Estimate the coastal vulnerability in the Balasore Coast of India: a statistical approach

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Abstract The vulnerability analysis is an estimation of the degree of loss or damage that would result from the occurrence of a natural phenomenon of given severity. Here, we can estimate the area of land vulnerable to loss, the number of displaced resident population considered at risk and the cost of protective engineering structures vulnerable to wide range of risk for any coastal extreme events. The present study therefore is an endeavour to develop a probability of coastal vulnerability (p) and their intimate coastal vulnerability score (CVS) for the coastal blocks of maritime Balasore block in Odisha considering the change of four resources (land, water, house/shelter and transport) during pre and post status of coastal extreme events like cyclone, flood, storm surges, beach erosion, wave action and salinity problem, which are frequent in nature at the low lying coastal stretch. In this study it emphasises on five groups that are likely to have least

protection against hazard. Nature and composition of such highly vulnerable groups may vary from place to place and situation to situation. Zones of vulnerability to coastal natural hazards of different magnitude are identified and shown on C.D block map with Gram Panchayat level. However, principle of binomial test (as applied in sign test) can be use for determining the probability with respect to each of the selected variables using the mean effects of those said coastal extreme events data base. After getting the vulnerability of probability, it has been multiplying with the respective population data to calculate the CVS of a particular coastal Gram Panchayat (considered spatial scale to study). This is the first such study that has been undertaken for a part of the Balasore coast. The map prepared for the Balasore coastal district under this study can be used by the state and district administration involved in the disaster lessening and executive plan.

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Introduction

The IPCC definitions of vulnerability to climate change, and its related components (exposure, sensitivity, and adaptive capacity) provide a suitable starting position to explore possibilities for vulnerability assessment but they are not operational. Therefore, a vulnerability assessment should start by defining the policy or scientific objective as clearly as possible, and to choose the scope and methods accordingly. Key questions in the scoping phase include: What is vulnerable or what specific parts of the system are most vulnerable? Which impacts are relevant? Vulnerable to what climate change effects? What is the timeframe

(time scenario) involved in the vulnerability assessment? Indeed the operational definition of the vulnerability concept is related to the specific issue and/or context (e.g. the coastal area) addressed by the analysis, also implying that spatial and temporal variations of vulnerability in general and coastal hazard vulnerability in particular are taken into consideration. Hegde and Reju (2007) developed a coastal vulnerability index for the Mangalore coast using geomorphology, regional coastal slope, shoreline change rates and population. However, they opined that additional physical parameters like wave height, tidal range, probability of storm, etc., can enhance the quality of the CVI. Gornitz (1990) assessed the vulnerability of the east coast of the United States with emphasis on future sea level rise. Dominey-Howes and Papathoma (2003) applied a new tsunami vulnerability assessment method to classify building vulnerability (BV) by taking the worse case of the tsunami scenario of 7 February 1963, for two coastal villages in the Gulf of Corinth, Greece. The result showed 46.5 % of all buildings are classified as highly vulnerable (BV) and 85 % of all businesses are located within buildings with a high BV classification and 13.7 % of the population is located within buildings with a high BV class. Rajawat et al. (2006) delineated the hazard line along the Indian coast using data on coastline displacement, tide, waves, and elevation. Pradeep Kumar and Thakur (2007) assessed the role of bathymetry in modifying the propagation of the tsunami wave of 26 December 2004 and concluded that undersea configuration has an important role in enhancing the wave height because some coastal stations on the eastern margin of India have suffered maximum damage wherein bathymetry has shown an anomalous pattern. Dinesh Kumar (2006) used sea-level rise scenario for calculating the potential vulnerability for coastal zones of Cochin, southwest coast of India, and concluded that climate induced sea-level rise will bring profound effects on coastal zones. Belperio et al. (2001) considered elevation, exposure, aspect, and slope as the physical parameters for assessing the coastal vulnerability to sea-level rise and concluded that coastal vulnerability is strongly correlated with elevation and exposure, and that regional scale distributed coastal process modelling may be suitable as a “first cut” in assessing coastal vulnerability to sea-level rise in tide-dominated, sedimentary coastal regions. Thieler and Hammar-Klose (1999) used coastal slope, geomorphology, relative sea-level rise rate, shoreline change rate, mean tidal range, and mean wave height for assessment of coastal vulnerability of the U.S. Atlantic coast. The result showed that 28 % of the U.S. Atlantic coast is of low vulnerability, 24 % of the coast is of moderate vulnerability, 22 % is of high vulnerability, and 26 % is of very high vulnerability. Pendleton et al. (2005)

assessed the coastal vulnerability of Golden Gate National Recreation area to sea level rise by calculating a coastal vulnerability index (CVI) using both geologic (shoreline-change rate, coastal geomorphology, coastal slope) and physical process variables (sea-level change rate, mean significant wave height, mean tidal range). The CVI allows the six variables to be related in a quantifiable manner that expresses the relative vulnerability of the coast to physical changes due to future sea-level rise.

Study area

The area under study in this paper constitutes part of the alluvium coast of the Burahbolong delta plain. It extends from the mouth of the Burahbolong river to the Rasalpur-I Gram Panchayat along the Bay of Bengal coast of Odisha. The study area lies between 87°5'45"E to 87°25'37"E and 21°12'25"N to 21°32'55"N in Fig. 1. The area is a coastal alluvial tract with unconsolidated substrates, and this stretch of the coastline is geomorphologically dynamic, rich in habitat diversity, and prone to hazards such as tropical cyclone-induced tidal waves, storm surges, and consequent coastal flooding.

The land consists of a monotonously flat alluvium surface that lies between 2.5 and 3.5 m above mean sea level (MSL). Geologically, the area is characterized by ordinary alluvium deposits of Holocene to recent origin that were brought down by the Burahbolong, Dugdugi, Hanskara and Subarnarekha river. The area has a natural gradient that runs from the east to the southeast direction, which is followed by the Subarnarekha river. The study area is covered mostly by sandy clay and silty loam soils that developed under a brackish environment. The pH of the soil varies between 6.5 and 8.0 (pre-monsoon season), and 6.2 and 8.2 (post-monsoon season). This type of soil has a high water retaining capacity. Climatic variations of the study area are more significant between monsoon and pre-monsoon seasons. The temperature varies from a minimum of 9 °C in winter to a maximum of 38 °C in summer. Relative humidity ranges between 90 and 96 % in most of the months. Low atmospheric pressure is often present during the summer and monsoon period. Wind dominantly blows in from offshore areas. There is no extensive forestland in the study area and natural vegetation primarily consists of grasses (e.g., *Sesuvium portulacastrum* and *Ipomoea bioloba*) and herbs (e.g., *Lantana camara*, *Acanthaceae* sp., and *Calotropis gigantea*). Trees like *casuarina*, *eucalyptus*, and *Acacia auriculiformis* have been planted in this area, while coconut, banana, bamboo and mango are indigenous floral species.

Fig. 1 Study area extending from 87°5'45"E to 87°25'37"E and 21°12'25"N to 21°32'55"N

Methods and materials

Vulnerability is a term that is essential to the full understanding and efficient management of risk and vulnerability analysis is an important stage of risk assessment. Vulnerability is defined as the characteristics of a person or group and their situation that influence their capacity to anticipate, cope with, resist and recover from the impact of natural hazards. Vulnerability is understood as the combination of societal, economic and environmental issues which give way to the natural hazards to become a disaster. Social characteristics like gender, age, occupation, marital status, race, ethnicity, religion of the people exposed to a hazard determine their loss, injury sufferings, life chances etc. Different types of vulnerability have been recognized by Aysan (1993) viz. economic vulnerability (poor access to resources); social vulnerability (weak social structure and deterioration of social relations); ecological vulnerability (degradation of environmental quality);

organizational vulnerability (lack of national and local institution); attitudinal vulnerability (lack of awareness); political vulnerability (lack of political power); cultural vulnerability (some orthodox beliefs and customs) and physical vulnerability (weak buildings and structures). The poorest and marginal people in a society to live with perpetual indebtedness, malnutrition, ill health, unhygienic living environment and violence are highly vulnerable in the face of a hazard. Therefore, any additional stress like loss of land, shelter, occupation, assets caused by hazard place those people in catastrophe. The operational model that helps in assessing risk as well vulnerability is as under.

$$R = f_1 \{ \text{Hazard (H), Vulnerability (V), Exposure (Ex)} \}$$

$$V = f_2 \{ \text{Social (S), Economic (E)} \}$$

$$S = f_3 \{ \text{Poverty (P), Education (Ed), Health quality (Q), Population (P)} \}$$

$$E = f_4 \{ \text{GDP, Income Level (IL), Indebtedness (ID)} \}$$

Information required for vulnerability analysis is summarized in the Table 1. In this study it emphasises

Table 1 The data acquisition format where symbols are used to signify whether a particular group is likely to experience enhanced (+), reduced (−) or no change (0) in its situation in accessing the resources. But the '0's are not considered because they are not significant with respect to vulnerability

Access to	Potential vulnerable groups											
	Poorest (33 %)				Middle (33 %)				Richest (33 %)			
	Women	Child	Elder	Minority	Women	Child	Elder	Minority	Women	Child	Elder	Minority
Respondent's perception in regard to change in condition between pre and post disaster event												
Responses'	+	0	+	−	0	+	0	−	+	0	+	−
Land	+	−	0	+	+	−	0	−	+	+	0	−
Water	+	+	0	−	+	0	−	+	+	0	−	+
House/-shelter	+	+	0	−	+	0	−	+	+	0	−	+
Trans-port	+	+	0	−	+	0	−	+	+	0	−	+

If the researcher understands that there is really no change in any variable at the face of hazards then he can put '0' in calculating vulnerability

on five groups that are likely to have least protection against hazard. Nature and composition of such highly vulnerable groups may vary from place to place and situation to situation. The disparities among the vulnerable groups in accessing four types of resources (land, water, house/shelter, and transport) in the wake of a disaster event helps in assessing socio-economic vulnerability of a particular community. The symbols are used in this study to indicate whether a meticulous group is probable to incident enhanced (+), reduced (−) or no change (0) in its circumstances in accessing the possessions. But the '0's are not well thought-out since they are not considerable with deference to their vulnerability. If the researcher understands so as to there is actually no change in any variable at the face of hazards then he can put '0' in calculating vulnerability in Table 2.

Obvious that, the data are ordinal scaled and not normally distributed. Hence, one can use the principle of binomial test (as applied in sign test) for determining the probability of positive or negative changes between pre- and post-event situations with respect to each of the selected variables. The probability for the k number of positive (or negative) observations is given by

Probability mass function

In general, if the random variable X follows the binomial distribution with parameters n and p , we write $X \sim B(n, p)$. The probability of getting exactly k successes in n trials is given by the probability mass function:

$$f = (k; n, p) = \Pr(X = k) = \binom{n}{k} p^k (1 - p)^{n-k} \quad (1)$$

for $k = 0, 1, 2, \dots, n$, where

$$\binom{n}{k} = \frac{n!}{k!(n-k)!} \quad (2)$$

This is the binomial coefficient, hence the name of the distribution. The formula can be understood as follows: we want k successes (p^k) and $n - k$ failures $(1 - p)^{n-k}$. However, the k successes can occur anywhere among the n trials, and there are $\binom{n}{k}$ different ways of distributing k successes in a sequence of n trials.

In creating reference tables for binomial distribution probability, usually the table is filled in up to $n/2$ values. This is because for $k > n/2$, the probability can be calculated by its complement as

$$f(k, n, p) = f(n - k, n, 1 - p) \quad (3)$$

Table 2 The binomial test results for each of the variables under every resource type and values are to be added to get the probability of vulnerability of a particular group

Block	G.P Code	Observation Station, G.P	Total population	Probability of vulnerability	Coastal vulnerability score
Balasore	1	Rasalpur 1	7973	0.394687	3146.839451
	2	Sashanga	4302	0.245436	1055.865672
	3	Joydebkasba	8717	0.394687	3440.486579
	4	Saragaon	5609	0.22097	1239.42073
	5	Genguti	9265	0.22097	2047.28705
	6	Gudu	699	0.245436	171.559764
	7	Padmapuri	4904	0.245436	1203.618144
	8	Ranasahi	6908	0.394687	2726.497796
	9	Patrapada	619	0.245436	151.924884
	10	Parikhi	11349	0.394687	4479.302763
	11	Bahabalpur	10650	0.394687	4203.41655
	12	Gopinathpur	5814	0.245436	1426.964904
	13	Chhanua	7697	0.245436	1889.120892
	14	Sindhia	10450	0.245436	2564.8062
	15	Olanda saragaon	8088	0.245436	1985.086368
	16	Odangi	4348	0.22097	960.77756
	17	Nagram	6769	0.22097	1495.74593
	18	Baunla	6013	0.22097	1328.69261
	19	Haldipada	9034	0.221121	1997.607114
	20	Kasipada	13158	0.221121	2909.510118
	21	Sartha	15900	0.394687	6275.5233
	22	Kashaphala	10301	0.394687	4065.670787
	23	Srirampur	7850	0.394687	3098.29295
	24	Rasalpur 2	4801	0.22097	1060.87697
	25	Hidigaon	6113	0.394687	2412.721631
	26	Srikona	12118	0.394687	4782.817066
	27	Kuradiha	4748	0.22097	1049.16556
		Balasore Town	66986	0.24246	16241.42556

Vulnerability score of the Grampanchayat can be determined by adding up the product of probability of vulnerability for the group and their total population

Looking at the expression $f(k, n, p)$ as a function of k , there is a k value that maximizes it. This k value can be found by calculating

$$\frac{f(k+1, n, p)}{f(k, n, p)} = \frac{(n-k)p}{(k+1)(1-p)} \quad (4)$$

and comparing it to 1. There is always an integer M that satisfies

$$(n+1)p - 1 \leq M < (n+1)p. \quad (5)$$

$f(k, n, p)$ is monotone increasing for $k < M$ and monotone decreasing for $k > M$, with the exception of the case where $(n+1)p$ is an integer. In this case, there are two values for which f are maximal: $(n+1)p$ and $(n+1)p - 1$. M is the *most probable (most likely)* outcome of the Bernoulli trials and is called the mode. Note that the probability of it occurring can be fairly small.

Cumulative distribution function

The cumulative distribution function can be expressed as:

$$F(k; n, p) = \Pr(X \leq k) = \sum_{i=0}^k \binom{n}{i} p^i (1-p)^{n-i} \quad (6)$$

where $q = (1-p)$ where $[k]$ is the “floor” under k , i.e. the greatest integer less than or equal to k . It can also be represented in terms of the regularized incomplete beta function, as follows:

$$\begin{aligned} F(k; n, p) &= \Pr(X \leq k) \\ &= I_{1-p}(n-k, k+1) \\ &= (n-k) \binom{n}{k} \int_0^{1-p} t^{n-k-1} (1-t)^k dt. \end{aligned} \quad (7)$$

where n = number of observations, $p = 0.05$ probability of positive changes = 0.5 and $q = 0.5$ probability of negative changes. Thus calculated probabilities may be expressed in zero to unity. The test is to be conducted for each of the variables under every resource type and values obtained are to be added to get the vulnerability of a particular group. Spatial vulnerability of the Gram Panchayat can be determined by adding up the product of vulnerability value for the group and their percentage in the total population in Table 2 of Balasore coastal region.

Results

In this study, we investigated how coastal vulnerability and their probability vary across the local GPs in the Balasore sadar block in Odisha, India. All of the 27 (including Balasore town) GPs in the study area were classified into five categories of a probability of coastal vulnerability (p) and their intimate coastal vulnerability score (CVS), which ranged from a very low vulnerability through intermediate classes to a very high vulnerability (Tables 3, 4, respectively). Accordingly, maps were prepared on the basis of the calculated probability of coastal vulnerability (p) and their intimate coastal vulnerability score (CVS), for each of the GPs to visualize the spatial variability of probability of vulnerability and vulnerability score within the block in Figs. 2 and 3, respectively. The results showed that the probability of their associated vulnerability ranges from 0.22 to 0.39 for entire 27 GPs and one municipality. In this regards, Saragaon (4), Genguti (5), Odangi (16), Nagram (17), Baunla (18), Rasalpur-II (24), Kuradiha (27) of Balasore block fell into Very –low probability of coastal vulnerability. In contrast, the Rasalpur-I (1), Joydebkasba (3), Ranasahi (8), Parikhi (10), Bahabalpur (11), Sartha (21), Kashaphala (22), Srirampur (23), Hidigaon (25), and Srikona (26) of Balasore block is under Very high probability of coastal vulnerability. Remaining GPs chop down

into intermediate classes according to their probability value of vulnerability that were calculated.

The present study therefore is an endeavour to develop a probability of coastal vulnerability (p) and their intimate coastal vulnerability score (CVS) for the maritime Balasore sadar block of Odisha using land, water, house/shelter and transport resources. Most of these parameters are dynamic in nature and require a large amount of data from different sources. Zones of vulnerability to coastal natural hazards of different magnitude (very high, high, moderate, low and very low) are identified and shown on Fig. 3. In this veneration, only Balasore town (Municipality) has experiences very high vulnerability score.

In contrast, Sashanga (2), Saragaon (4), Gudu (6), Padmapuri (7), Patrapada (9), Gopinathpur (12), Odangi (16), Nagram (17), Baunla (18), Rasalpur-II (24) and Kuradiha (27) of Balasore block is underneath Very low vulnerability scores. Lingered GPs split down into intermediate classes according to their vulnerability scores that were calculated.

For GPs like Rasalpur-I (1), Joydebkasba (3), Ranasahi (8), Parikhi (10), Bahabalpur (11), Sartha (21), Kashaphala (22), Srirampur (23), Hidigaon (25), and Srikona (26) of Balasore block having very high probability of vulnerability even though these areas experienced high to moderate vulnerability score due to their uneven population distribution, on the other hand, Balasore town has a moderate probability of vulnerability but it's very high population density, which transform it as very high vulnerability area concerned.

The present study also showed that some of the GPs like Saragaon (4), Genguti (5), Odangi (16) Nagram (17), Baunla (18), Rasalpur-II (24), Kuradiha (27) of Balasore block have very high probability of their associated vulnerability but, in spite of very high probability of their associated vulnerability only due to their less population which is not accelerated to become high vulnerable score in respective GPs. Similarly, having the moderate or

Table 3 Grampanchayat wise probability of coastal vulnerability with their assigned attribute grouping into five classes

Probability of vulnerability occurrence	Assigned attribute	Block	G.P code	Identified G.P
0–0.22	Very low	Balasore	1, 3, 8, 10, 11, 21, 22, 23, 25, 26	Rasalpur 1, Joydebkasba, Ranasahi, Parikhi, Bahabalpur, Sartha, Kashaphala, Srirampur, Hidigaon, Srikona
0.22–0.221	Low	Balasore	2, 6, 7, 9, 12, 13, 14, 15	Sashanga, Gudu, Padmapuri, Patrapada, Gopinathpur, Chhanua, Sindhia, Olanda Saragaon
0.221–0.242	Moderate	Balasore	Balasore town	Balasore town
0.242–0.245	High	Balasore	19, 20	Haldipada, Kasipada
0.245–0.394	Very high	Balasore	4, 5, 16, 17, 18, 24, 27	Saragaon, Genguti, Odangi, Nagram, Baunla, Rasalpur 2, Kuradiha

Table 4 Grampanchayat wise distribution of coastal vulnerability scores (CVS) with their assigned attribute assemblage into five classes

Coastal vulnerability score (CVS)	Assigned attribute	Block	G.P code	Identified G.P
151.92–1520.27	Very low	Balasore	2, 4, 6, 7, 9, 12, 16, 17, 18, 24, 27	Sashanga, Saragaon, Gudu, Padmapuri, Patrapada, Gopinathpur, Odangi, Nagram, Baunla, Rasalpur 2, Kuradiha
1520.27–2412.71	Low	Balasore	5, 13, 15, 19, 25	Genguti, Chhanua, Olanda Saragaon, Haldipada, Hidigaon
2412.71–3542.32	Moderate	Balasore	1, 3, 8, 14, 20, 23	Rasalpur 1, Joydebkasba, Ranasahi, Sindhia, Kasipada, Srirampur
3542.32–6275.52	High	Balasore	10, 11, 21, 22, 26	Parikhi, Bahabulpur, Sartha, Kashaphala, Srikona
6275.52–16241.40	Very high	Balasore	Balasore town	Balasore town

Fig. 2 Probability of coastal vulnerability map is to be prepared for each of the variables under every resource type and values obtained are to be added to get the probability of vulnerability of a particular group

intermediate probability of its associated vulnerability, Balasore town has got very high vulnerability scores. So as to clear that high populated GPs possesses more vulnerable than less one.

According to respondents, the land, house/shelter and transport system damage intensities of pre and post hazard events were very high in the coastal facing GPs and the

GPs, located along the river bank, because these regions were mostly used for the purpose of agriculture and aquaculture practices. Settlements near these areas are located on the top of the back barrier dune to escape the frequent flooding. Conversely, the coastal GPs with interior settlement locations mostly suffered from drinking water and road damage because this area is densely populated.

Fig. 3 Coastal vulnerability score map of different Grampanchayat can be determined by adding up the product of probability of vulnerability for the group and their total population

Discussion

Geomorphologically and ecologically, in attendance the study area belongs to the Burahbolong delta Chenier plain along down the eastern bank of the Burahbolong river. The area is represented by regressive younger back beach ridges and open land ward mudflats and floodplains come into viewing as low lying zones are frequently renewed into customary agricultural fields.

The southernmost seafront part of the Balasore district is self-possessed of seashore beach barrier intricate and washes down over put down. Generally speaking, the Balasore district is dominantly a part of the Subarnarekha flood plain so as to fashion for the reason that of the westward avulsion of the river and exchanges among marine transgression processes. Enormous supplies of sediments and predominant wave-tide dynamics were conscientious intended for the development of this sandy flat and dreary area, which is delimited by the Subarnarekha river in the east, the young chenier complex to the west and north, and the beach barrier complex and

wash over deposits to the south. The geomorphological signatures in the region suggest that this coastal area has probably started to experience a phase of marine transgression. The frequency and intensity of cyclones have increased to a certain extent. Cyclone-induced storm surges and torrential rain in the upper catchment of the Burahbolong river have been found to be responsible for storm induced flooding in the study area and the intensity and severity of the coastal hazards have increased possibly due to recent climate driver and environmental changes. Moreover, the Subarnarekha, Dugdugi and Burahbalam river carries large volumes of discharge loaded with enormous quantities of sediment. This discharge flow receives resistance to their drainage from a number of factors including the strong southwesterly monsoon wind and resultant cross-shore current, waves and high magnitude tidal inflows. These conditions cause the accumulation of large amounts of water at and near the mouth of the Burahbalam river, which causes flooding at the sea front GPs of the study area. Moreover, this area is only 0.5–1 m above sea level, which makes the area more vulnerable to

flooding and cyclone induced storm surge as well as beach ridge breaching. The landward margin of the studied blocks is characterized by an intricate network of tidal inlets along which sea water can enter into the nearby GPs and cause flood during the peak monsoon phase and cyclones. The above stated GP is barely exposed to the sea with scrappy sand dunes. An earthen embankment was once built to protect the Rasalpur-I GP of Balasore block from flood hazards, but it has been completely washed away by episodic strong sea waves and only remnants of its basement can be found in a few places on the beach. Sparse mangrove patches, which were present in this area a few years ago, have disappeared because of changes in sedimentological properties of the shore deposits that constitute substrates for mangrove swamps. Landuse patterns in the area have also undergone recent changes that have increased the probability for flooding.

The coastal facing GPs with estuarine location become flooded in two different ways. The first is due to the spilling of the said rivers (sweet water flood) and the second is caused by coastal flooding (saline flood) from high magnitude waves or storm surges. Moreover, these GPs are densely populated mainly owing to people here have easy access to marine resources, which the coastal dwellers utilize for their livelihoods. Therefore, hazards damages in those GPs are usually very high even in the event of moderate intensity floods.

Land use alteration in the studied blocks is likely responsible for frequent flooding in the area. Aquaculture has recently emerged as a profitable economic activity. Hence, vast stretches of land have been converted to fish farms. At these fish farms, high earthen embankments have been constructed around the fish ponds that restrict the spread of flood water over the flood plain; this has caused the flooding situation to become more severe. River engineering in the form of embankment construction along both banks of the Burahbolong and other said rivers have also changed the hydro-geomorphological conditions in this region. These river embankments restrict sedimentation to within the area between the banks and leave no extent for sediments to distribute over the floodplain. Ultimately, this has reduced the capacity of the river valley to retain flood water and has resulted in large deposits of sediment near the river mouth, which has caused a gradual narrowing of the channel.

Conclusion

The Balasore block in Odisha, India, consists of 27 GPs with a municipality that are to be found on the coastline and the banks of the Burahbalam rivers. This areal vicinity

is geomorphologically susceptible to coastal hazards and lying face down to recurrent cyclones and associated natural exposures. Spatial changeability of coastal vulnerability among the GPs was assessed quantitatively by considering both the probability of vulnerability and intimate populations of concerned GPs.

The analysis clearly demonstrated that the GPs located along the river bank and those exposed to the sea because of the lack of natural barriers have very high probability of vulnerability, whereas GPs in interior locations are generally in zones of lower probability of vulnerability. The gradual decline in the capacity of the Subarnarekha, Dugdugi and Burahbalam rivers to hold large volumes of water mass received from high-magnitude storm events has augmented this vulnerability. The situation has become super critical during monsoons when the inflow of tidal water along the river channel raises the water levels. Storm surges during cyclonic episodes and high astronomical tides also lead to the build-up of ocean water that can enter the area along tidal inlets. The last two processes were responsible for exacerbating previous floods in many of the GPs under study. Moreover, embankments used in aquaculture around fish ponds may be responsible for intensifying the severity of the coastal hazards as well as vulnerability. Variation was also observed among the GPs with respect to the probability of vulnerability. The results from this study show that having the high probability of vulnerability of some GPs, their vulnerability score is lower only owing to its less population.

Overall, the essence of this work lies in the fact that it explores the cause and consequences of coastal vulnerability in a quantitative manner through the use of probability of vulnerability and intimate population. In addition, this study was done at a convincingly small spatial scale (GPs wise), where it may be feasible to put into practice coastal vulnerability lessening programs. Specifically, the results from this study may help environmental managers to better understand coastal vulnerability in different local GPs in the Balasore sadar block in Odisha, India. Notably, the probability of vulnerability of pre and post events in terms of changes in said four resources does not always linearly dependent on the physical severity of the coastal extreme events. As such, the results from this study may be helpful for identifying factors that improve resilience and can be incorporated into future planning decisions for coastal vulnerability management. Moreover, this type of study can be carried out for other coastal district as well as block level, which would be allowed for the creation of more comprehensive coastal vulnerability maps and a better assessment of the risks associated with coastal vulnerability.

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