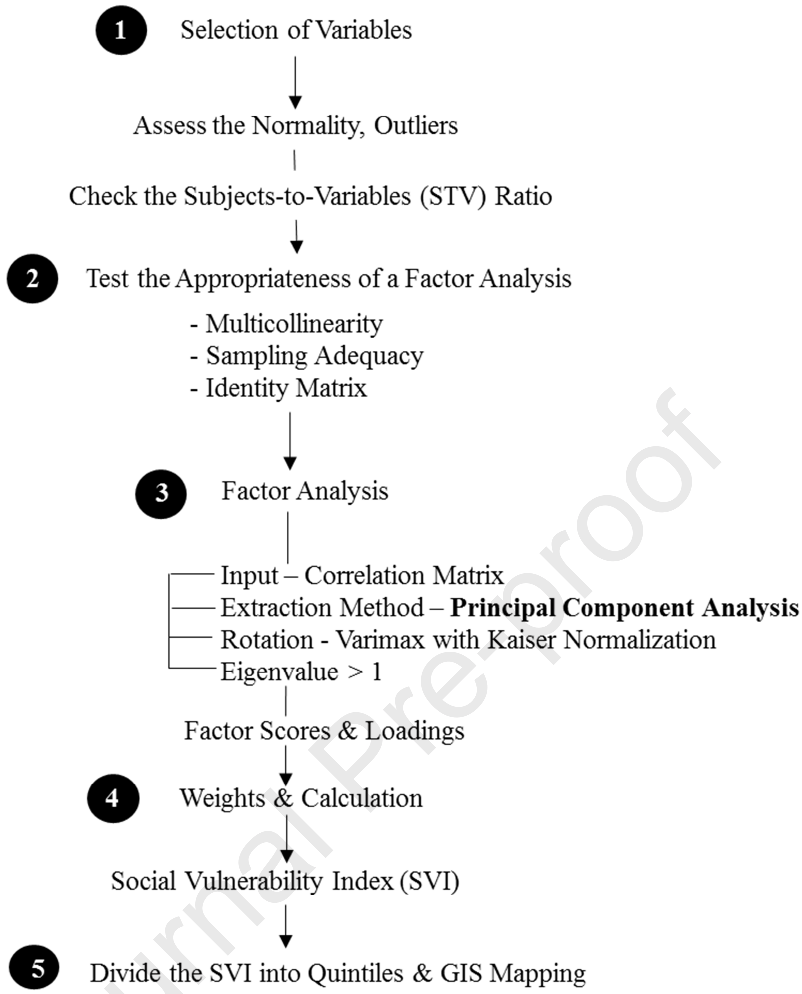

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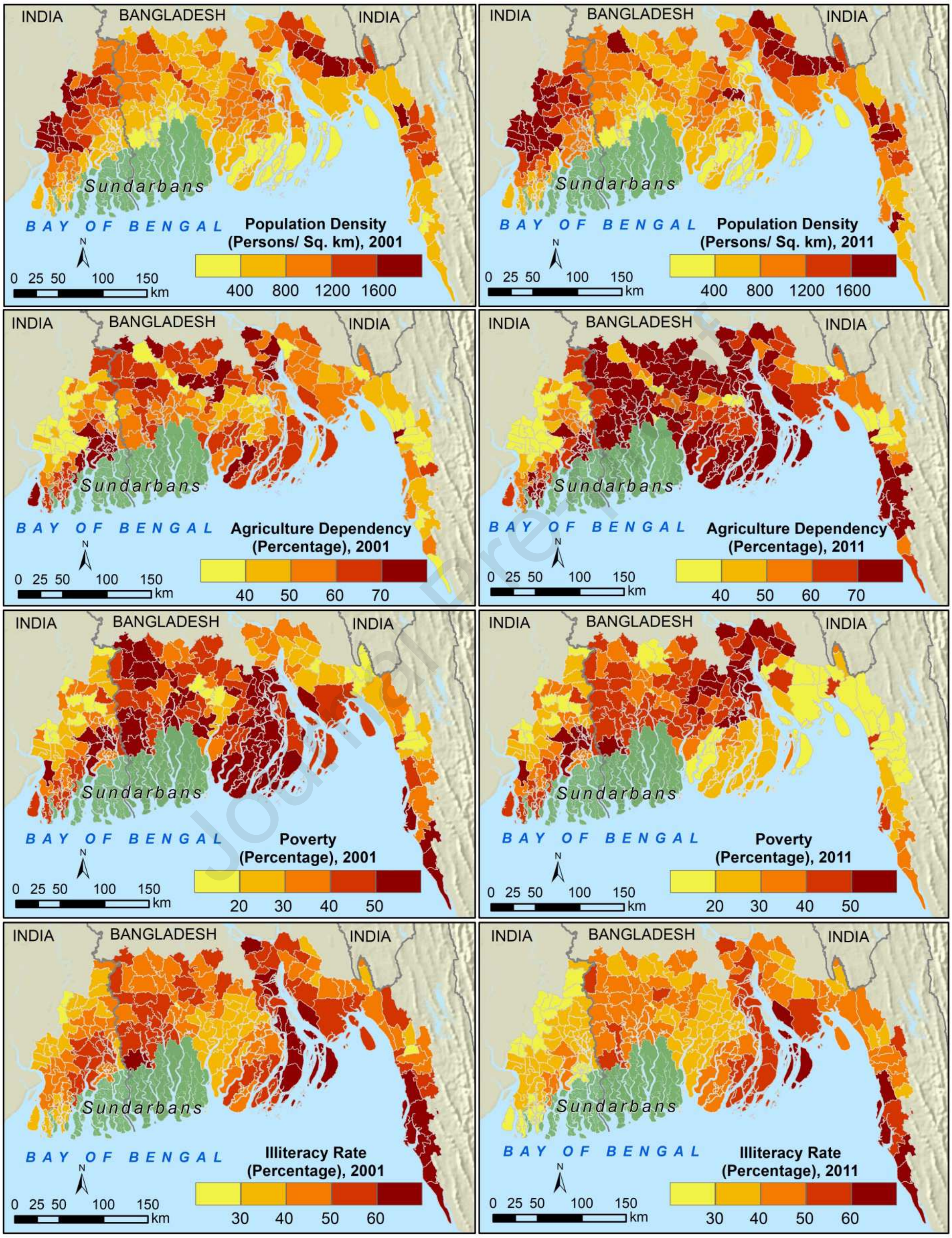

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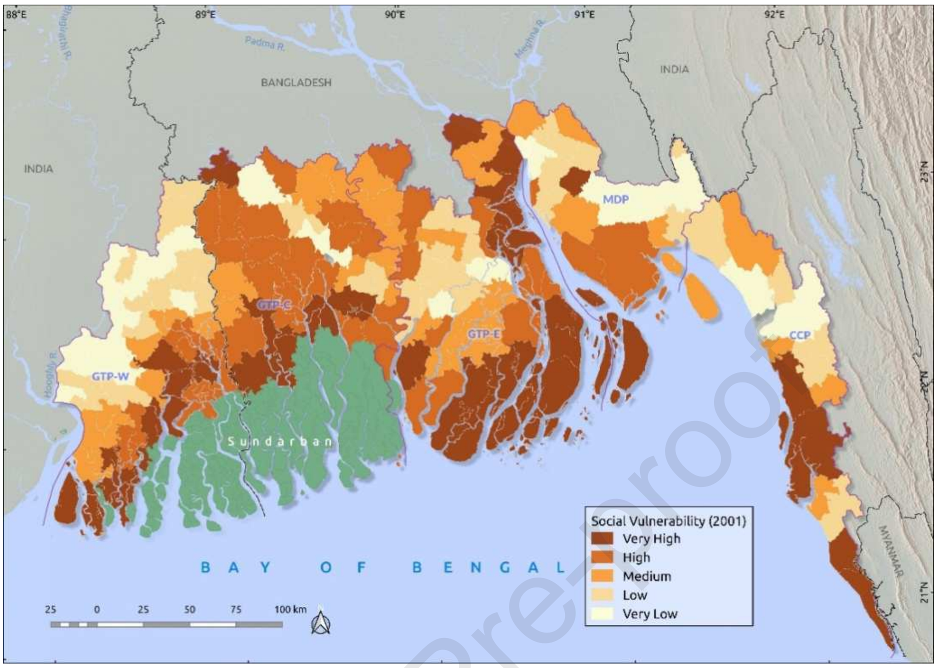


Figure 5a. Sub-district level Social Vulnerability map of the GBM Delta for 2001

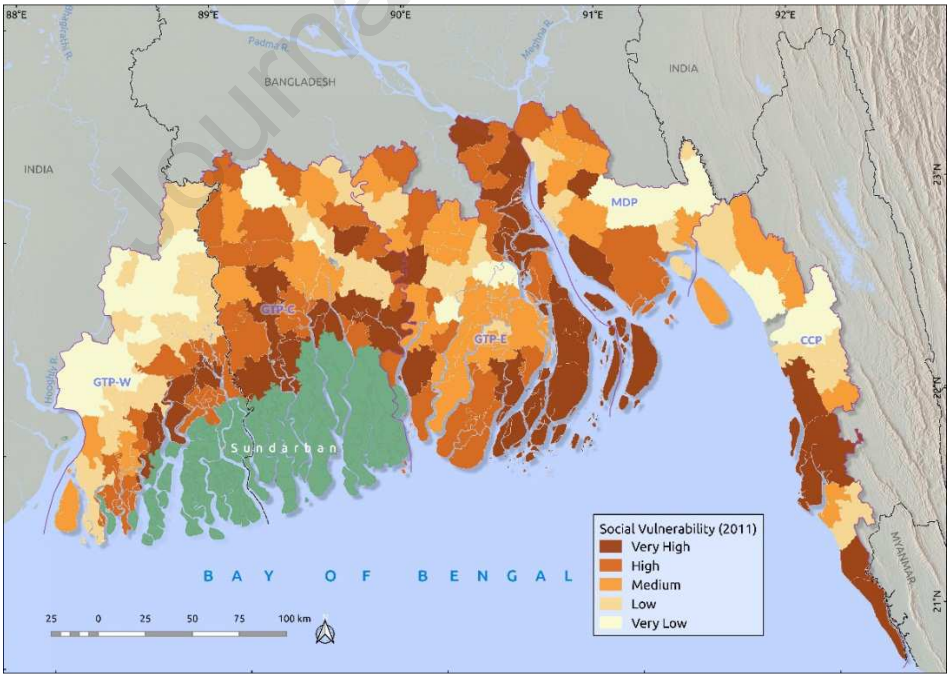
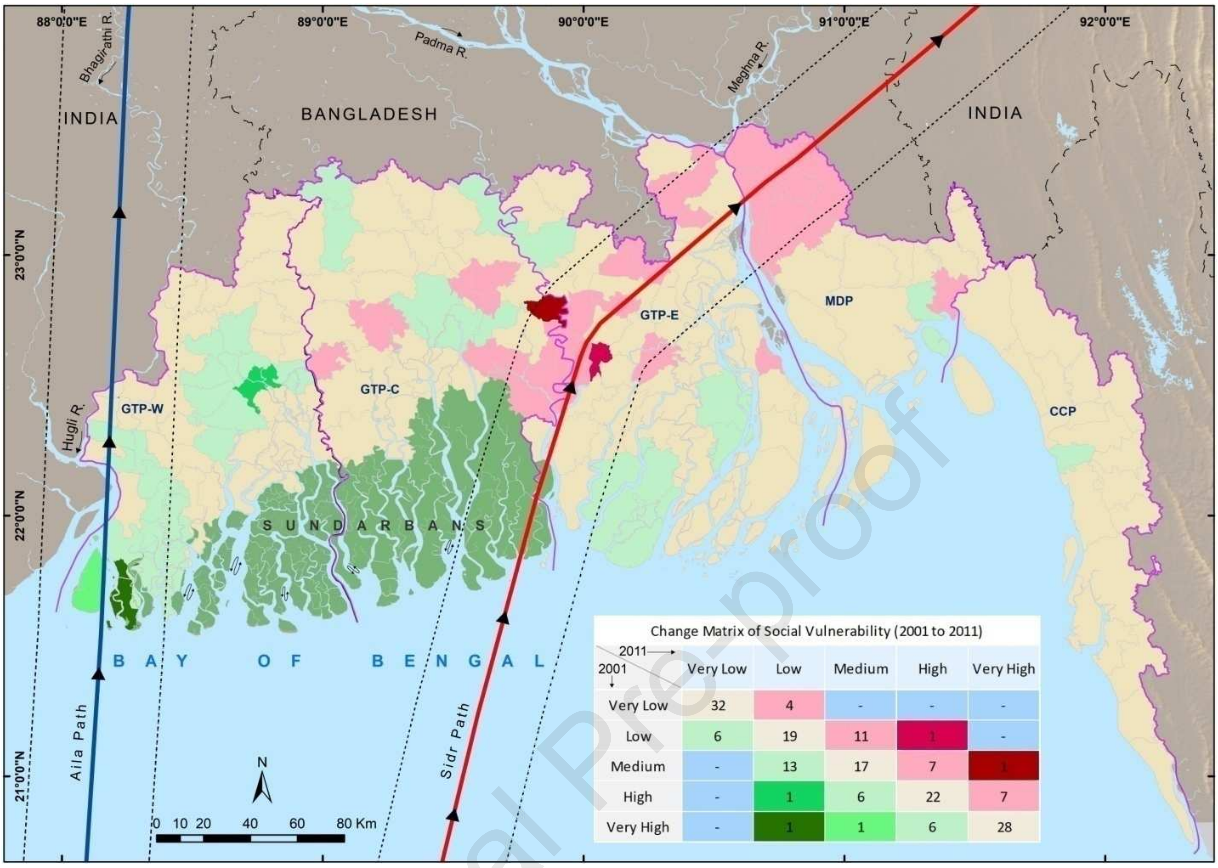


Figure 5b. Sub-district level Social Vulnerability map of the GBM Delta for 2011



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Tables

Table 1. Description of the Socio-Economic Variables Considered in the Social Vulnerability Analysis of the GBM delta.

Variables		**Rationale**	**References**
Population density	Number of people per square kilometer	Areas with high population density are more exposed to environmental hazards.	Armas and Gavris, 2013; Das et al., 2020
Average household size	Average number of people per household	Families with large number of people have limited resources, more work responsibilities that reduce the resilience to and recovery from hazards.	Adger, 1999; Cutter et al., 2003
Female population	Percentage of female population to total population	Females have a more difficult time during recovery from disaster than male, due to their family care responsibilities, sector-specific employment, and lower wages.	Cutter et al., 2003; Armas and Gavris, 2013; Nguyen, 2015
Illiteracy rate	Percentage of illiterate persons to total population	Illiteracy or lower level education constrains the ability to understand warning information and access to recovery information.	Cannon et al., 2003;Schmidlin, 2009
Agricultural dependency	Percentage of cultivators and agricultural labours (dependent on agriculture) to total working population	Agricultural dependents are more impacted by hazard events and climate variability than other workers.	Cutter et al., 2003; Heltberg&Bonch-Osmolovskiy, 2011; Nguyen, 2015
Non-workers	Percentage of total non-workers (not work at all in any economically productive activity - students, persons engaged in household duties, dependents) to total	Non-workers slow recovery from the disasters.	Myers, 2008; Holand et al., 2011; Armas and Gavris, 2013

	population		
Kutcha house	Percentage of households living in Kutcha (walls and/or roof are predominantly made by mud, bamboos, grass, reeds, thatch, plastic/ polythene) houses (temporary structure)	People living in Kutcha house are more sensitive to environmental hazards.	Cutter et al., 2003; Schmidlin, 2009; Samanta et al., 2017; ; Das et al., 2020
No Home ownership	Percentage of households that do not own their home (rented, occupied and others)	People who don't own their home have less access to information about financial aid during recovery.	Cutter et al., 2003; Tate, 2012
No Electricity connection	Percentage of households live without electricity connection	Households without access to safe/improved source of drinking water, electricity connection and sanitation facility are more sensitive to environmental hazards. They have a lower ability to respond to and recover from the impacts of hazards.	Cannon et al., 2003;Nguyen, 2015; Das et al., 2020
Unsafe Drinking water	Percentage of households reported 'others' category (i.e. ponds/canal/spring/river) as the main source of drinking water		Spence and Walters, 2012; Das et al., 2020
No Sanitation facility	Percentage of households that have no sanitation facility		Cannon et al., 2003; Das et al., 2020
Poverty	Percentage of population living below the poverty line*	Poor people have lower access to resources and lower ability to absorb losses and enhance resilience to hazard impacts.	Adger& Kelly, 1999; Cutter et al., 2003; Vincent, 2004; Siagian et al., 2014; Nguyen, 2015
Rural population	Percentage of population living in rural areas (total population minus urban population)	Rural population are more dependent on natural resources and have lower incomes.	Cutter et al., 2003; Vincent, 2004; Fekete, 2009; Nguyen, 2015
Data Source: Population & Housing Census (2001, 2011), Bangladesh Poverty Maps (Upazila) (2005, 2010), *Bangladesh Bureau of Statistics*; Primary Census Abstract, House listing and Housing Census, *Census of India* (2001, 2011); District Statistical Handbook (South & North 24			

Parganas), *Bureau of Applied Economics & Statistics* (2012); District Human Development Report (South & North 24 Parganas), *United Nations Development Programme-India* (2009-10)
Note: • *Bangladesh estimates the incidence of poverty (percentage of people living below the upper poverty line) and the incidence of extreme poverty (percentage of people living below the lower poverty line).The incidence of poverty has been considered for the analysis. • All variables are in percentages, with the exception of population density (persons per sq. km.) and average household size (numbers). • All the variables show a positive (+) functional relationship with social vulnerability, which means that the higher the value, the higher the social vulnerability.

Table 2. Descriptive Statistics of the Socio-Economic Variables for 2001 and 2011

Variables	N	Range		Mean		Standard Deviation	
		2001	2011	2001	2011	2001	2011
Population Density (person per sq. km.))	183	10008.46	14522.51	1085.41	1238.15	885.14	1208.98
Average Household Size (number)	183	1.85	1.94	5.15	4.61	0.38	0.40
Female Population (%)	183	6.10	7.64	48.90	50.25	1.11	1.51
Illiteracy Rate (%)	183	49.22	52.17	47.35	41.75	10.33	10.03
Agricultural Dependency (%)	183	68.95	87.50	51.92	61.59	14.70	20.52
Non-workers (%)	183	17.39	27.06	66.11	63.52	3.24	3.71
Kutcha House (%)	183	97.82	97.00	71.36	62.60	33.30	31.54
No Home Ownership (%)	183	53.86	46.30	6.31	7.06	6.85	6.74
No Electricity Connection (%)	183	73.28	93.40	75.73	53.13	17.11	20.67
Unsafe Drinking Water (%)	183	77.85	88.80	9.22	6.92	12.98	13.22
No Sanitation Facility (%)	183	79.44	71.00	56.21	29.15	16.31	15.02
Poverty (%)	183	71.90	63.79	40.59	34.36	17.33	14.52
Rural Population (%)	183	100.00	89.22	86.38	84.75	19.09	12.76

Table 3. Statistical Tests for the Principal Component Analysis (PCA)

Statistical Tests		**2001**	**2011**	**Remarks**
Kolmogorov-Smirnov test (Normality)	**Sig.**	0.000	0.000	Significant
Correlation Matrix	**Determinant**	0.001	0.001	> 0.00001, No multi-collinearity or Singularity issue
Kaiser-Meyer-Olkin Measure of Sampling Adequacy	**KMO**	0.728	0.658	Mediocre - Good
Bartlett's Test of Sphericity	**Approx. Chi-Square**	1326.936	1220.062	Significant, not an identity matrix
	Df	78	78	
	Sig.	0.000	0.000	
Communalities	**Average**	0.744	0.711	> 0.7, Good
Total Variance Explained [Eigen Values (> 1)]	**Component**	4	4	More than 70%, Good
	% of Variance	74.408	71.071	
Reproduced Correlation	**Residuals (0.05)**	34 (43.0%)	35 (43.0%)	Less than 50%, Fair

Table 4.PCA Results for the GBM delta in 2001 and 2011: Varimax Rotation Factor Matrix

Variables	Component (2001)				Variables	Component (2011)			
	1	2	3	4		1	2	3	4
Rural Population	.877				*No Home Ownership*	-.874			
No Home Ownership	-.867				*Rural Population*	.816			
No Electricity Connection	.798				*Population Density*	-.721			
Agricultural Dependency	.763				*No Electricity Connection*	.665		.435	
Population Density	-.653				*Kutcha House*		.918		
Non-workers		-.787			*Female Population*		.716	-.491	
Female Population		-.785			*Agricultural Dependency*	.568	.625		
Poverty		.579	.536		*Unsafe Drinking Water*				
No Sanitation Facility	.491	.513		.429	*Non-workers*			-.859	
Kutcha House			.897		*Poverty*			.593	
Unsafe Drinking Water			.641		*No Sanitation Facility*				.761
Average Household				.898	*Average Household*			-.522	.683

Size					*Size*				
Illiteracy Rate				.678	*Illiteracy Rate*		.601		.667
Percent of Variance	28.05	17.30	16.45	12.61	Percent of Variance	22.65	19.61	15.68	13.13

Extraction Method: Principal Component Analysis; **Rotation Method:** Varimax with Kaiser Normalization.

Suppress small coefficients (absolute value below .40)

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: