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Linking IPCC AR4 & AR5 frameworks for assessing vulnerability and risk to climate change in the Indian Bengal Delta

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ABSTRACT

The term 'vulnerability' is used to examine the interlinkages between humans and their social and physical surroundings. This approach is similar to the IPCC AR4's (2007) conceptual framework of vulnerability to climate change. The IPCC AR5 (2014) introduces a new approach and terminology that is in line with the concept of risk, thus differing from the previous understanding of vulnerability as mentioned in the IPCC AR4. This study attempts to link the new concept of risk (AR5) with the previous concept of vulnerability (AR4). Based on IPCC AR4 and AR5 frameworks, different bio-physical and socio-economic variables have been used for vulnerability (AR4) and risk (AR5) assessments in the 51 sub-districts (community development blocks) of the Indian part of Ganges-Brahmaputra-Meghna Delta (Indian Bengal Delta or IBD) applying principal component analysis (PCA). The results show that Basanti is the most vulnerable sub-district using the AR4 approach, whereas Gosaba is found to be the highly exposed to risk using the AR5 approach. Both sub-districts are spatially contiguous and with similar geographic characteristics which reflects the validity of the IPCC frameworks of assessment.

1. Introduction

In its Fifth Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) mentions that "Coastal systems and low-lying areas will increasingly experience adverse impacts such as submergence, coastal flooding, and coastal erosion due to relative sea level rise" ([1], p. 364). Low-lying deltas are highly sensitive to changes in sea leve [2,124]. At least 100 million people are at very high risk, living within 1 m of mean sea level [3]. It is estimated that by 2050, >1 million people in three mega deltas namely Ganges-Brahmaputra-Meghna delta (Bangladesh and India), Mekong delta (Vietnam) and Nile delta (Egypt) will be directly affected by sea-level rise [4]. The surface area of flooding in 33 deltas around the world is estimated to increase by 50% under sea level rise [5] and for Indian Bengal Delta (Indian part of Ganges-Brahmaputra-Meghna Delta or IBD) such increase could be as high as 70% [6]. It is also estimated that without protection from submergence and erosion, 72 to 187 million people would be displaced by 2100 [7].

Climate change, including climate variability and extreme events can directly and indirectly impact on the environment and socio-economic sectors like water resources, agriculture and food security, human health, and biodiversity [8,9]. Agricultural production worldwide is already being adversely affected by increasing temperature, changes in precipitation, and the extreme events associated with climate variability [10–12,125]. Furthermore, climate change has the potential to reduce crop yields by increasing soil salinity [13–15]. Other ecosystem based livelihoods such as fisheries and aquaculture are already under multiple stresses including acidification, changes in sea temperatures, extreme events, and sea level rise and related ecological changes [10,16]. Climate change is also impacting on the water resources by changing the flood or drought frequency, water availability, and seasonality of water discharge [17,18]. Climate variability and related extreme events already pose a serious threat to people's lives through impacts on livelihoods, such as decreases in crop production, food insecurity, and destroyed homes [19,20]. The health system is also sensitive to climate variability [21], and the interaction of climate variability with food security can exacerbate malnutrition [22]. Climate change is likely to impact the rural, poor, disabled, elderly, marginalized population, which further exacerbates existing social vulnerabilities [23–26]. Along with broad-scale influences, local factors also affect vulnerability at the household level [12]. In addition, population pressure, land use change and more intensive agricultural use, and urbanization can magnify risks and exposure to climate change impacts [25]. These factors can result in the displacement of vulnerable people, in an increased number of trapped

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populations and drive internal and international forms of population movement [27,28,29,121].

Policy and scientific communities are particularly interested on climate change impacts/vulnerabilities/risks because of their frequency, magnitude and persistence [1,30,31]. Vulnerability in particular is a key concept for climate and social sciences [32,33]. There are many different definitions of vulnerability in the literature [34–38]. To quantify multi-dimensional issues using variables as proxies, previous studies have employed the IPCC working definition of vulnerability (2007), which is a combination of exposure, sensitivity, and adaptive capacity [12,39]. The Fifth Assessment Report (AR5) of the IPCC introduces the concept of risk. This approach is different from the concept of vulnerability as expressed in the IPCC AR4 [40]. Hence, there is limited understanding and empirical work on risk assessment following the IPCC AR5 approach.

The main purpose of this study is to link the new concept of risk (AR5) with the existing concept of vulnerability (AR4) using the basic underlying assumptions present in both IPCC frameworks. This study assesses the vulnerability (AR4) and risk (AR5) at the local level (sub-district) to identify climate change impact hotspots to provide input for successful adaptation options and mitigation measures. This study also tries to identify the robust approach for assessing the vulnerability/risk to climate change.

This manuscript is organised as follows: the first section provides an introduction to climate change, low-lying areas and vulnerability, and the gaps in literature that are addressed by this study. Section 2 provides administrative, demographic and socio-economic characteristics of the study area. Section 3 describes the data and the methodological approach of the study. Section 4 discusses research findings and the final section concludes the manuscript.

2. Description of the Indian Bengal Delta

The Ganga-Brahmaputra-Meghna (GBM) delta is one of the world's most dynamic deltas, and it covers most of Bangladesh and parts of West Bengal in India [4,41–43]. The Indian part of the Ganges-Brahmaputra-Meghna delta is known as the Indian Bengal Delta (IBD) [44,45]. The IBD, a natural habitat of the Royal Bengal Tiger, presents a complex ecosystem developed by an intricate system of tidal rivers, mudflats, and salt-tolerant mangrove forests [45]. The socio-economic profile of the IBD is non-uniform due to its geographical settings and population composition, access to different sets of resources, and unavailability of sufficient fresh water. The study area is 14,054 sq. km and comprises of 51 sub-districts within two large districts - North 24 Parganas and South 24 Parganas (Fig. 1).

According to the 2011 census, the total population of IBD is 18.17 million, of which 9.29 million (51%) are male and 8.88 million (49%) are female [46,122]. The population density in 2011 was 1293 persons per sq. km and the decadal growth rate between 2001 and 2011 was 15%. North 24 Parganas is the most populated district with a population of 10 million and the population density of 2445 persons per sq. km. The total population of South 24 Parganas is 8.16 million and growing at an estimated rate of 1.82% per year, which is higher

Fig. 1. The study area map of Indian Bengal Delta.

than that of the state of West Bengal (1.38%) and India (1.76%) between 2001 and 2011. Census data (2011) shows that the sex ratio in IBD is 955 females per 1000 of males whereas the sex ratio in West Bengal is 950 and India is 940. The crude literacy rate is 72.31%, and the male literacy rate (76.39%) is higher than the female literacy (68.04%). The percentage of scheduled caste (SC) and scheduled tribe (ST) population to total population is 27.49. This percentage is >50% in several sub-districts like Hingalganj, Basanti, Sandeshkhali-I & II. IBD has the highest proportion (66.50%) of population aged 15–64 years which is reflected in the age dependency ratio i.e. 0.51, which indicates the working-age population face a moderate burden in supporting the non-working age population. Total workforce in IBD is 6.54 million, and the male work participation rate is 57%, whereas the female participation is only 14%. Female workers are mainly engaged in household industries both in rural and urban areas.

In IBD, 57% of the total population live in rural areas [46,122]. They are mainly dependent on agriculture, working as cultivators and agricultural labourers. Around 32% of IBD inhabitants are extremely poor [47,48]. The total cropped area during 2010–11 was 0.59 million ha (42% of total area) [49]. The average size of land holdings is 0.61 ha. Overall soil conditions are favourable for agricultural activities, but the saline soil of South 24 Parganas district is considered uneconomical [50]. The presence of several rivers, creeks and canals is beneficial to the cropping pattern of this delta. The major crop grown in the delta is rice. The yield rate of rice is 2698 kg per hectare in North 24 Parganas and 2322 kg per hectare in South 24 Parganas [49]. Gradual increase in soil salinity forced crop farmers to choose salt tolerant cropping practices instead of traditional cultivation practices. Along with agriculture, rural people practice multiple secondary livelihood activities such as aquaculture, honey collection, boat maintenance and net making [51].

The Indian Bengal Delta is highly sensitive to climate change impacts including sea level rise, coastal erosion, salinization, frequent cyclones, and floods [45,52] (Fig. 2). In the past three decades, the Relative Mean Sea Level (RMSL) has risen to the order of 8 mm [53] to 12 mm [54] per year in the Bay of Bengal. The rate is significantly higher than earlier observations and also considerably higher than the global mean (3.2 mm per year). With accelerated sea level rise and subsequent changes in the hydrodynamic regime, the IBD faces

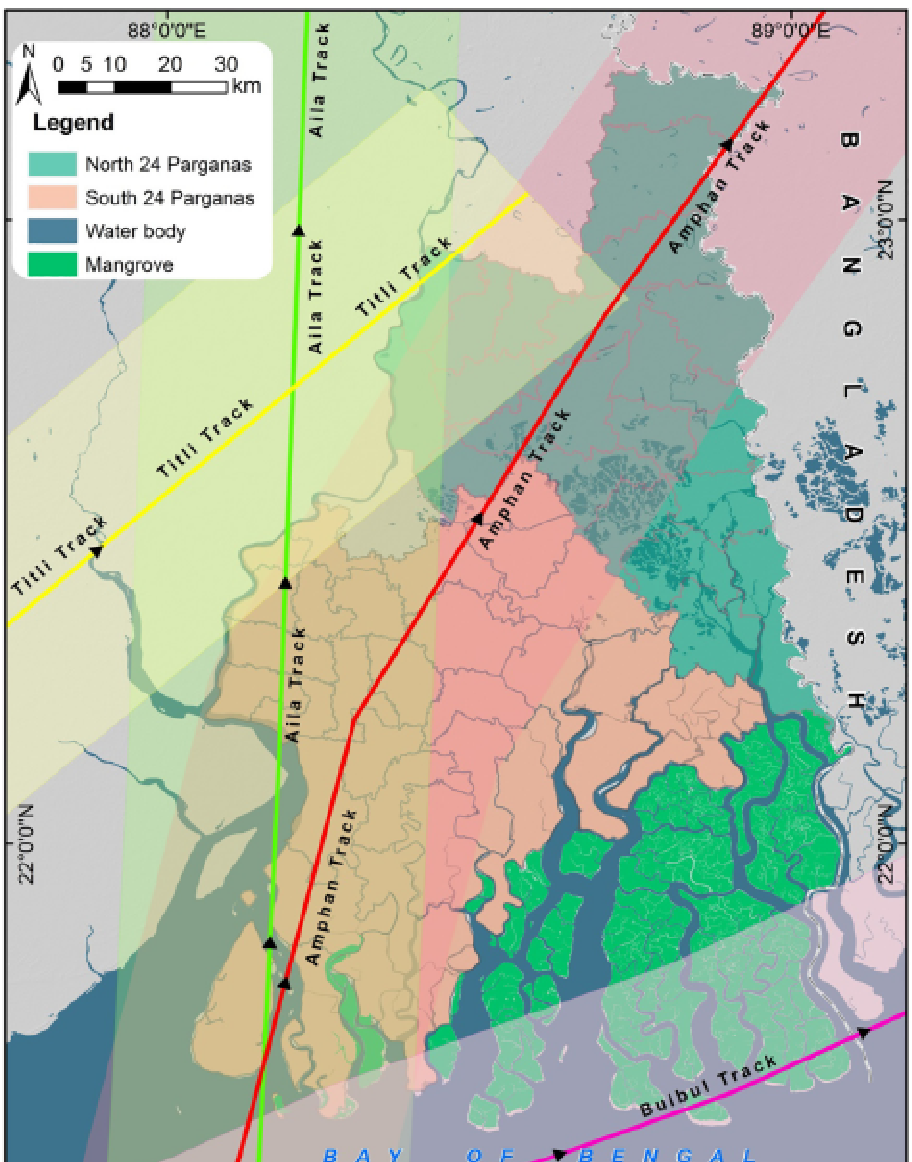

Fig. 2. Cyclone tracks on IBD in the last 10-15 years.

severe land loss. Among 102 islands, 3 islands, viz. Lohachora and Suparibhanga and New Moore (Purbasha) [54,55] are already submerged in the western region of the delta. Severe coastal erosion is being observed in several other islands- Ghoramara, Sagar, Mousuni, Jambudwip, Namkhana, G-Plot, Dhanchi, Bulcheri, Dulibhasani, Dalhousie, Bhangduni islands and coastal villages [56–59]. The entire populations of the villages of Khasimara, Baisbanpara, Khasimara Char, Lakshmi Narayanpur and Baghpara of Ghoramara island had to leave its usual place of residence and seek refuge in nearby islands such as Sagar [28,56,60,61]. Recent studies suggest that in Mousuni island 224 families are likely to be displaced within the next 5 years due to the impacts of coastal erosion [59]. The Bay of Bengal normally registers 7% of the major cyclones of the world [62] and the frequency of high to very high intensity cyclones has increased between 20% to 26% in the last 120 years [63,64].

Intense cyclones such as Aila (2009), Bulbul (2019), Amphan (2020) as well as severe floods have caused massive devastation to coastal regions. For example, in May 2009, cyclone Aila hit as many as 34 sub-districts, 16 urban local bodies, and 3704 villages in the IBD damaging 380 thousand houses and impacting almost 2.45 million people and 0.12 million hectares of agricultural area [47]. Cyclone Amphan, which made landfall on 20th May of 2020, has barrelled through the IBD at wind speeds of up to 190 kmph and heavy rains, destroyed the river embankment across the Sundarban which has led to salt water entering the land (Fig. 2). Home dwellings and infrastructure rebuilt after cyclone Aila have been lost due to the most recent cyclone. The areas worst hit by Amphan are Ghoramara, Kakdwip, Namkhana, Sagar and Patharpratima. In the aftermath of the cyclone, it is estimated that >0.2 million farmers could be severely affected, potentially triggering a wave of human migration from the IBD.

3. Vulnerability and risk: linking new concepts

The Intergovernmental Panel on Climate Change (IPCC) defines vulnerability in the Fourth Assessment Report (AR4) as 'the degree to which geophysical, biological and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of climate change, including climate variability and extremes' ([31], p.783). The term 'vulnerability' in AR4 is used to refer to the vulnerable system itself (e.g. low-lying islands or coastal cities); and the impact to this system (e.g. flooding of coastal cities and agricultural lands) [65]. According to IPCC AR4, vulnerability is a function of three factors which are exposure, sensitivity, and adaptive capacity [12,65]. Exposure in AR4 is the magnitude and duration of the climate-related stress such as a drought or change in precipitation, whereas sensitivity is the degree to which the system is affected by the climate related stress or extreme events. Adaptive capacity in AR4 refers to the system's ability to withstand or recover from the extreme events/damage [12,40,65,66].

$$V = f\,(E, S, AC)$$

where, V = Vulnerability, E = Exposure, S = Sensitivity and AC = Adaptive Capacity.

It has to be noted that the adaptive capacity of a system determines the vulnerability by modulating exposure and sensitivity [67].

The Fifth Assessment Report of the IPCC (AR5) introduces a new approach and terminology. This approach is similar to the concept of disaster risk, which differs from the current understanding of vulnerability as mentioned in the IPCC AR4 [40]. According to IPCC AR5, risk is 'the potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. It is often represented as the probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur' ([1], p. 1048). The term 'risk' is used primarily to refer to the risks of climate-change impacts [22] (Fig. 3).

$$R = f\,(H, E, V)$$

where, R = Risk, H = Hazard, E = Exposure, and V = Vulnerability.

The terms 'exposure' and 'vulnerability' are common but used differently in IPCC AR4 and AR5. According to IPCC AR5, exposure is 'the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected' ([1], p. 1048) and vulnerability is 'the propensity or predisposition to be adversely affected' ([1], p. 1048). Vulnerability in AR5 includes the concepts of sensitivity (susceptibility to harm) and adaptive capacity. Hazard is a new term in AR5, defined as 'the potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure,

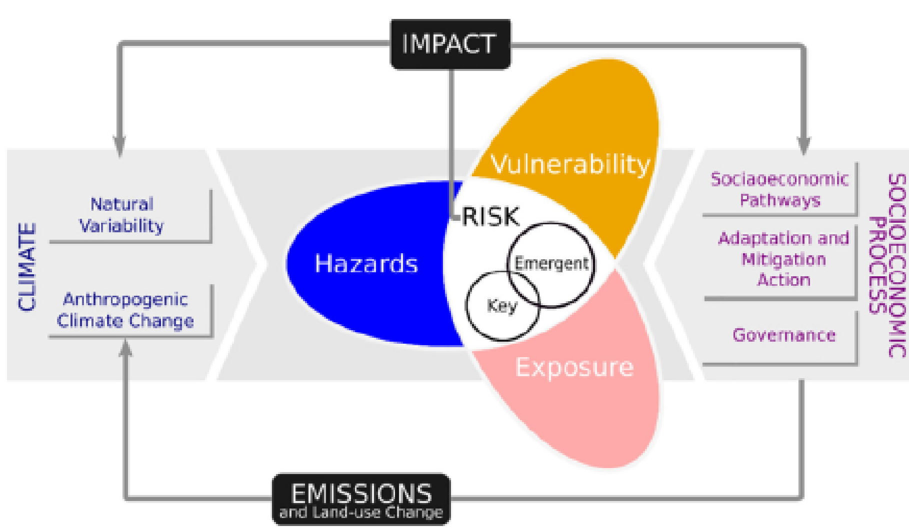

Fig. 3. The contributing factors of risk.
(Adapted from IPCC AR5, 2014, P.1046.)

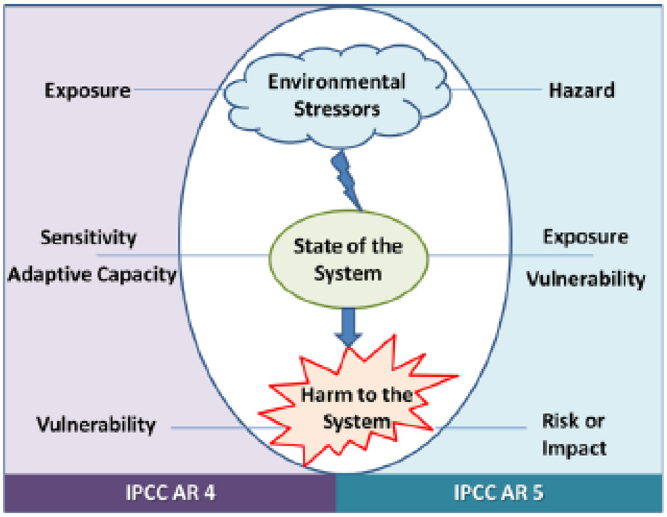

Fig. 4. General logic of two different approaches (IPCC AR4 & AR5).

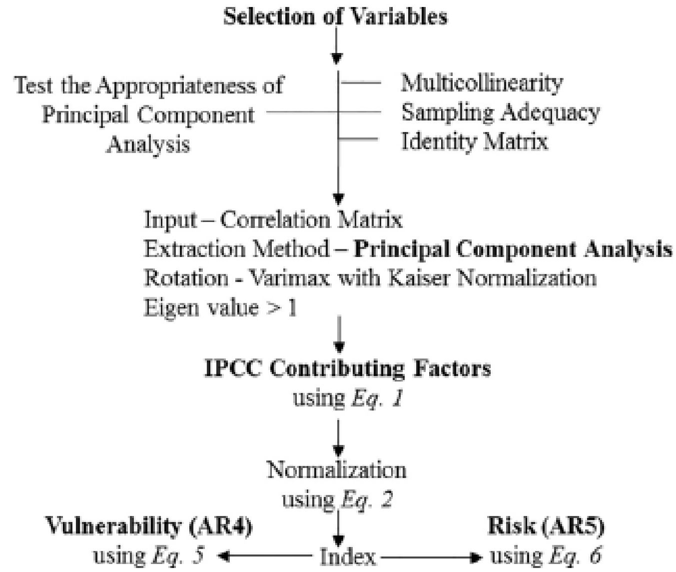

Fig. 5. Methodological framework of vulnerability (AR4) and risk (AR5) assessments.

livelihoods, service provision, ecosystems, and environmental resources'([1], p. 1048).

In both IPCC's AR4 and AR5 working definitions it is clear that vulnerability and risk include an external element, which is climate-related stress (e.g. extremes weather events) represented by the "exposure" according to AR4 and "hazard" in AR5, as well as an internal element, which comprises "sensitivity" and "adaptive capacity" in AR4 and "exposure" and "vulnerability" in AR5. The internal element describes the moderating attributes (socio-economic, physical or environmental) of the system. It can be said that the terminology employed in both the IPCC assessment reports is different but the basic underlying assumptions follow a similar logic (Fig. 4).

4. Methodology and materials

The construction of an index based on specific sets of variables is commonly used in quantitative approaches to assess vulnerability [32,34]. Previous studies have employed a wide range of methods based on IPCC contributing factors - exposure, sensitivity, and adaptive capacity to quantitatively assess vulnerability at different scales [12,26,39,40,66,68–71]. In this study, vulnerability and risk indexes have been constructed at the sub-district level using the data reduction technique – 'Principal Components Analysis' (PCA) using the Statistical Package for the Social Sciences (SPSS) software version 22 (Fig. 5). A similar approach has been used in previous studies on vulnerability assessment [37,71–82]. PCA is the most common statistical method used to extract a smaller and more coherent set of uncorrelated (orthogonal) components from a large number of variables [83]. First component accounts for the largest possible amount of variation in the original variables, and each following component accounts for as much of the remaining variability as possible [80,83,84].

Based on the IPCC AR4 and AR5 working definitions, the methodological frameworks of vulnerability and risk have been designed for this study. The term 'vulnerability' in AR5 has been divided into 'sensitivity' and 'adaptive capacity' for the simplification of the methodological framework of risk. In other words, risk is the function of four factors which are hazard (H), exposure (E), sensitivity (S) and adaptive capacity (AC).

4.1. Selection of variables

Based on a comprehensive review of the literature and available secondary data sets, 33 theoretically important and policy-relevant bio-physical and socio-economic variables have been selected under ten major components (concepts) - climate variability, natural hazards, demographic profile, socio-economic status, livelihood activity, human resource capacity, economic security, infrastructure, basic facilities and agricultural livelihood strategies (Tables 1 & 2). The first two major components are related to the external element which in the AR4 is categorized as exposure, and as 'hazard' in the AR5. Climate variability has been measured by the average standard deviation of the monthly - maximum and minimum temperatures and precipitation over last 30 years. Frequent cyclones, floods, coastal erosion are the major environmental stressors in IBD therefore these have been used to measure the second major component namely natural hazards. The data sources of climate-related stress or extremes events are National Remote Sensing Centre (2003–2014), Indian Meteorological Department (1951–2014), United States Geological Survey (2001 & 2011).

In addition, eight major components show an internal element, which comprises sensitivity and adaptive capacity in AR4 and exposure and vulnerability in AR5. In terms of socio-economic resources (e.g., low-income groups, rural population, illiterates and females) and physical mobility (e.g., children, aged, and disabled persons) people who are disadvantaged are often considered to be the most vulnerable to climate change impacts. Females have more challenges to overcome from the disasters compared to males due to family care responsibilities, sector-specific employment, and lower wages [37]. Rural population are more vulnerable due to low incomes and greater dependency on natural resources [26]. People whose main livelihood is dependent on agriculture are severely impacted by climate variability and natural hazards [37]. It is noted that a few variables like population density, rural population and agricultural dependents have been considered as exposure in AR5 and as sensitivity in AR4. Marginal workers have work for <6 months in a year, are economically disadvantaged people [98]. Poverty is a variable that captures lack of access to resources and income opportunities [97]. On the other hand, literate people who are working in the formal sector have access to early-warning information and can plan in advance how to respond to climate related stress or extreme events [37,102,113]. Access to sanitation, safe drinking water, electricity, and infrastructures such as road density, health and educational institutes determine the ability of the system to respond to and recover from the impacts of extreme events [109]. The socio-economic data sets used in this study

Table 1
A detailed description of the selected variables for vulnerability and risk assessments.

Sl. no.	Concepts	Variables	Explanation of variables	IPCC contributing factors	References
1	Climate variability	Maximum temperature	Standard deviation of the average daily maximum temperature by month last 30 year is averaged	E1	[12,85]
2		Minimum temperature	Standard deviation of the average daily minimum temperature by month last 30 year is averaged	E2	[12,85]
3		Average precipitation	Standard deviation of the average monthly precipitation last 30 year is averaged	E3	[12,85,86]
4	Natural hazards	Flood	Percentage of area inundated with high return period flood during last 10 years	E4, H1	[12,39,86–91]
5		Cyclone	Interpolated (kernel density estimation) wind speed (m/s) of tropical cyclone over last six decades	E5, H2	[12,92]
6		Coastal erosion	Rate of coastal erosion (sq. km/year)	E6, H3	[92,93]
7	Demographic profile	Population density	Number of people per square kilometre	S1, EX1	[73,94]
8		Average household size	Average number of people per household	S2, SS1	[37,95]
9		Female population	Percentage of female population to total population	S3, SS2	[37,39,73]
10		Child population	Percentage of population under 7 years age (0–6 age group) to total population	S4, SS3	[37,39]
11	Socio-economic status	Socially disadvantaged people	Percentage of scheduled caste and scheduled tribe population to total population	S5, SS4	[59]
12		Food insecurity	Percentage of households that can manage less than one or one square meal a day for the major part of the year	S6, SS5	[39,85]
13		Land holding	Percentage of households without land holding	S7, SS6	[59]
14		Poverty	Percentage of population living below the poverty line (BPL)	S8, SS7	[26,37,96,97]
15		Rural population	Percentage of rural population to total population	S9, EX2	[26,37,77]
16	Livelihood activity	Agricultural dependency	Percentage of cultivators and agricultural labours (dependent on agriculture) to total working population	S10, EX3	[37,85]
17		Marginal workers	Percentage of marginal workers (not work for the major part of the reference period i.e. < 6 months) to total working population	S11, SS8	[98]
18		Non-workers (dependents)	Percentage of total non-workers (not work at all in any economically productive activity - students, persons engaged in household duties, dependents) to total population	S12, SS9	[73,99,100]
19	Human resource capacity	Literacy rate	Percentage of literates to the total population age 7 years and above	A1, AC1	[101,102]
20		Work participation rate	Percentage of total workers (main and marginal) to total population	A2, AC2	[103]
21	Economic security	Salaried job	Percentage of population working in organised/formal sector (regular salaried employed)	A3, AC3	[104]
22		Home ownership	Percentage of households have their own home	A4, AC4	[37,82]
23		Household assets	Percentage of households have household assets	A5, AC5	[26,59,90,105]
24	Infrastructure	Pucca houses	Percentage of households living in Pucca houses (permanent structure)	A6, AC6	[59]
25		Health care centres	Number of health care centres	A7, AC7	[106]
26		Educational institutes	Number of educational institutes	A8, AC8	[107]
27		Road density	Length of roads (in km) per sq. km	A9, AC9	[108]
28	Basic facilities	Sanitation	Percentage of households have sanitation facility within premises	A10, AC10	[109]
29		Electricity	Percentage of households have electricity connection	A11, AC11	[90,109]
30		Safe drinking water	Percentage of households reported tap water from treated source as main source of drinking water	A12, AC12	[110]
31	Agro livelihood strategies	Crops	Number of crops grown in a year	A13, AC13	[12]
32		Irrigation	Percentage of irrigated area to total cultivated area	A14, AC14	[111]
33		Fertilizer	Number of fertilizer depots	A15, AC15	[112]

IPCC AR4: E - exposure, S - sensitivity, A - adaptive capacity; IPCC AR5: H - hazard, EX - exposure, SS - sensitivity; AC - adaptive capacity.
All the variables are showing the positive (+) functional relationship with IPCC contributing factors which means the higher the value, higher the hazard/exposure/sensitivity/adaptive capacity.

are available in Census of India (2001 & 2011), Bureau of Applied Economics & Statistics (2011), United Nations Development Programme -India (2009 & 2010).

4.2. Testing the appropriateness of principal component analysis

All variables are measured at the interval-level. The initial analysis revealed that some of the socio-economic variables are highly correlated with each other. For example, 'agricultural dependency' is highly correlated with 'landholding', 'Pucca houses' is correlated with 'electricity' and 'household assets'. It is very difficult to determine the unique contribution to a component of the highly correlated variables. To address this limitation, the list of variables has been reduced to 29 variables in AR4 framework by removing redundant variables ($r > \pm 0.8$) to avoid multi-collinearity (highly correlated) and singularity (perfectly correlated). In the case of AR5 framework, 28 variables have been considered by excluding the correlated variables (Table 3). The issue of multi-collinearity can also be identified by looking at the determinant of the R-matrix ($|R|$), which should be >0.00001 [84].

In the present study, the sample size is 51 sub-districts of IBD. The subjects-to-variables (STV) ratio is different for the different contributing factors indicated in the IPCC framework but it is not lower than 3 (3:1 ratio) [114]. Histogram, box plot and descriptive statistics have been used to identify the outliers in SPSS software. The Kaiser-Meyer-Olkin (KMO) test [115] has been used to measure the sampling adequacy and also to detect multi-collinearity in the data. Using the Bartlett's Test of Sphericity [116], another test of the strength of the relationship among variables has been performed, and this tells whether correlation matrix is considerably different from an identity matrix [80]. Results across all tests suggest that principal component analysis is an appropriate approach to interrogate the data.

Table 2
Descriptive statistics of the selected variables for vulnerability and risk assessments.

Variables		Range	Mean	Std. deviation
1	Maximum temperature	0.14	0.43	0.02
2	Minimum temperature	0.08	0.41	0.02
3	Average precipitation	129.17	301.60	22.68
4	Flood	1.00	0.13	0.20
5	Cyclone	1.00	0.59	0.32
6	Coastal erosion	1.00	0.07	0.18
7	Population density	4837.34	1682.21	864.01
8	Average household size	1.29	4.50	0.29
9	Female population	1.29	48.78	0.24
10	Child population	8.52	12.29	1.84
11	Socially disadvantaged people	62.05	33.43	15.56
12	Food insecurity	16.11	4.54	2.86
13	Without land holding	63.01	60.67	13.46
14	Poverty	58.45	31.76	13.30
15	Rural population	76.11	85.00	19.00
16	Agricultural dependency	70.10	44.47	18.62
17	Marginal workers	44.98	28.29	12.33
18	Non-workers	20.25	63.69	3.09
19	Literacy rate	19.20	77.10	4.76
20	Work participation rate	16.42	36.23	2.82
21	Salaried job	24.14	13.23	5.26
22	Home ownership	17.40	94.86	3.48
23	Household assets	3.50	0.61	0.78
24	Pucca houses	74.60	47.76	21.63
25	Health care centres	13.00	6.00	3.50
26	Educational institutes	560.00	516.69	135.03
27	Road density	10.21	1.54	1.70
28	Sanitation	65.40	67.17	17.48
29	Electricity	88.80	43.86	23.39
30	Safe drinking water	84.00	14.21	18.67
31	Crops	85.71	49.58	23.58
32	Irrigation	93.50	40.11	23.51
33	Fertilizer	371.00	95.27	82.33

Valid cases (N) = 51.

4.3. 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 [80]. Only those components with an eigenvalue (the variances extracted by the components) >1.0 have been retained using the "eigenvalue-greater-than-one" rule proposed by Kaiser [117]. The varimax (orthogonal) rotation has been opted to improve the interpretability of components [84]. For the computation of a composite index, component score coefficients have been estimated. Component scores are the scores of each case, on each component.

To calculate the value of the contributing factors indicated in the IPCC for all the sub-districts, component score coefficients are multiplied by the proportion of the corresponding component's variance and summed these products in SPSS software [80]. The value of contributing factors has been calculated using the formula:

$$CF = \sum (Fi/TV) * FSi \tag{1}$$

where, CF is an contributing factor (hazard, exposure, sensitivity and adaptive capacity), F_i is the percentage of variance explained by each component (i), TV is the total variance explained by all the retained components, FSi is the component score coefficients on each component (i).

The value of the CF can be positive or negative, making difficult to use it for final calculation. It is necessary to *normalize* all the CFs to ensure that they are comparable. This has been carried out using the methodology developed for the calculation of the Human Development Index [118]. The equation is expressed as:

$$Xij = \frac{(Xi - \ Min\ Xj)}{(\ Max\ Xj - \ Min\ Xj)} \tag{2}$$

where Xij is the normalized value of CF (j) with respect to sub-district (i), Xi is the actual value with respect to sub-district (i), and Min Xj and Max Xj are the minimum and maximum values, respectively, of CF (j) among all the sub-districts.

The normalized value ranges from 0 to 1. The next step after normalization is to *combine* all the normalized CFs into single *composite index*.

According to the framework proposed by Fussel and Klein [33], exposure (E) and sensitivity (S) together compose the *potential impact* (PI), while adaptive capacity (AC) is the potential of a system to cope with these impacts.

$$PI = E \times S \tag{3}$$

It can be said that people who live in exposed areas and are also sensitive to climate change impacts are likely to become a 'potential vulnerable group'. This potential vulnerable group can be divided into two - with and without adaptive capacity. The latter part will be an *immediately vulnerable group*, as they cannot cope with climate change impacts [39]. In other words, a system is more vulnerable if it is exposed and sensitive to the impacts of climate change and has only limited/no capacity to adapt.

Vulnerability therefore can be expressed with the following mathematical equations:

$$V = PI - PI \times AC \tag{4}$$

or,

$$V = PI(1 - AC) \tag{5}$$

Eq. (5) has also been employed in the final calculation of risk, where 'potential impact' is the combination of hazard, exposure, and sensitivity (Fig. 6).

$$R = H \times E \times S\ (1 - AC) \tag{6}$$

The final value represents current vulnerability and risk of IBD in changing climate conditions. The value for vulnerability and risk indexes ranges from 0 to 1, with higher values reflecting higher degree of vulnerability and risk. Finally, the entire range has been equally divided into five categories and each is assigned a qualitative indicator of vulnerability and risk (from very low to very high). In order to visualize and analyze the results in a geographic context, two separate maps have been prepared using ArcGIS software (10.5).

5. Results and discussion

IBD inhabitants are facing multiple challenges associated with climatic hazards and under-development. Cyclone, coastal erosion/embankment breaching and flooding are the hazards that affect the delta region quite frequently. The low intensity cyclonic disturbances originated in the Bay of Bengal occur almost every year and severe cyclonic storms like Aila-2009, Bulbul-2019, and Amphan-2020 also make landfall in the delta from time to time. In most cases, saline floods are the result of embankment breaching and storm surges. Results derived from the analysis of multi-hazard data (flood, cyclone, and coastal erosion) of IBD suggest that coastal sub-districts such as Gosaba, Basanti, Patharpratima, Kultali, Hingalganj, and Sandeshkhali-II sub-districts are at very high risk. Another issue which magnifies the risk in the region is economic vulnerability of its inhabitants. The continuous degradation of natural resources and unsustainable pattern of economic activity combine to increase local poverty, which further exacerbates the existing vulnerability of this delta. Monsoon dependent mono cropping economy prevails in most of the physically vulnerable areas of IBD, with exception of multiple crop practices in few places. Furthermore, limited access to markets difficult economic trade, which in turn creates poverty. Basanti, Sandeshkhali II, Sandeshkhali I, Kulpi, Canning II, Patharpratima, Namkhana and Kultali sub-districts have 45% of their population in conditions of chronic poverty. This poverty is associated with food insecurity, malnutrition, illiteracy, lack of primary health services and access to drinking water and sanitation facilities.

The spatial assessment of vulnerability/risk in the delta is a crucial element to consider, as it varies from place to place. Based on the results of PCA, vulnerability and risk have been estimated and mapped for all the sub-districts of IBD (Table 3). In the vulnerability analysis (AR4), two components have accounted for 75.37% of the total variance in the data of exposure, whereas three components of sensitivity and four components of adaptive capacity have accounted for 73.96% and 73.80% of the total variance respectively. It is important to note that the first component has explained the maximum variance in the data.

For the first component in AR4, *maximum and minimum temperature, average precipitation, coastal erosion, agricultural dependency, literacy rate, household assets, sanitation* have shown markedly higher positive loadings, while variables *like landholding* and *home ownership* have shown strong negative loadings. Loadings refer to the correlations between the variables and the components, and they range from −1 to +1. The second component explains the variations in *flood, cyclone, average household size, child population, crop diversity, irrigation*. The third component explains *female population,*

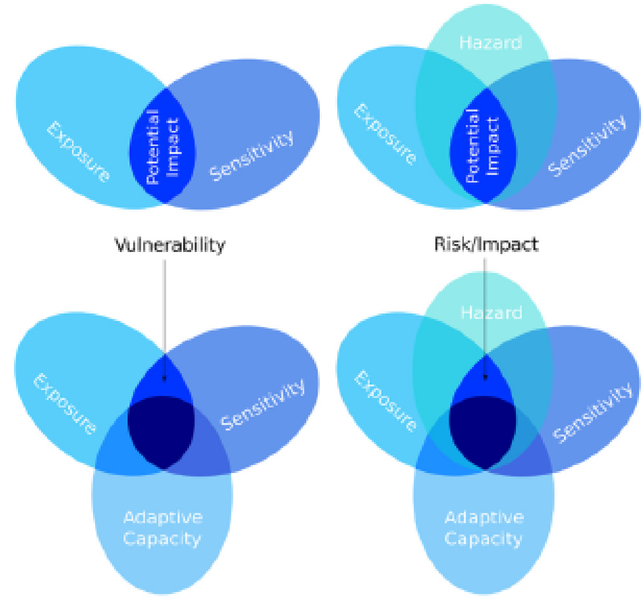

Fig. 6. IPCC contributing factors for final calculation of vulnerability (AR4) and risk (AR5) indexes.

Table 3
PCA results for the Indian Bengal Delta: Varimax rotation factor matrix.

Variables		Component (AR4)				Component (AR5)			
		1	2	3	4	1	2	3	4
1	Maximum temperature	0.755	−0.474			N.A.			
2	Minimum temperature	0.816							
3	Average precipitation	0.800							
4	Flood		0.768			0.843			
5	Cyclone		0.881			0.762			
6	Coastal erosion	0.885				0.761			
7	Population density	N.C.				−0.959			
8	Rural population	N.C.				0.947			
9	Average household size		0.904			0.921			
10	Female population			0.866				0.693	
11	Child population		0.850			0.921			
12	Socially disadvantaged people	0.476	−0.408				−0.689		
13	Food insecurity			0.567				0.793	
14	Without land holding	−0.925				−0.509	0.737		
15	Poverty	0.690		0.480		0.576	−0.415	0.541	
16	Agricultural dependency	0.911				0.940			
17	Marginal workers	0.708		0.417		0.643	−0.553		
18	Non-workers	−0.506	0.679				0.810		
19	Literacy rate	0.767				Same			
20	Work participation rate				0.767				
21	Salaried job	N.C.							
22	Home ownership	−0.876							
23	Household assets	0.866							
24	Pucca houses	N.C.							
25	Health care centres		−0.520						
26	Educational institutes				0.777				
27	Road density			0.768					
28	Sanitation	0.762	0.455						
29	Electricity	0.659		0.544					
30	Safe drinking water			0.831					
31	Crops		0.857						
32	Irrigation		0.822		0.407				
33	Fertilizer	0.514							
Percent of variance	Exposure	45.217	30.167			Hazard	62.312		
	Sensitivity	33.969	23.785	16.207		Exposure	90.076		
	Adaptive capacity	27.020	16.650	15.099	15.035	Sensitivity	31.978	24.720	17.349

Extraction method: Principal Component Analysis; rotation method: Varimax with Kaiser Normalization.
a. Adaptive capacity is same for AR4 and AR5.
b. Only one component was extracted. The solution cannot be rotated.
N.C. = not considered (to avoid multi-collinearity issue); N.A. = not applicable (as per definition of hazard in IPCC AR5).
Suppress small coefficients (absolute value below 0.40).
Statistical tests: Kaiser-Meyer-Olkin Measure of Sampling Adequacy ≥ 0.700; Determinant of Correlation Matrix ≥ 0.00001; Bartlett's Test of Sphericity = 0.00 (Significant); Communalities (Average) ≥ 0.750.

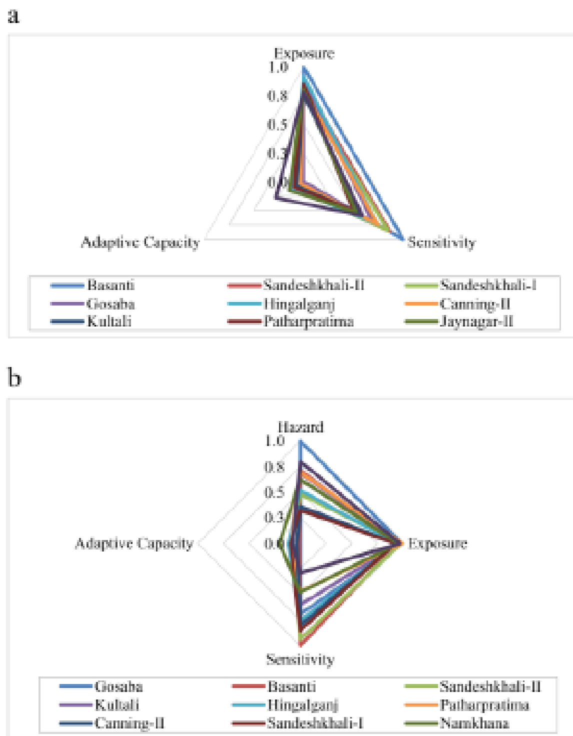

Fig. 7. a. Top 10 most vulnerable sub-districts in the Indian Bengal Delta. b. Top 10 highest risk sub-districts in the Indian Bengal Delta.

road density and *safe drinking water*. The fourth component which is mainly related to adaptive capacity explains *work participation rate* and *educational institutes*.

The results based on risk analysis (AR5) approach reveal a slight different scenario. One component has explained 62.31% of the variance in the data of hazard and 90.08% in case of exposure. For sensitivity, three components have explained 74.05% of the variance. Adaptive capacity is same as in vulnerability analysis (AR4). *Flood, coastal erosion, average household size, child population, rural population, agricultural dependency* have shown higher positive loadings and *population density* has shown negative loadings. The second component explains the variations in *landholding, non-workers* and third component explains *food insecurity, female population*. It is understood that eight variables largely determine the contributing factors of vulnerability and risk are *flood, coastal erosion, agricultural dependency, average household size, landholding, household assets, sanitation,* and *rural population*.

The climate change impact hotspots (vulnerability and risk) have been identified at the sub-district level considering both the IPCC working definitions of AR4 and AR5 (Figs. 8 & 9).

Fig. 7a and b shows the influence of the contributing factors indicated by IPCC on top 10 most vulnerable sub-districts (AR4), and top 10 highest risk sub-districts (AR5). Coastal sub-districts like Gosaba, Basanti, Sandeshkhali-II, Kultali, and Patharpratima are at greatest risk/vulnerability due to both higher sensitivity and lower adaptive capacity.

The results indicate that the majority of the vulnerable communities are living in the marginal areas of the delta (Figs. 8 & 9). Basanti is assessed as the most vulnerable sub-district according to the AR4 approach whereas Gosaba is found to be exposed to highest risk based on the AR5 method. Both are spatially contiguous and geographically similar. Basanti is bordered by vulnerable sub-districts Canning-II, Sandeshkhali-II and Gosaba and Sundarban forests. Gosaba is the last settlement at the margin of the deep forests of the Indian Sundarban. Limited livelihood opportunities,

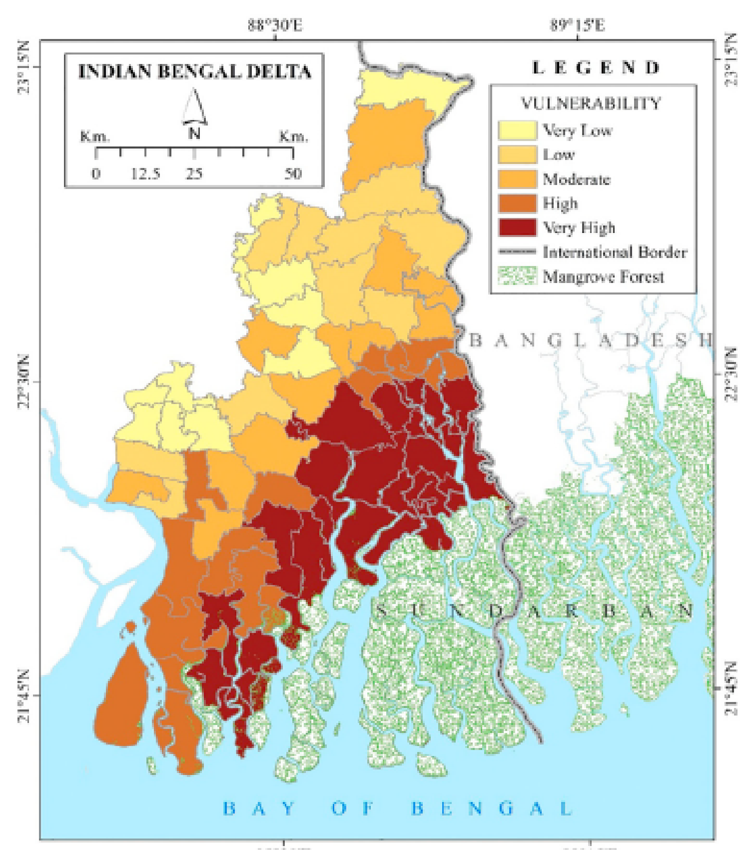

Fig. 8. Vulnerability map of Indian Bengal Delta (following the IPCC AR4 approach, 2007).

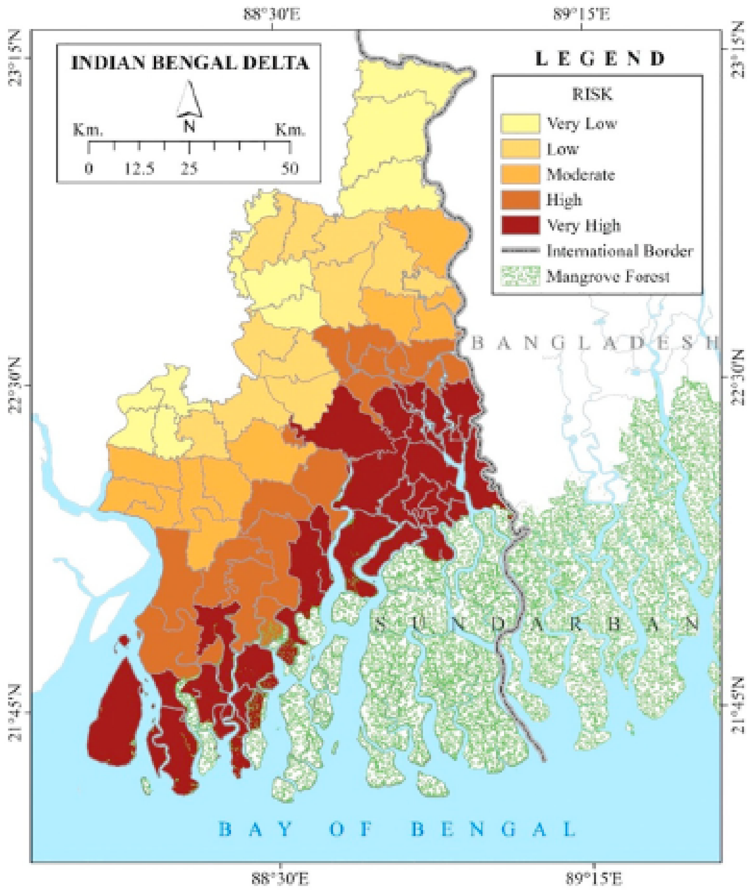

Fig. 9. Risk map of Indian Bengal Delta (following the IPCC AR5 approach, 2014).

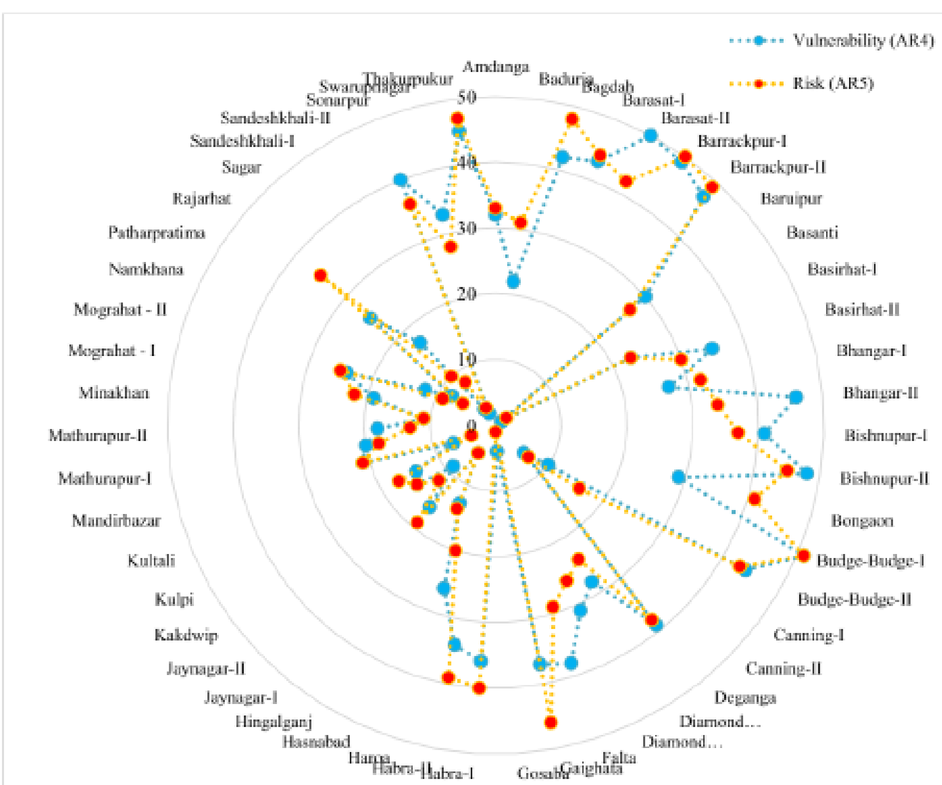

Fig. 10. Sub-district level relative ranking of Indian Bengal Delta.

poor socio-economic and institutional resilience, and increasing bio-physical vulnerabilities combine to make these two sub-districts the most vulnerable and exposed to highest risk in the IBD [123]. Other vulnerable (AR4)/ highest risk (AR5) sub-districts are Sandeshkhali-I & II, Hingalganj, Canning-II, Kultali, Patharpratima. These sub-districts have maximum vulnerability/risk, and have the potential to be adversely affected by climate change, where focused adaptation measures are immediately needed. The least vulnerable sub-districts (AR4) are Barrackpur-I & II, Barasat-II, Budge-Budge-I, Bishnupur-II and lowest risk sub-districts (AR5) are Barrackpur-I & II, Budge-Budge-I, Thakurpukur-Maheshtala, Bagdah. All sub-districts are closer and connected to Kolkata city and fall within the Kolkata Metropolitan Area (KMA) which results in greater advantages in terms of livelihood opportunities and access to frontline services. It can be noted that local governance plays an important role to deal with these variations of vulnerability/risk as this requires local knowledge to target adaptation or mitigation interventions.

The most significant difference between the results of the AR4 and AR5 approaches is the change in sub-district level relative ranking (Fig. 10). The overall level of vulnerability/risk (very low to very high) is almost the identical for all the sub-districts (Figs. 8 & 9). This result suggests a link between the new concept of risk (AR5) and the existing concept of vulnerability (AR4). It can be noted that the concept of exposure or system (people, livelihoods, etc.) in AR5 is more adequate to identify the vulnerable communities in any areas. This is considered as an advantage of AR5 over the AR4 framework.

6. Conclusions

This study provides a representation of the risk of a coastal region following the IPCC AR5 approach. Applying the IPCC AR4 and AR5 frameworks to the same data set, two different sub-districts located in the IBD delta have been identified to be the most vulnerable or exposed to highest risk. Interestingly, the two sub-districts are spatially contiguous and geographically similar. This is also similar for other sub-districts of IBD. The difference between the results of the AR4 and AR5 approaches is the change in sub-district level relative ranking. This suggests a link between the new concept of risk (AR5) and the existing concept of vulnerability (AR4).

The focus of the IPCC AR5 is on the system (exposure) and not on the impact(s) of hazard on the system. This is considered as an advantage of AR5 over the AR4 framework. The concept of vulnerability in AR5 is presented as not-dependent on exposure and hazard [119]. IPCC AR5 framework helps to identify the adaptation measures based on the current weaknesses of a system, and also shows the climate-resilient pathways that can reduce the climate change impacts [120]. It can be said that IPCC AR5 offers a robust approach for vulnerability and risk reduction under an uncertain future.

This study can help to prepare location specific emergency plans/responses to combat hazards associated with climate change and variability. These responses could be in the form of implementation of a forecasting system for extreme weather events in combination with grass root dissemination of these forecasts. The construction of multipurpose cyclone and flood shelters would help improve the resilience of impacted communities. Other response strategies such as retreat and realignment of embankments, mangrove plantations, introduce sluicing of smaller creeks could be also implemented at the local level.

Scaling up existing central and state government schemes by mechanisms such as sustainable agricultural practices, diversification to off-farm activities, seasonal employment schemes in agriculture to support to farmers/marginal workers 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 inherent vulnerability of a system. By doing so, it will also address the socio-economic and environmental issues that threatens the lives of the inhabitants of in climate-sensitive areas of IBD and drives distress migration as a response to recurrent extreme events such as cyclones, floods. In situ responses such as safe drinking water, sanitation facilities, primary health services, multiple livelihood options through skill development projects, eco-tourism development may help to improve the standard of living of residents and reduce the overall vulnerability and risk.

Author contributions

SD contributed to conception and data collection, data analysis and manuscript preparation.

AG, SS prepared the maps.

SH, TG, RSC provided critical contributions to the final version of the manuscript.

Declaration of competing interest

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.

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