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Multi-hazards Coastal Vulnerability Assessment of Goa, India, using Geospatial Techniques

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ABSTRACT

The state of Goa in West India has a 105 km long coastline with beaches and cultural heritage sites of significant importance to tourism. The increasing incidence of tropical cyclones in the Arabian Sea in recent decades and the devastating impacts of the December 2004 tsunami in India stressed the importance of assessing the vulnerability of coastal areas to flooding and inundation, notably in view of climate change induced sea-level rising (SLR). This study aims to develop a Coastal Vulnerability Index (CVI) for the state of Goa and to use this index to examine the vulnerability of the different administrative units of the state, known as *talukas*. This is accomplished by using seven physical and geologic risk variables characterising the vulnerability of the coast, including historical shoreline change, rate of relative sea-level change, coastal regional elevation, coastal slope, mean tidal range, significant wave height, and geomorphology using conventional and remotely sensed data, in addition to two socio-economic parameters: population and tourist density data. Using a composite CVI based on those relative risk variables, each of the seven coastal *talukas* was categorised according to its vulnerability. The resulting vulnerability map depicts the *talukas* that are the most and least vulnerable to erosion, flooding and inundation of coastal lands, and that the inclusion of socio-economic parameters influences the overall assessment of vulnerability. This study provides information aimed at increasing awareness amongst decision-makers to deal with disaster mitigation and coastal zone management, and is a first step towards prioritising areas for climate change adaptation in view of the projected SLR and increased storminess.

1. Introduction

History shows a long and intrinsic relationship between coastal areas and human settlements (UNEP, 2005). In India, about 25 percent of the population lives within 50 km of the coast (Krishna, 2005). The coastal regions of India are under serious threat from tropical cyclones and tsunamis (Chaudhuri et al., 2013), whose destruction and loss of human life is mainly attributed to flooding as a result of a storm surge (Sindhu and Unnikrishnan, 2012). In the North Indian Ocean, tropical cyclones form over both the Arabian Sea and the Bay of Bengal (Chaudhuri et al., 2013). West India is impacted by tropical cyclones originating from the southeast Arabian Sea where one or two tropical cyclones form every year (Evan and Camargo, 2011). The west coast of India is also impacted by cyclones originating over the Bay of Bengal. However, these storms weaken after making landfall and travelling across the Indian subcontinent. Two recent tropical cyclones that formed in the Arabian Sea are Gonu and Phyan. Gonu, which developed in June 2007, and made landfall in Oman, is the strongest tropical cyclone on record in the Arabian Sea (Fritz et al., 2010). Phyan formed on November 4, 2009, and caused intensified waves and a moderate storm surge along west coast of India (Joseph et al., 2011).

Tsunamis refer to a vertical displacement of a water column as a result of an earthquake, volcanic eruption, or submarine mudslide (Krishna, 2005). Tsunamis are rare in the Indian Ocean in comparison to the Pacific Ocean. Nonetheless, past records show that parts of the Indian coastline have been inundated as a result of tsunamis (Patel et al., 2013). For instance, in 1945, a giant tsunami generated in the Arabian Sea affected the Makran coast in Pakistan with waves traced back to Mumbai and the coast of Goa (Jordan, 2008). However, except for the occurrence of these disastrous events, there is no detailed documentation either on the impact or magnitude of the disasters.

Although the frequency of tropical cyclones and the associated storm surge and coastal flooding is lower in the Arabian Sea than the Bay of Bengal (Dube et al., 1997), the recent occurrence of cyclones of the magnitude of Gonu and Phyan reminded residents and policy officers of the vulnerability of the coastal regions of western India to such hazards. In addition, the tsunami of December 2004 and its devastating impacts on the coastal zone reminded the country of its lack of preparedness to natural hazards (Krishna, 2005), and stressed the importance of performing scientific studies on its vulnerability to such coastal hazards, particularly in view of climate change induced sea–level rising (SLR) and an increasing coastal population, as well as the demand for reliable information from community residents, developers, and government decision-makers (Kumar and Kunte, 2012). One way to address this stakeholders' need is to classify coastal lands according to their sensitivity to erosion, flooding, and inundation. In the past, the major constraint in undertaking vulnerability assessments has been a lack of data (Sterr et al., 2003). However, recent advances in spatial data gathering and processing techniques, including satellite remote sensing and Geographic Information Systems (GIS), have helped to overcome this barrier.

There are numerous definitions of vulnerability. The Intergovernmental Panel on Climate Change (IPCC) defines vulnerability as a function of exposure, sensitivity, and adaptive (or coping) capacity (Das, 2012). Exposure in this case refers to frequency and magnitude of a climatic event, for example, a drought, while sensitivity represents the degree to which the system under analysis is impacted by that exposure. The third element, adaptive capacity, represents the ability of the system to adapt to or recover from that exposure (Hahn et al., 2009).

According to the natural hazards' perspective, risk is the probability of an hazardous event to occur (Boruff et al., 2005), e.g. cyclone, tsunami, while vulnerability can be defined as the degree to which a person, community or a system is likely to experience harm due to exposure to that event (Kumar and Kunte, 2012). Vulnerability comprises a set of conditions and processes resulting from environmental and socio-economic factors that increase the susceptibility of a community to the impact of hazards, and can also encompass the notion of coping capacity of the community to respond to disasters (Mahendra et al., 2011). Vulnerability assessments are performed to estimate the degree of loss or damage that could result from a hazardous event of a given severity, including damage to infrastructure, interruption of economic activities, and impacts on livelihoods (Kumar and Kunte, 2012).

A common way to assess vulnerability is by using indicators, which are usually combined together in a composite index. An example of a composite index is the Human Development Index, which incorporates various national indicators, notably, life expectancy, health, education, and standard of living, to provide an overall picture of well-being for a particular country (Hahn et al., 2009). Indicators and indices are useful to provide a simple representation of a complex issue and to make comparisons across time and between regions (Heltberg and Bonch-Osmolovskiy, 2010). Coastal environments are exposed to multiple threats, and for this reason, assessing vulnerability in such environments has led to the construction of composite indices, with a common index known as the Coastal Vulnerability Index (CVI). Integrated indices such as the CVI enable information from various sources to be combined together. They represent a complex issue in a simple way and are therefore a useful prioritisation tool for policy officers (Addo, 2013).

Thieler and Hammer-Klose (1999, 2000a, b) used such a CVI based on the work of Gornitz et al. (1994) and Shaw et al. (1998) to assess the vulnerability of the Atlantic, Pacific and Gulf of Mexico coasts of the United States to SLR (Boruff et al., 2005). Their index incorporated six physical variables, i.e., historical shoreline erosion or accretion, rate of relative sea-level change, coastal slope, mean tidal range, mean wave height, and geomorphology, with the end product highlighting the coastal areas where the impacts of SLR are expected to be the most severe. A CVI was also developed by Pendleton et al. (2005) to assess the vulnerability of the coast of the Golden Gate National Recreation area in Northern California to SLR by ranking the same variables as Thieler and Hammer-Klose (1999, 2000a, b). The variables selected for the construction of both the index of Thieler and Hammer-Klose (1999, 2000a, b) and Pendleton et al. (2005) accounted for the exposure and sensitivity of the coastal zone to SLR, but without considering the capacity of the affected communities to adapt to the projected changes.

The CVI methodology initially developed for the continental United States was subsequently applied to coastal locations in Alaska (Gorokhovich et al., 2014), Argentina (Diez et al., 2007), Brazil (Szlafsztein and Sterr, 2007), the Canary Islands (Di Paola et al., 2011), China (Yin et al., 2012), Ghana (Addo, 2013), Greece (Doukakis, 2005a, b; Gaki-Papanastassiou et al., 2010; Karymbalis et al., 2012), the Philippines (Clavano, 2012), South Africa (Hughes and Brundrit, 1992; Palmer et al., 2011), Thailand (Duriyapong and Nakhapakorn, 2011), and Turkey (Ozyurt and Ergin, 2009, 2010). The majority of those studies used the same geologic and physical variables as Thieler and Hammer-Klose (1999, 2000a, b), or a number of them depending on data availability, while a few also incorporated mean elevation and geology, two risk variables used in the original CVI studies by Gornitz et al. (1991; 1994). In most studies, coastal vulnerability to SLR was determined on the basis of geologic and physical parameters only. However, vulnerability is also influenced by social, economic, and built-environment characteristics (Boruff et al., 2005).

Many studies that developed a physically-based CVI acknowledged the need to include demographic and economic variables to produce a more useful index (Clavano, 2012; Diez et al., 2007; Dominguez et al., 2005; Gornitz et al., 1994). For instance, Clavano (2012) suggested the inclusion of population density and coping capacity. Even though most of the socioeconomic variables influencing coastal vulnerability are known conceptually very few empirical studies incorporating human factors have been conducted (Boruff et al., 2005; Gorokhovich et al., 2014). Previous studies that included socioeconomic indicators in their vulnerability index include Boruff et al. (2005), Reyes and Blanco (2012), Szlafsztein and Sterr (2007), and Duriyapong and Nakhapakorn (2011). In these four studies a Socioeconomic Vulnerability Index (SVI) was linked to a physically-based CVI to assess the vulnerability of the coast of the 48 contiguous US states, a study site in the Philippines, the state of Pará in Brazil, and the Samut Sakhon coast of Thailand, respectively.

The SVI of Boruff et al. (2005) was based on Cutter et al. (2003) and incorporated 39 socioeconomic and demographic variables derived from the United States census; for example, median age of population, percent of elderly population, birth rate, ethnicity, per capita income, median rent or value of properties, percentage of population renting, housing unit density, and density of commercial development. Similarly, Reyes and Blanco (2012) computed their SVI using population and demographic data (i.e., age and gender), employment, and household size, but obtained it from questionnaires distributed to households in the study area. The index of Szlafsztein and Sterr (2007) also aimed to represent the adaptive capacity of the communities using population and demographic data such as population density, children population, elderly population, non-local population, as well as economic variables like poverty and municipal wealth.

The SVI of Di Paola et al. (2011), however, was different in its approach to the above three studies and was limited to four variables, namely population density, land use, roads and railways, and cultural heritage. These variables are similar to those of McLaughlin and Cooper (2010) who developed a CVI comprising three sub-indices, including a socioeconomic sub-index to assess the infrastructure potentially at risk to coastal hazards. The socioeconomic variables considered in this sub-index included those of Di Paola et al. (2011), i.e., population, land use, roads and railway, and cultural heritage, but also conservation status. Thatcher et al. (2013) examined the vulnerability of the northern Gulf of Mexico coast of the United States using socioeconomic in addition to physical factors, which included human population, urban land cover, economic value of key types of infrastructure such as energy infrastructure, location of essential facilities, and residential and commercial building values.

Including socioeconomic variables in a CVI had significant impact on the outcomes of a vulnerability assessment. For instance, Boruff et al. (2005) found that although physical factors were more influential in determining the vulnerability of the Atlantic and Pacific coastal counties to erosion, the social characteristics were more important in the counties along the Gulf of Mexico. Across the study area of Duriyapong and Nakhapakorn (2011), it was found that the socioeconomic variables made a larger contribution to the spatial variability of the CVI than the physical variables.

Duriyapong and Nakhapakorn (2011) suggested including the presence of existing structures for coastal protection in a CVI, which Di Paola et al. (2011) incorporated in the same year in an alternative methodology to the CVI and which was also considered, together with *engineered frontage*, in an index published the year before in Turkey (Ozyurt and Ergin, 2010). Infrastructural variables other than the presence of coastal protection structures, for example, can also influence positively the adaptive capacity such as proximity to a metallic road, which increases economic well-being (Das, 2012), and eases evacuation efforts during a disaster, for example.

Other projects have not included socioeconomic variables in their CVI *per se*, but compared the highly vulnerable areas identified by their CVI to the land use/cover of those areas in order to assess the socioeconomic impacts of SLR (Gaki-Papanastassiou et al., 2010; Karymbalis et al., 2012; Palmer et al., 2011). It is the presence of infrastructure or the perceived high value of the land use that influence the level of protection to an area at risk (Gornitz et al., 1994). Yin et al. (2012), in contrast, incorporated land use as one of the risk variable in a CVI applied to the Chinese coast rather than linking the outcome of the CVI to land cover/use.

In India, a number of studies have developed a CVI to examine vulnerability to coastal hazards and SLR (Table 1). Dwarakish et al. (2008; 2009) developed a CVI for the Udupi coast of the state of Karnataka in South West India. Their assessment used the same variables as Thieler and Hammer-Klose (1999, 2000a, b) in the United States, and included the rate of historical shoreline change and SLR, coastal slope, mean tidal range, wave height, and geomorphology. Sheik Mujabar and Chandrasekar (2011) and Joevivek et al. (2013) used the same geologic and physical variables as Dwarakish et al. (2008; 2009) to map the vulnerability of the southern Tamil Nadu coast to erosion while Nageswara Rao et al. (2009) used five of the six variables, omitting the rate of SLR in their development and application of a CVI to the Andhra Pradesh coast of India.

Other CVI studies performed in India incorporated additional risk variables to those included in Thieler and Hammer-Klose (1999, 2000a, b). Kumar et al. (2010) assessed the coastal vulnerability of the state of Orissa, East India, based on the same variables as Dwarakish et al. (2008; 2009), Sheik Mujabar and Chandrasekar (2011), and Joevivek et al. (2013), but also adding coastal regional elevation and tsunami run-up as additional parameters (Table 1). Mean elevation is a risk variable that was also incorporated in the original CVI studies by Gornitz et al. (1991; 1994), and which was also used in the CVI of other countries, notably by Di Paola et al. (2011) and Diez et al. (2007) in Argentina and the Canary Islands, respectively. Many studies did not include *elevation* but instead considered *coastal slope* in their CVI with areas of low coastal slope considered more vulnerable. However, this assumption does not always hold as areas of low coastal slope with high coastal regional elevation would not be as vulnerable as similar coastal segments of low coastal regional elevation. Hence, such inconsistency can only be addressed by incorporating both variables in a CVI (Kumar et al., 2010). Mahendra et al. (2011) examined the vulnerability of the Cuddalore-Villupuram coast in East India using a more limited number of variables than previous CVI studies, but adding information about extreme storm surges, a variable that was also considered by Kumar and Kunte (2012). Extreme storm surges was a variable preferred to tsunami run-up as the occurrence of the latter is rare and tsunamis are nonetheless included under the extreme storm surge parameter (Kumar and Kunte, 2012).

As mentioned above, many studies that developed a CVI acknowledged that the inclusion of socio-economic variables would contribute to the identification of vulnerable areas along the coast and add a different dimension to the analysis (Dominguez et al., 2005; Lichter and Felsenstein, 2012; McLaughlin et al., 2002). However, our review of the coastal vulnerability literature suggests that most studies using a CVI to assess the vulnerability of different coastal areas of India are limited to the incorporation of geologic variables, i.e., historical shoreline change, coastal slope, elevation, and geomorphology, which account for trends in erosion and accretion, the sensitivity of the coast to flooding, and the relative resistance of the shoreline to erosion, and physical variables, i.e., relative rate of SLR, mean tidal range, and mean wave height (Table 1), which influence the risk of coastal inundation (Dwarakish et al., 2009). Hedge and Reju (2007) is the only study accomplished to date in India that incorporated a socio-economic variable, i.e., population, in the development of a CVI. This study was not as comprehensive as others, however, as their CVI was limited to geologic variables and did not include any of the physical variables typically used in a CVI.

Although tropical cyclones and the associated storm surges are not as frequent in the Arabian Sea, which the state of Goa borders, as in the Bay of Bengal, major destructive storms have occurred in the past in this region (Dube et al., 1997; Kumar and Kunte, 2012). Moreover, a classification of the Indian coast into three categories based on its vulnerability to storm surge from wind data revealed that most of the West coast of India, including Goa, falls into the moderate risk category, which is a higher vulnerability category than many coastal areas on the Bay of Bengal (Dube et al., 1997). In addition, climate change and SLR will increase the impact of existing hazards as well as introducing new ones in some areas, for example, loss of land through increased erosion and inundation (Joevivek et al., 2013) as well as potentially causing changes in the frequency and intensity of severe storms (Doukakis, 2005b). These natural pressures on the coastal system are in addition to anthropogenic factors inducing erosion and the narrowing of the beach, notably as a result of tourism development and a growing coastal population.

The state of Goa, whose economy is closely related to coastal tourism, has to date not been included in any vulnerability study making use of a CVI. To help with decision-making, there is a need to develop CVIs at a scale appropriate for local management, as local or regional variations in vulnerability could be concealed if the analysis were performed at the state or national scale (McLaughlin and Cooper, 2010). Following a disaster, evacuation and relief efforts in Goa are undertaken at the *taluka* or village level and thus knowledge of the relative vulnerability of the coastal *talukas* comprising the state is important to decision-makers (Das, 2012). A *taluka* is an administrative unit hierarchically above the local city, town, or village, but subordinate to a larger district of the state, and thus contains a number of villages (Noronha et al., 2002). A vulnerability analysis at the *taluka* level would help understanding and mitigating coastal problems locally. Hence, this study aims to develop a CVI to examine the vulnerability of the different administrative units of the state of Goa to erosion, coastal flooding, and inundation as a result of coastal hazards such as tropical storms, tsunamis, and SLR. In addition, unlike most previous studies, the CVI developed as part of this study is not limited to geologic and physical risk variables, but also includes data on the distribution of the resident and tourist population. Hence, this paper also examines the importance of including these two socio-economic variables in the overall assessment of vulnerability.

Socio-economic variables, even if only information about the resident and tourist population, are important variables to consider when assessing vulnerability (Hegde and Reju, 2007). Population and tourist data can influence vulnerability in two opposing ways, however. On the one hand, an area with a greater population would generally be of higher economic value (Hughes and Brundrit, 1992), and lead to greater investment to protect properties (Hegde and Reju, 2007). It is the perception of the social and economic worthiness of the houses and infrastructure in a coastal region that will determine the level of efforts made to protect that area (Gornitz et al., 1994; McLaughlin et al., 2002). Areas frequented by international tourists are often more affluent than others, and have better infrastructure, communication, and transportation links, which affect the capacity of the community to respond to natural hazards (Krishna, 2005). Thus, population and tourist density data can contribute to the adaptive capacity component of a vulnerability assessment. In a state like Goa with a relatively high level of economic development in comparison to neighbouring states (Pillai et al., 2013), this information would thereby act to reduce the vulnerability of some coastal *talukas*. On the other hand, population and tourist density data can be can be interpreted as a direct 'erosion-inducing variable' and therefore exert a negative pressure on the coastal system (McLaughlin et al., 2002).

In India, Joevivek et al (2013) noted that sand dunes were destroyed for tourism development and coastal areas with high population density were causing erosion and decreasing the width of beaches. Hence, according to this perspective a region with a low population density would exert less (negative) pressure on the environment as opposed to one with a higher population density. Moreover, mangroves, which are well known to protect communities from coastal hazards are cut, dried and burned for cooking oil, which one could argue is an activity that would be more important in an area that is more populated. In addition, sand mining, which is associated with economic activities and indirectly with number of people, does increase the sensitivity of the coastal system to coastal hazards.

2. Study area

The study area stretches for 105 km along the coast of the state of Goa, which is situated in West India (Fig. 1). It is surrounded by the state of Maharashtra to the north, Karnataka to the east and south and the Arabian Sea to the west. Goa has a surface area of about 3,702 km^2, it is India's smallest state and in 2011 it had a total population of approximately 1.4 million inhabitants (Pillai et al., 2013). The coast line of Goa is characterized by headlands, bays, creeks, promontories, sea cliffs, estuaries, and world famous beaches (Chandramohan et al., 1997; Modassir and Sivadas, 2003). In fact, there are 17 sandy beaches in Goa of significant importance to tourism, for example, Baga, Calangute, and Anjuna in the state of Bardez, Miramar beach in Tiswadi, and Colva, the second longest beach of India, situated further south in Salcete (Fig. 1) (Chandramohan et al., 1997). The state of Goa is subdivided into 11 *talukas* with seven of them bordering the coast.

3. Material and methods

The methodology used in this paper followed the procedure of the United States Geological Survey (USGS) published in Thieler and Hammer-Klose (1999, 2000a, b). Accordingly, coastal vulnerability is assessed using a CVI, which is a composite of different risk variables, each of which capturing a specific characteristic of vulnerability. In this study, eight variables were considered in the creation of the CVI: the historical rate of shoreline change (erosion or accretion), rate of relative sea-level change, coastal regional elevation, coastal slope, mean tidal range, significant wave height, geomorphology, and socio-economic data. These are the same geologic and physical variables as used in the USGS studies with the exception of coastal regional elevation. Elevation was a variable used by Gornitz et al. (1991) and was also included in three other CVI studies in India (i.e., Kumar et al. (2010), Mahendra et al. (2010), and Kumar and Kunte (2012)). Geology is another risk variable included in the CVI of Gornitz et al. (1991) and which was incorporated in the CVI of a coastal region of Argentina (Diez et al.,

2007) and Ghana (Addo, 2013), for example; this variable was not incorporated in the USGS studies and is also not considered in this paper. Table 2 provides information on the source of data for each of the eight risk variables used in this study.

There are different ways to rank each of the variables in a CVI. The USGS methodology (Thieler and Hammer-Klose, 1999, 2000a, b) consists of ranking each variable on an ordinal scale from one to five. Most studies have followed this ranking procedure but without necessarily using the same range for the ranking of the risk variables. Even Pendleton et al. (2005) used different ranges for the vulnerability ranking of a number of variables depending on the geographical location of the national park under consideration. Other studies have also adopted the risk variables of Gornitz et al. (1991), i.e., substituting coastal slope for mean elevation and adding geology as an additional parameter, with a few of those studies using the same ranges as Gornitz et al. (1991) in the categorization of most risk variables (Addo, 2013; Di Paola et al., 2011; Diez et al., 2007). Nonetheless, no standards exist to determine what should be considered very low, low, moderate, high, or very high vulnerability and even some studies used a different number of risk rating categories than the USGS studies. For instance, Boruff et al. (2005) followed the USGS methodology but ranked the variables into four rather than five categories, while Kumar and Kunte (2012) classified the coastline of Chennai, India, into three vulnerability categories.

Gorokhovich et al. (2014) who applied the CVI methodology to the coast of Alaska is to the authors' knowledge the only study that directly applied the ranges of the risk variables as published in the USGS studies. The majority of previous studies based on the USGS methodology have modified the ranges of some variables under each risk ranking category (Duriyapong and Nakhapakorn, 2011; Dwarakish et al., 2008; Dwarakish et al., 2009; Gaki-

Papanastassiou et al., 2010; Hegde and Reju, 2007; Jana and Bhattacharya, 2013; Joevivek et al., 2013; Karymbalis et al., 2012; Nageswara Rao et al., 2009; Ozyurt and Ergin, 2010; Sheik Mujabar and Chandrasekar, 2011), as when the ranking is done relative to the entire region the resulting CVI was reported to be more useful to end-users (Clavano, 2012). An illustrative example is Karymbalis et al. (2012) who used a five risk ranking categorization but with the ranges of the risk ranking determined by taking into consideration the maximum and minimum values of each variable rather than using the ranges of Thieler and Hammer-Klose (1999, 2000a, b). Such an approach allows for the determination of the degree of risk of different coastal stretches relative to the average of the region under investigation but does not allow for direct comparison between regions.

In the current study, each quantitative variable was ranked into three categories according to the level of risk it represents: low, medium and high, with the ranges of each risk ranking category determined based on the maximum and minimum values and the average for the state as a whole. Such an approach was favoured as the purpose of this study was to rank the coastal *talukas* of Goa according to their relative vulnerability to erosion, coastal flooding, and inundation; nonetheless, the level of vulnerability for the different risk variables are compared throughout the paper with other coastal regions of India as reported in the literature. In the case of the rate of relative SLR, mean tidal range, and significant wave height, the entire coast of the state was assigned the same risk ranking category, as changes in those variables are marginal along the coast of Goa; this approach was also adopted in studies focusing in other regions of India (Kumar and Kunte, 2012; Kumar et al., 2010). The geomorphological variable was ranked qualitatively into the low, medium, and high risk category according to the resistance of the prevailing coastal landform to erosion. The calculations involved in the computation of each of the eight variables comprising the CVI are described below.

3.1 Rate of shoreline change

A change in the location of the shoreline is an indication of the sensitivity of the coast to erosion. Coastal erosion is considered a risk not only because it threatens buildings and infrastructure, but also because it degrades and diminishes the extent of the beach, potentially impacting negatively on tourism (Dominguez et al., 2005). This is unless the shoreline and beach is not obstructed from moving landward, which is often not the case in regions with a developed coast such as tourist destinations. The shoreline was digitised using data for the year 1973, 1989, and 2006 obtained from the Landsat MSS, Landsat Thematic Mapper (TM), and Enhanced Thematic Mapper (ETM+) satellite, respectively. These satellite images were processed using the ERDAS Imagine 9.2 software, which included image enhancement, geo-referencing, and band extraction, while GIS software (ArcGIS version 9.2) was used for vectorization of coastline and contours. These digitised shorelines (Fig. 2) were used as inputs into the Digital Shoreline Analysis System, which was downloaded from the USGS (2005) to calculate the rate of shoreline change.

The digitized shorelines for the year 1973, 1989, and 2006 along with a reference baseline were marked on a map (Fig. 2a) and used to calculate the rate of shoreline change. Different techniques can be used to calculate the rate of shoreline change, nonetheless all techniques involve the computation of the change in the position of the shoreline through time by drawing perpendicular transects to the baseline (Hegde and Reju, 2007). Accordingly, 300 m long transects at a spacing of 500 m were casted along the 105 km long shoreline of Goa with the help of the DSAS TOOLBAR in ArcGIS 9.3 (Fig. 2b). The different methods used to calculate the rate of shoreline change include the End Point Rate (EPR), as illustrated in Fig. 2c for the *taluka* of Pernem, Net Shoreline Movement (NSM), Average Of Rates (AOR), Linear Regression (LR), and Jackknife (JK) (Hegde and Reju, 2007). Figure 2d illustrates an example of the NSM, also for Pernem *taluka*. The advantage of the EPR method is its ease of computation, as it considers only two shoreline positions to calculate the rate of shoreline change (Dolan et al., 1991). At each transect along the shoreline, the NSM and EPR were estimated and the rate of shoreline change and associated risk ratings were calculated for each coastal *taluka*. Table 3 displays the rates of shoreline change corresponding to the low, medium, and high risk rating categories. According to this classification, areas with a shoreline change rate greater than 0.6 m/yr are given a high risk rating.

3.2 Rate of relative SLR

An important impact of climate change is SLR. This study defines mean sea level as the height of the sea with respect to a local land benchmark, averaged over a certain period, such as a month or a year, i.e., a period long enough so as to remove fluctuations caused by waves and tides (Kumar and Kunte, 2012; Kumar et al., 2010). With respect to vulnerability, coasts that are subject to a high rate of SLR are considered as highly vulnerable and vice versa. In the present study, the rate of SLR was computed using annual mean relative SLR rate data from tide gauge stations surrounding the Indian Ocean over the period 1969-2007.

3.3 Coastal regional elevation

Regional elevation refers to the average elevation of a particular coastal area above mean sea level. Coastal regional elevation is an important parameter in the analysis of coastal vulnerability as it provides an estimate of the extent of land threatened by projected SLR (Kumar and Kunte, 2012; Kumar et al., 2010), as well as the sensitivity of the coast to flooding during a storm surge (Diez et al., 2007) or tsunami. Hence, areas with high coastal elevation will be considered less vulnerable and vice-versa (Gornitz et al., 1994). The coastal regional elevation for the coast of Goa was determined using satellite data obtained from the Shuttle Radar Topography Mission (SRTM) for the year 2000. The procedure consisted of first generating elevation contours for the case study region using the SRTM data. Then, to calculate the coastal regional elevation parameter, coastal area extending inland from the shoreline was buffered and cropped using GIS. The average height of this entire coastal area was subsequently calculated as well as that of each *taluka.* Risk ratings were assigned for each *taluka* by comparing the average height of the coastal stretch of each *taluka* with that of the entire coastal area of the state.

3.4 Coastal slope

Bathymetry refers to the depth from the shoreline towards the open ocean. It is the essential baseline for all forms of hydrodynamic, wave, and inundation modelling as near-shore bathymetry decides the fate of waves as they approach the coast (Kumar and Kunte, 2012). Hence it is an important parameter to consider when estimating the extent of land at risk of flooding following a storm surge or tsunami (Krishna, 2005). The parameter *coastal slope* can be estimated using near shore bathymetry and loss of land due to inundation can be represented as a function of the coastal slope (Sterr et al., 2003), as locations with gentle slope values retreat faster than steeper ones (Gaki-Papanastassiou et al., 2010) and are more prone to flooding from storm surges and tsunamis (Kumar et al., 2010). Thus, coastal areas having gentle slopes are considered as highly vulnerable while areas of steep slope were given low risk rating.

Bathymetric data were obtained from the modified ETOPO2 dataset of the National Institute of Oceanography (NIO), Goa (India), which was derived from satellite altimetry (Sindhu et al., 2007). The procedure for calculating the coastal slope parameter consisted of first vectorizing the depth contours from the bathymetric map, and then a GIS-based Triangulated Irregular Network (TIN) model was developed after geo-referencing the data using the Universal Transverse Mercator (UTM) projection system together with World Geodetic System (WGS)-84 datum. The depth contours were drawn using a 5 m interval scale using the spatial analyst extension of ArcGIS 9.3 (Fig. 3). Using this depth contour map, the coastal slope was calculated at each *taluka* with the slopes categorised as high, medium or low risk rating according to the thresholds displayed in Table 3.

3.5 Mean tidal range

Tides are the result of the gravitational attraction of the moon and the sun and are therefore periodic and highly predictable (Kumar et al., 2010). Tidal range is defined as the vertical difference between the highest high tide and the lowest low tide and is linked to both permanent and episodic inundation hazards (Diez et al., 2007; Doukakis, 2005b; Kumar et al., 2010). From a vulnerability point of view, some studies have designated coastal regions with a high tidal range as highly vulnerable (Addo, 2013; Di Paola et al., 2011; Diez et al., 2007; Doukakis, 2005b; Duriyapong and Nakhapakorn, 2011; Gornitz et al., 1994; Kumar et al., 2010; Yin et al., 2012) while others, including the USGS studies, ranked coastal areas with a low tidal range as the most vulnerable (Dwarakish et al., 2008; Dwarakish et al., 2009; Gaki-

Papanastassiou et al., 2010; Gorokhovich et al., 2014; Joevivek et al., 2013; Karymbalis et al., 2012; Ozyurt and Ergin, 2010; Pendleton et al., 2005; Sheik Mujabar and Chandrasekar, 2011).

Coastal areas with high tidal range are considered highly vulnerable on the basis that a large tidal range is associated with strong tidal currents that can transport unconsolidated sediments away from the coast (Gornitz et al., 1994; Kumar et al., 2010). A large tidal range also has intertidal zones of near zero elevation that would be susceptible to inundation as a result of SLR (Doukakis, 2005b), and impact on the ecology of wetlands (Gornitz et al., 1994). Others argue that a large tidal range increases the resilience of a coastal area to SLR (Chauhan et al., 2004) and that coastal areas with micro-tidal conditions (i.e., low tidal range) have a higher likelihood to be at high tides during a storm and therefore are at greater risk of erosion and flooding (Dwarakish et al., 2009; Gaki-Papanastassiou et al., 2010). Tide-gauged data are available from several coastal locations across India, and the mean tidal range data used in this study were obtained from the NIO, Goa, for the year 2011.

3.6 Significant wave height

Significant wave height is used as an alternative to wave energy and is an important parameter to consider when assessing coastal vulnerability, because it drives the transport of coastal sediments, thereby influencing coastal erosion (Gaki-Papanastassiou et al., 2010). Hence wave height gives an indication of the amount of beach materials that may be moved offshore and thereby removed from the coastal sediment system (Doukakis, 2005b). Significant wave height is defined as the average height (trough to crest) of one-third of the waves in a wave spectrum for a given period of time (Kumar et al., 2010). Wave energy is directly related to the square of wave height by the following formula:

$$E = \frac{1}{8} \rho g H^2 \quad (1)$$

where E is energy density, ρ is water density, g is acceleration due to gravity, and H is wave height. Thus an increase in wave height causes an increase in wave energy, which subsequently results in increased erosion along the shore (Kumar et al., 2010). Hence, coastlines experiencing high wave heights are considered more vulnerable than those exposed to low wave heights. Significant wave height was estimated using wave height data obtained from the NIO in Goa, which were recorded using a directional wave rider buoy off Mormugao in the *taluka* of Mormugao (Vethamony et al., 2009).

3.7. Geomorphology

The geomorphology parameter expresses the degree of resistance of the different landforms and the materials that compose them (Thieler and Hammer-Klose, 1999). The landforms with the most erodible feature, for example, active sand dunes, are the most sensitive and inevitably this feature was given the highest risk rating, whereas landforms with the least erodible feature, such as rocky cliffs, have low sensitivity and are thereby the least vulnerable. A geomorphologic map was prepared at the 1:25,000 scale using data for January 1999 from the high resolution Linear Imagery Self Scanner (LISS) as part of the Indian Remote Sensing Satellite (IRS) P6. These satellite images were used for delineating the shoreline into the dominant landform type, including rocky cliffs, exposed rocks, lateritic mesas, beaches, estuaries, tidal flats, mangroves, stabilized dunes, and active sand dunes; each of which having a different degree of sensitivity to erosion (Table 3).

3.8. Socio-economic data

Population is one of the major socio-economic variables influencing the vulnerability of a region to coastal hazards. As previously mentioned, population can exert a negative pressure on the coastal environment as areas with high population and tourist density would often lead to greater erosion rates. However, population can also be related to the capacity of a coastal community to protect itself against natural hazards and SLR and hence act to reduce vulnerability. In the present study, the population and tourist data were considered as exerting a further pressure on the coastal system and hence areas with a higher concentration of people and/or tourists were considered as more susceptible to erosion, in a way similar to Hedge and Reju (2007), albeit the latter study limited its analysis to the resident population without considering tourism data. Including tourism data is particularly important in many parts of Goa where the number of tourists outnumbers the local population (Fig. 4). This approach was selected as the current study did not aim to make an assessment of adaptive (coping) capacity, but focused instead on exposure and sensitivity of the coastal system. This is further supported by previous research, which noted the destabilization of some of the beaches of Goa as a result of pressure from tourism related activities (Chauhan et al., 2004).

The majority of Goa's population resides near the coast (Fig. 4). Goa is an important tourism destination for both domestic and international tourists, and the number of people visiting the state in a year outnumbers three times the resident population (Government of Goa, 2010). For this reason, both population and tourism have a significant influence on the coast and were accordingly considered as two subcomponents of the socio-economic variable to be incorporated into the CVI of the present study. Population and tourism data (i.e., number of foreign and domestic tourists) for each *taluka* were gathered from the state government for the years 2008 and 2009. For the risk ranking, the *talukas* with the highest population and tourist density were considered as the most vulnerable.

3.9 Calculation of the CVI

Once each of the seven *taluka* with a coastline in the state of Goa was assigned a risk value for every variable, the CVI was calculated as the square root of the product of the ranked variables divided by the total number of variables (Pendleton et al., 2005):

$$CVI = \sqrt{\frac{a * b * c * d * e * f * g * h}{8}} \qquad (2)$$

where a = rate of shoreline change, b = rate of relative SLR, c = coastal regional elevation, d = coastal slope, e = mean tidal range, f = significant wave height, g = geomorphology, and h = the sum of population and tourism density.

There are different ways to combine variables in a composite index. Some composite indices are calculated using weighted averages of individual parameters, which inevitably require a degree of judgment about the influence of each variable (Hahn et al., 2009). In the present study, however, equal weight was given to every variable; an approach that is the most widely used in the literature (Addo, 2013; Boruff et al., 2005; Clavano, 2012; Di Paola et al., 2011; Dwarakish et al., 2008; Dwarakish et al., 2009; Gaki-Papanastassiou et al., 2010; Gorokhovich et al., 2014; Hegde and Reju, 2007; Joevivek et al., 2013; Karymbalis et al., 2012; Kumar and Kunte, 2012; Kumar et al., 2010; McLaughlin and Cooper, 2010; Ozyurt and Ergin, 2009, 2010; Pendleton et al., 2005; Sheik Mujabar and Chandrasekar, 2011), including the USGS studies (Thieler and Hammer-Klose, 1999, 2000a, b) and Gornitz et al. (1991).

A few studies have developed a CVI composed of weighted variables (Diez et al., 2007; Doukakis, 2005b; Duriyapong and Nakhapakorn, 2011; Nageswara Rao et al., 2009; Szlafsztein and Sterr, 2007; Yin et al., 2012). Palmer et al. (2011) did not weight the risk variables of their CVI *per se*, but included additional weighting to grid cells that covered an estuarine area. Diez et al. (2007) assessed the coastal vulnerability of a region of Argentina using equation 2 above, albeit without socio-economic data and using elevation as opposed to coastal slope. However, they also used another CVI formula as published in Gornitz et al. (1997), with each indicator carrying different weights, and found that the outcome of the vulnerability assessment differed considerably between the two approaches. In their alternative CVI, elevation, SLR, and the rate of shoreline change were given twice the weight of the other variables, which included geomorphology, wave height, and mean tidal range.

Doukakis (2005b) also used weighted variables in their CVI, giving three times more weight to all risk variables with the exception of coastal slope. Coastal slope was also the variable carrying the lowest weight in the CVI of Yin et al. (2012) with SLR given the highest weight, followed by elevation and geomorphology. However, this is in contrast to Duriyapong et al. (2011) who determined the weight of the risk variables based on consultations with experts and of the four physical risk variables, coastal slope was given the highest weight (0.35) then wave height (0.29), erosion (0.25), and tidal wave (0.11). Nageswara Rao et al. (2009) is yet the only study in India that developed a CVI based on weighted variables. As in Diez et al. (2007) they gave a lower weight to wave height and tidal range but multiplied geomorphology and coastal slope by a factor of four and the rate of shoreline change by a factor of two.

As there is no agreement in the literature on the weight assigned to the different variables comprising a CVI, the more widely used method of assigning equal weight to all variables was preferred, otherwise the process of assigning weights would be subjective and hence the outcomes of the vulnerability assessment would be influenced by personal judgement. Nonetheless, the influence of each variable on the outcome of the CVI was estimated by excluding one variable at a time.

Equation 2 was calculated for each taluka and the resulting CVI values were ranked into three classes, depending on their overall level of vulnerability: low, medium, and high, corresponding to the 25^{th} percentile, 25^{th} to 50^{th} percentile, and 50^{th} percentile, respectively.

4. Results

4.1 Rate of shoreline change

The calculations of the rate of shoreline change indicate that the *talukas* of Bardez and Salcete are the most sensitive to coastal erosion and thus have a high risk rating (Fig. 5), recording erosion rates of more than 0.6 m per year. The coastline of Pernem, Tiswadi, Quepem and Canacona with erosion rates between 0.3 and 0.6 m/year are ranked as medium risk. The coast of the *taluka* Mormugao has experienced the lowest erosion rates (< 0.3 m/year) and is thereby ranked as low risk level.

4.2 Rate of relative SLR

Sea level has increased at a rate varying between 1.06 and 1.75 mm/year during the period 1969-2007, depending on the tide gauge recording site, with an estimated regional average of 1.29 mm/year, subsequent to a global isostatic adjustment correction (Unnikrishnan and Shankar, 2007). This regional average is within the 1-2 mm/year global SLR estimate reported by the IPCC for the past 100 years (Hegerl, 2007). Since variations across Goa are minimal, which is not surprising for a state with a relatively small surface area, one could categorise the entire 105 km coastline in the same risk rating category, which in this case was considered as medium risk, given that it is within the IPCC range. Sea level will continue to rise given the projected increase in emissions of greenhouse gases (GHG), with SLR projected to be approximately 4 mm/year by the end of this century (Unnikrishnan et al., 2004).

4.3 Coastal regional elevation

The coastal elevation for Goa ranges between sea level 0 and 100 m. Accordingly, *talukas* with a coastal regional elevation of less than 35 m were categorised as high risk while those with a coastal elevation greater than 55 m were classified as low risk (Table 3). This study revealed that the 30 km of the coast of the *taluka*s of Salcete, Bardez and Tiswadi has a coastal regional elevation of less than 35 m, which was assigned a high risk rating (Fig. 6). About 35 km of coastline covering the *talukas* of Pernem and Mormugao falls within the medium risk rating category whereas the remaining 40 km of coast Quepem and Canacona *talukas* in the south of the state has a high coastal regional elevation and was therefore assigned a low risk rating.

An inundation map was prepared for the study area to show the potential risk of inundation based on various synthetic SLR scenarios. As figure 7 illustrates, river systems in the study region are corridors for inundation as they allow the flood water to be carried upstream for long distances resulting in flooding along the proximal areas of the rivers. During high tide, for example, sea water can reach up to 40 km upstream (Shetye et al., 2007). Figure 7 also shows the vulnerability of a number of coastal locations to submergence as a result of SLR, notably parts Bardez and Tiswadi, and most of the coastal area of Salcete, which are the *talukas* with the lowest elevation as mentioned above.

4.4 Coastal slope

The present study revealed that about 35.7 km of Pernem and Salcete *taluka* coastline has a low risk rating as coastal slope is steep, i.e., more than 0.3 degree (Fig. 8). The 21.2 km of the coastline of the *taluka* of Bardez and Quepem has a moderate risk rating with a coastal slope varying between 0.1 and 0.3 degree. About 73.9 km of Tiswadi, Mormugao and Canacona *taluka* coastlines have low coastal slopes and are therefore considered more sensitive to storms and SLR and were accordingly given a high risk rating (Fig. 3).

4.5 Mean tidal range

The tidal range for a short shoreline such as Goa does not fluctuate much in a year (Kumar and Kunte, 2012). The mean tidal range was calculated as 0.2 m to 2.4 m for the year 2011. Hence, the entire 105 km coastline of Goa was classified under the moderate risk ~~catergory~~category, which is consistent with Kumar et al. (2010) who considered a tidal range below 2.5 m in the same risk rating category.

4.6 Significant wave height

During the non-monsoon months (October - May) significant wave heights do not exceed 2.0 m off Mormugao Port. During the monsoon months (June - August) and in September, the significant wave height reaches more than 2.5 m (Fig. 9). Given the magnitude of the significant wave heights, the entire coast of Goa was classified in the medium risk rating category, in agreement with Dwarakish et al. (2009) who considered coastlines with significant wave heights ranging from 1.6 to 2.8 m as moderately vulnerable. For a small state such as Goa significant wave height does not vary significantly across the state and the entire coastline was given the same risk rating.

4.7 Geomorphology

Some beaches such as Baga, Calangute, and Anjuna, all located in the Bardez *taluka* (Fig. 1), as well as Arambol in the Pernem *taluka* are backed by stabilized sand dunes and are therefore moderately vulnerable, whereas low-lying beaches like Colva in Salcete *taluka* and Caranzalem in the Tiswadi *taluka* are highly vulnerable. Coastlines such as the Quepem, Canacona and Mormugao are backed by headlands or cliffs and are thus the least vulnerable. There are limitations, however, to the categorisation of risk level at the spatial scale of a *taluka.* For example, the presence of mangroves and river size are factors that influence local vulnerability but may not always be considered depending on the scale of analysis. Previous research has shown that the width of mangrove forest reduces death significantly during severe events. Major rivers carry away surge water and help in reducing surge velocity to flooding, hence nearness to a major river decreases vulnerability while minor rivers can have the opposite effect likely because of their low water carrying capacity (Das, 2012).

4.8 Socio-economic data

In terms of population, *talukas* with high population density and high number of tourists in a year were ranked as the most vulnerable and vice-versa. According to this criterion, the *talukas* of Salcete, Tiswadi and Bardez with their high population density and high number of visitors were ranked as the three most vulnerable talukas (Fig. 4). The *taluka of* Mormugao has moderate population and receive smaller number of tourists than the above three *talukas* and was thus ranked as moderately vulnerable. The coastal *talukas* of Pernem, Quepem, and Canacona are the least vulnerable as few tourists visit these less populated *talukas*.

4.9 Coastal vulnerability in the state of Goa

Table 4a illustrates the results of the CVI for each coastal *taluka* of the state of Goa while their relative ranking is depicted in Table 4b and Figure 10. This classification was based on the exposure and sensitivity of the coast to seven physical and geologic risk variables plus population and tourist density data representing the socio-economic component. The CVI values for the seven coastal *talukas* of Goa varied from 2.0 to 12.7. The 25th and 50th percentiles of the CVI values are 2.7 and 3.5, respectively. Hence, the *talukas* of Quepem and Canacona, i.e., the two southernmost *talukas* of the state, are considered to have low vulnerability. Since the *talukas* of Pernem and Mormugao have CVI values of 2.8 and 4.2, respectively, they fall within the moderate vulnerability category, while the *talukas* of Salcete, Bardez and Tiswadi, are classified as the most vulnerable.

Since the three physical risk variables of the CVI, i.e., rate of relative SLR, mean tidal range, and significant wave height, were given the same value across the state, the relative vulnerability across the different *talukas* was consequently determined on the basis of geologic parameters, i.e., historical rate of shoreline change, coastal slope, coastal regional elevation, and geomorphology in addition to population and tourist density data, which were considered as an additional erosion-inducing variable on the coastal system. The *talukas* of Bardez, Tiswadi, and Salcete were considered the most vulnerable. Bardez and Salcete have both experienced erosion rates of more than 0.6 m/year while the erosion rate for Tiswadi was found to be above 0.3 m/year. These are also the most populated *talukas* and where the world famous beaches attracting domestic and international tourists to the state are located, hence further increasing the erosion risk of those *talukas*. In addition, these three *talukas* are vulnerable to coastal flooding and inundation due to their low-lying topography, which is further accentuated in the case of Bardez and Tiswaldi because of their gentle coastal slope. Salcete has low elevation, but it has a relatively steep coastal slope, and it is for this reason that the overall vulnerability of this state is lower than Bardez and Tiswaldi located further north. This further shows the importance of considering these two parameters in a CVI, which few studies have done so far.

The *talukas* of Quepem and Canacona were ranked the least vulnerable to erosion due to presence of rocky cliffs, exposed rocks, and mesas, and also because they have low population density and do not attract many tourists. Even though these two *talukas* have relatively gentle coastal slope, they are not considered at significant risk of flooding and inundation due to their relatively high coastal regional elevation. The *talukas* of Pernem and Mormugao were categorized as moderately vulnerable. Pernem has experienced significant erosion in recent decades owing to its geomorphology but its elevation is relatively high and it has a steep coastal slope. Mormugao is one of *the talukas* with the lowest erosion rates but it is moderately vulnerable, due to its gentle coastal slope and moderate elevation.

4.10 Sensitivity of the CVI to socioeconomic characteristics

The sensitivity of the CVI to the inclusion of socioeconomic characteristics was examined by recalculating the vulnerability of the coastal *talukas* without considering information about population and tourist density. This resulted in a significant decrease in the vulnerability value for the three touristic *talukas* of Bardez, Tiswadi, and Salcete, but these *talukas* would, on a relative basis, still remain the three most vulnerable in the state. The vulnerability of the Pernem *taluka* increased slightly after incorporating the socioeconomic variable while that of Mormugao had its vulnerability ranking decreased from moderate to low, resulting in this *taluka* having a vulnerability value similar to the two southernmost *talukas* of the state.

5. Discussion and conclusions

Concerns about climate change has led to a growing body of research on coastal vulnerability to SLR (Boruff et al., 2005). This study used seven physical and geologic risk variables in addition to population and tourist density data in the creation of a CVI for the state of Goa. The seven physical and geologic risk variables, i.e., rate of shoreline change, mean SLR, coastal regional elevation, coastal slope, mean tidal range, significant wave height, and geomorphology were selected on the basis of a review of the international literature and are in agreement with the variables used in the most comprehensive vulnerability assessments undertaken to date in other coastal regions of India.

Few studies have attempted to include socioeconomic indicators in their coastal vulnerability assessment (Gorokhovich et al., 2014), even though incorporating population density as a risk factor was suggested in one of the first studies making use of a CVI (Gornitz, 1991). Socio-economic variables and, in particular, information on the distribution of the resident and tourist population along the coast are important variables to consider especially when assessing local vulnerability to erosion. This is particularly important in Goa in view of the state’s growing population and the importance of tourism to the state economy; the latter causes mounting pressure for the development of new facilities, infrastructure, and transportation links (Murali et al., 2006; Noronha, 2004; Wilson, 1997).

The CVI was calculated for all *talukas* having a coast in the state of Goa. Indicators-based methods such as the CVI are relatively simple to calculate, yet they are built on detailed quantitative analyses and are able to assess non-linear effects as well as considering interactions between different processes (Ramieri et al., 2011). Such analyses have become possible in recent years in view of satellite data, numerical modelling, and tools to process such data, e.g. GIS.

One issue facing planners and other decision-makers is to identify how, where, and when to adapt to the impacts of coastal hazards and SLR (Moser et al., 2012). The CVI provides a comparative metric of vulnerability of the coastal *talukas* of the state (Chandramohan et al., 1997). In the state of Goa, information for all disasters is collected at various levels, i.e., the district, *taluka*, and village. Based on this information, decisions are taken by the Chief Minister in consultation with his ministers and district administrators (Collector). The decisions are implemented by the village (Panchayat - a locally elected body) and *taluka* administrators. The current *taluka*-based vulnerability map provides a useful tool to decision-makers by depicting areas most vulnerable to erosion, coastal flooding, and inundation.

It is expected that this vulnerability map in addition to the inundation map based on synthetic SLR scenarios will be useful in 1) land use planning and zoning ordinances to protect community resources as well as guiding new development by formulating regulations and building codes that are area specific, and 2) developing emergency management plans to prepare for natural disasters like flooding as a result of tropical storms. In view of projected SLR, this vulnerability map explains why some parts of the 105 km long coast of the state of Goa are more vulnerable than others and would therefore allow policy makers to direct funding to the most vulnerable sections of the coast.

This study focused on the vulnerability to coastal hazards and SLR. Other impacts of SLR not mentioned here and that are relevant to Goa include salt water intrusion of estuaries and groundwater aquifers (Gornitz, 1991) while other hazards also affecting coastal environments include industrial/sewage pollution and harmful algal blooms (Krishna, 2005). The potential of oil spills is another hazard affecting the coast of Goa because of the fact that the Arabian Sea lies in an important traffic zone for oil transport, which is likely to continue or increase further in importance (Yap and Lam, 2013). Oil slicks can easily reach the shore during favourable wave or tidal actions, causing major ecological damage when this occurs. Such hazards were not considered in the present vulnerability analysis; nonetheless, it is important to mention that the natural hazards studied in this study also have the potential to increase the likelihood of hazardous events with regards to oil spills.

We trust that the results of this assessment based on the most reliable scientific information currently available will serve to increase awareness about the vulnerability of the coastal zone of Goa to erosion, coastal flooding, and SLR, as well as catalyzing policy options by coastal planners and government authorities with regards to prioritizing coastal areas for adaptation. A follow-up on this study could be the development of an action plan map, which would integrate the outcome of this CVI plus information about the presence of coastal infrastructure decreasing vulnerability, e.g. sea walls.

This study included two socio-economic characteristics in the calculation of the vulnerability of the coastal *talukas* of Goa. However, there are also human activities that could increase erosion along the coast. Beach erosion is influenced by the interception of silt and sand by upstream reservoirs, coastal engineering structures such as groins and jetties, which trap sand moving along the shoreline and hence reduce the supply of sand to some areas, and sand mining on the beach (Gornitz, 1991; Joevivek et al., 2013). The first two of these human influence parameters were incorporated in the CVI of Ozyurt and Ergin (2010) by considering reduction of sediment supply, river flow regulation, and the percentage of the land in the presence of engineered frontage and coastal protection structures.

Further work should include more social, economic but also built environment characteristics in the vulnerability assessment. The work presented here is beyond what has been achieved to date in India but it remains only a first step towards a comprehensive vulnerability assessment, which should include an assessment of the adaptive (coping) capacity. Future work includes the adoption of an Integrated Assessment Model to evaluate the vulnerability of coastal systems to the impacts of multiple natural hazards. Such a model can include the cross-sector analysis of interaction among different impacts and the synergetic effects of changes in climate and other key variables affecting the coastal system such as socio-economic development and adaptation measures. The ability of a fully integrated assessment of coastal vulnerability, also considering dynamic interactions between sectors and/or processes, makes integrated assessment models very useful in supporting policy and decision-making at various spatial scales.

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Research Highlights

- A Coastal Vulnerability Index (CVI) is developed using eight risk variables
- The data from conventional and remote sensing sources were processed using GIS
- Socio-economic data supplemented the geologic and physical risk variables
- The CVI was used to assess the vulnerability of the coast of Goa, India
- The vulnerability map depicts the coastal zones most at risk to multiple hazards

Graphical Abstract (for review)

Multi-hazards Coastal Vulnerability Assessment of Goa, India, using Geospatial Techniques

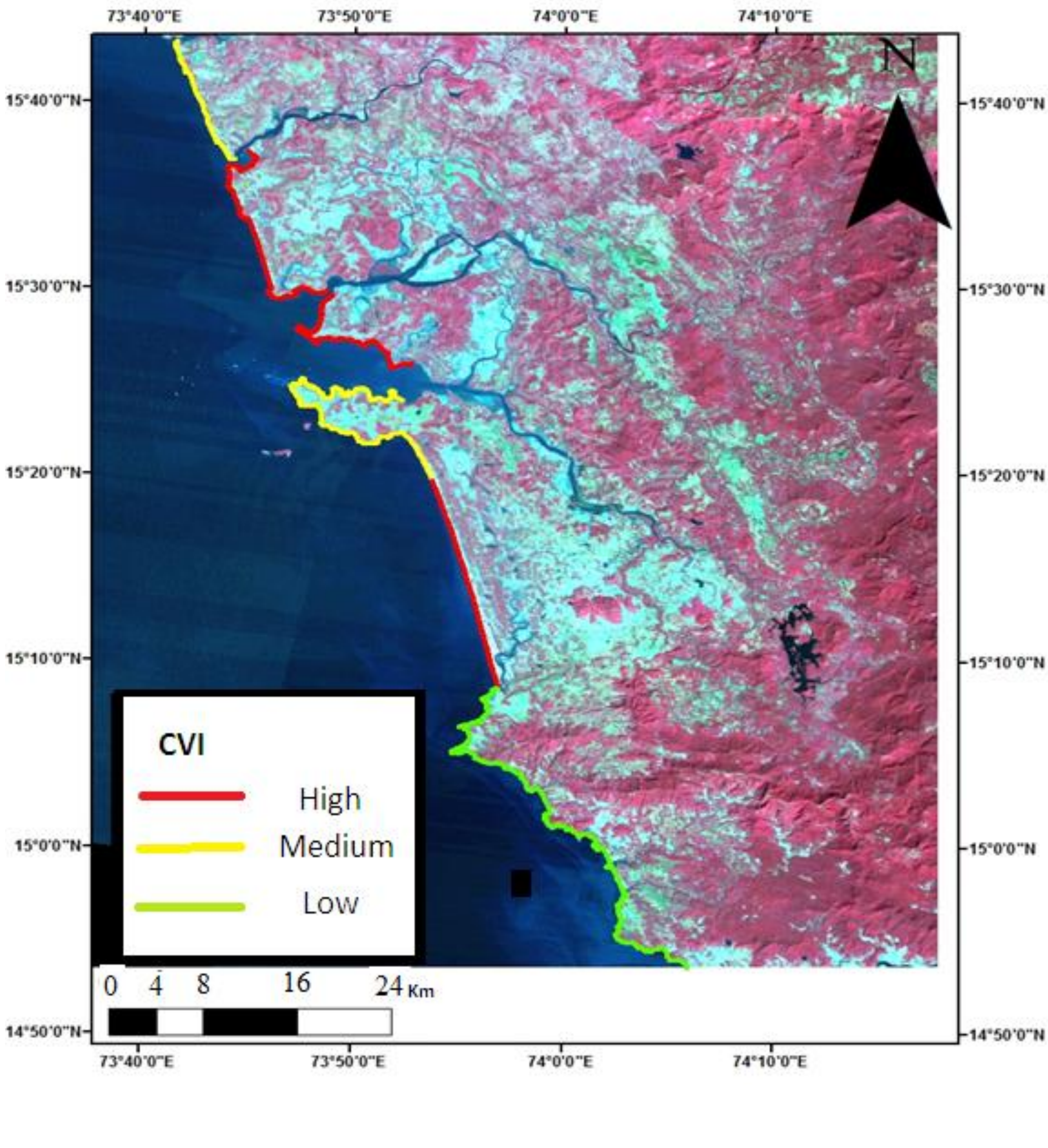

Table 1

<table>
<tr><th>Study/ parameter</th><th>Study area</th><th>Historical shoreline change (erosion or accretion)</th><th>Rate of relative sea-level change</th><th>Coastal regional elevation</th><th>Coastal slope</th><th>Mean tidal range</th><th>Significant wave height</th><th>Geomorphology</th><th>Storm surge</th><th>Tsunami run-up</th><th>Population</th></tr>
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Table 1 Parameters used in the development and application of a CVI in different coastal areas of India

Table 2

Table 2 Source and period of the different parameters used in the construction of the CVI.

Parameter	Source of data	Period
Historical rate of shoreline change	Landsat TM, ETM and MSS (http://glcfapp.glcf.umd.edu:8080/ esdi/index.jsp)	1973,1989, 2006
Rate of relative SLR	Annual mean relative sea level data from Indian Ocean tide gauge stations	1969-2007
Coastal regional elevation	Shuttle Radar Topography Mission (SRTM) and ArcGIS 9.3	2000
Coastal slope	ETOPO2 bathymetric dataset from the National Institute of Oceanography, Goa (India)	1971-1984
Mean tidal range	National Institute of Oceanography, Goa (India)	2011
Significant wave height	National Institute of Oceanography, Goa (India) using studies on directional waves off Mormugao Port	2009
Geomorphology	High resolution Linear Imaging Self Scanner of the IRS-P6 satellite of the India Space Research Organisation	January 1999
Population and tourist density data	Statistical Handbook of Goa, Directorate of Planning Statistics and Evaluation, Government of Goa	2008-2009

Table 3

Table 3 Risk rating assigned to the different CVI parameters.

Parameter	Risk rating		
	Low	Medium	High
Geologic			
Historical rate of shoreline change (m/year)	< 0.3	0.3 - 0.6	> 0.6
Coastal slope (degrees)	> 0.3	0.1 - 0.3	< 0.1
Coastal regional elevation (m)	> 55	35 - 55	< 35
Geomorphology	Rocky cliffs, exposed rocks, lateritic mesas	Stabilized sand dunes, beaches	Estuaries, mangroves, active sand dunes, tidal flats
Physical			
Rate of relative SLR (mm/year)	----	1.29	----
Mean tidal range (m)	----	0.2 - 2.4	----
Significant wave height (m)	----	0.6 - 2.0	----
Socio-economic			
Population density (persons/km^2) Tourist density (persons/km^2)	< 300 < 200	301 - 1000 201 - 2500	> 1000 > 2500

Table 4

Table 4. a) Relative risk ranking for all variables, b) CVI values for the coastal *talukas* of the state of Goa. Numbers one, two, and three refer to low, medium, and high risk ranking, respectively.

a)

Factors / **Talukas**	**EPR**	**Mean Sea Level Rise**	**Coastal Elevation**	**Coastal slope**	**Tidal Range**	**Significant wave height**	**Geomor-phology**	**Socio-Economic**
Pernem	2	2	2	1	2	2	2	1
Bardez	3	2	3	2	2	2	2	3
Tiswadi	2	2	3	3	2	2	3	3
Mormugao	1	2	2	3	2	2	1	2
Salcete	3	2	3	1	2	2	3	3
Quepem	2	2	1	2	2	2	1	1
Canacona	2	2	1	3	2	2	1	1

b)

Taluka	**CVI**
Pernem	2.8
Bardez	10.4
Tiswadi	12.7
Mormugoa	3.5
Salcete	9.0
Quepem	2.0
Canacona	2.4

Figure captions

Figure 1: Location map of study area

Figure 2: Shoreline change detection in the *taluka* of Pernem. a) Change in the location of the shoreline from 1973 to 2006, b) visual representation of the parameters transect spacing and transect length (USGS 2005), c) End Point Rate (EPR), and d) Net Shoreline Movement (NSM)

Figure 3: Near shore bathymetric map of Goa

Figure 4: Total population and number of domestic and international tourists annually per *taluka*

Figure 5. Risk rating of the coast of Goa according to the rate of shoreline change

Figure 6. Areas of high, medium, and low risk based on the coastal regional elevation parameter

Figure 7. Inundation map of Goa state based on various SLR scenarios

Figure 8. Risk rating of the coast of Goa according to coastal slope

Figure 9: Significant wave heights at various water depths off the coast of Goa (Vethamony et al., 2009)

Figure 10. CVI for the coast of Goa

Figure 1

Fig. 1

Figure 2

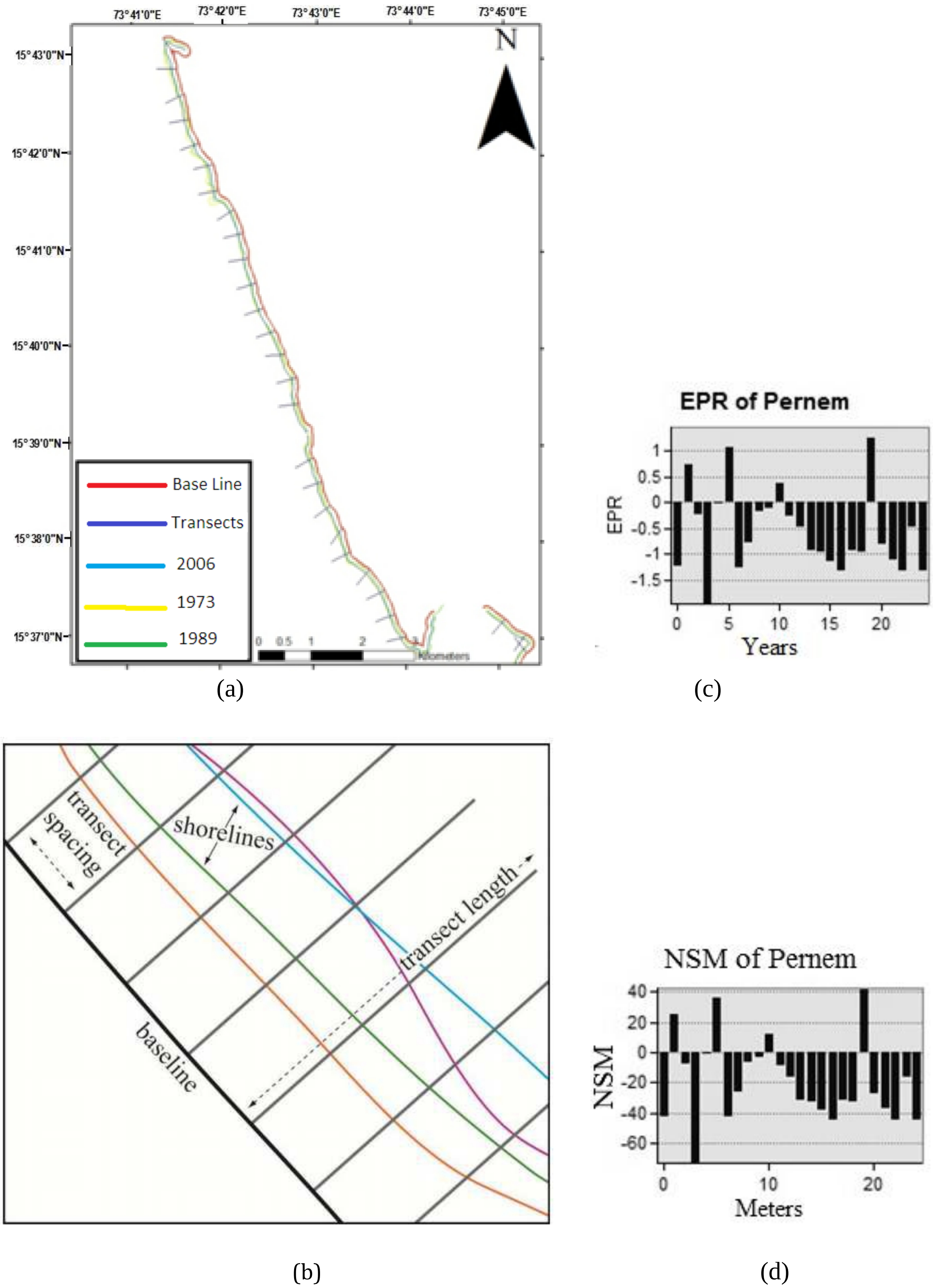

Fig. 2

Figure 3

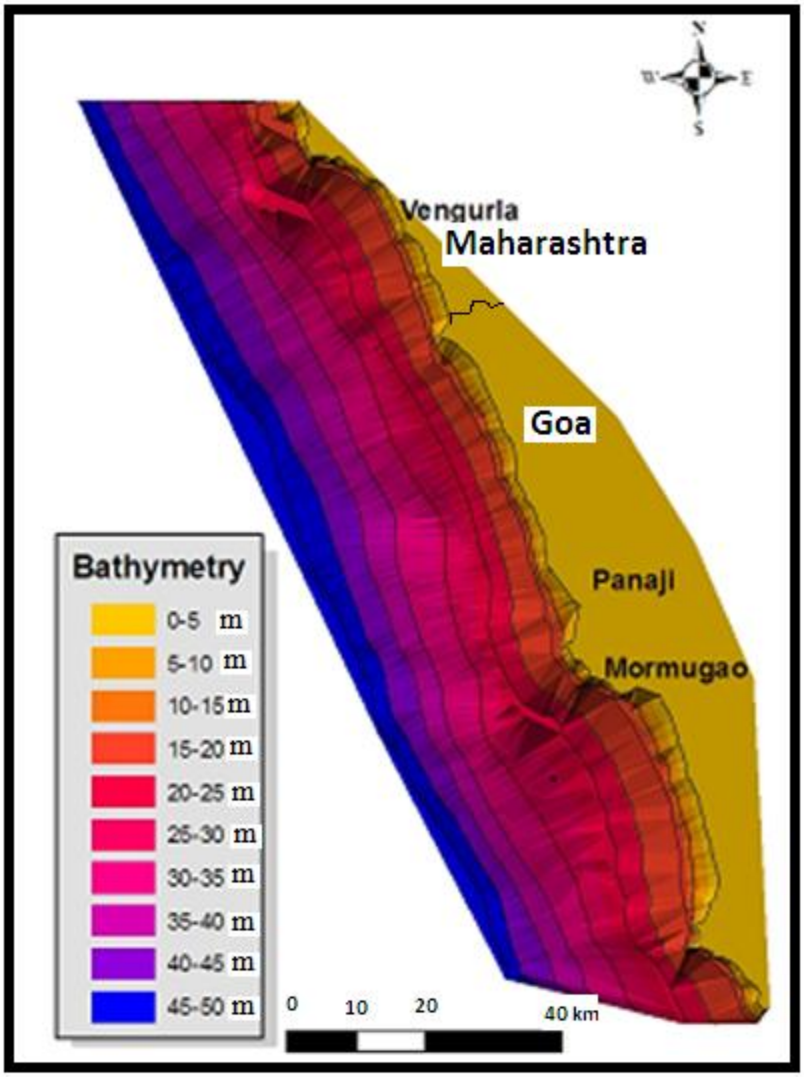

Fig. 3

Figure 4

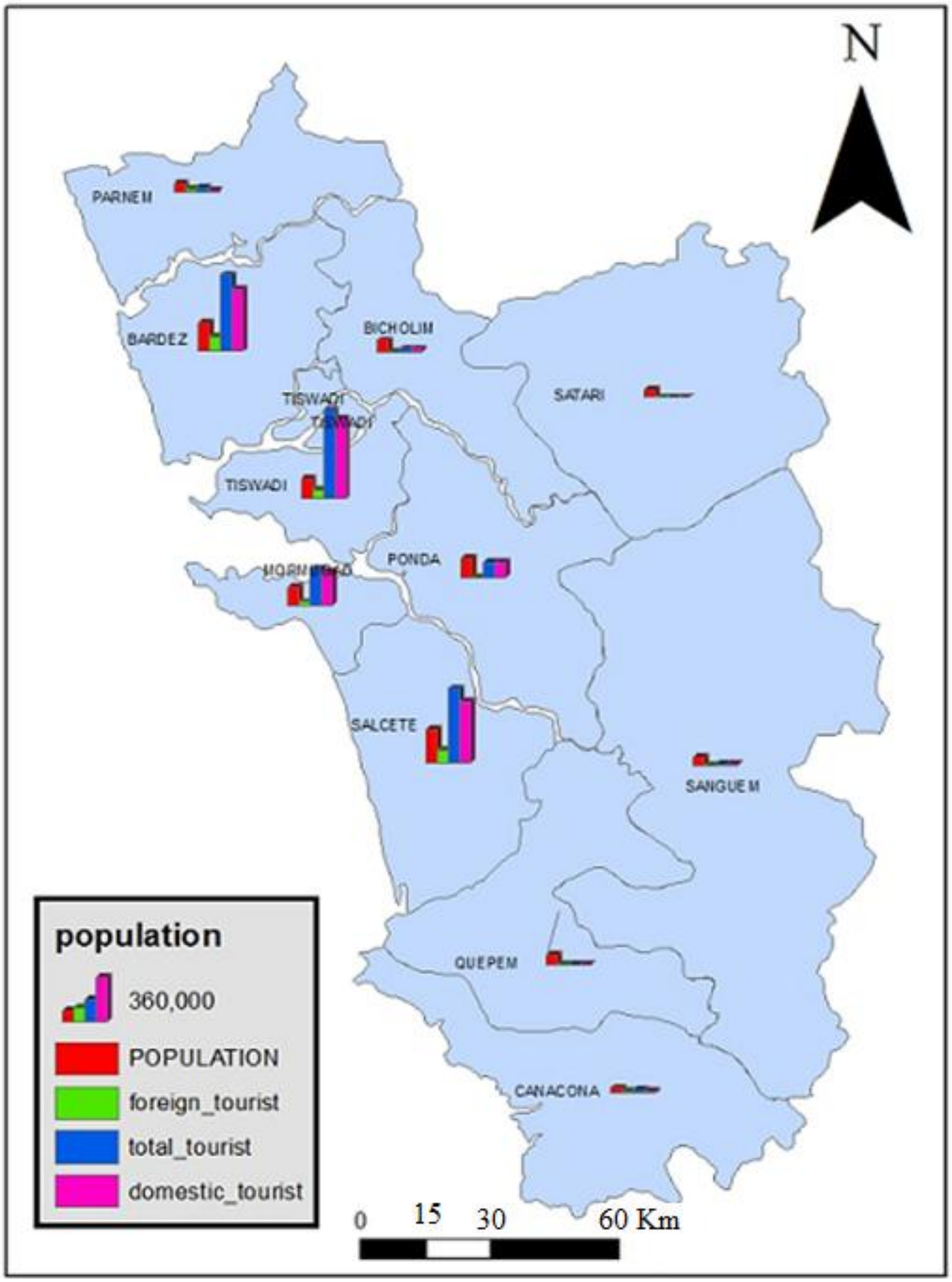

Fig. 4

Figure 5

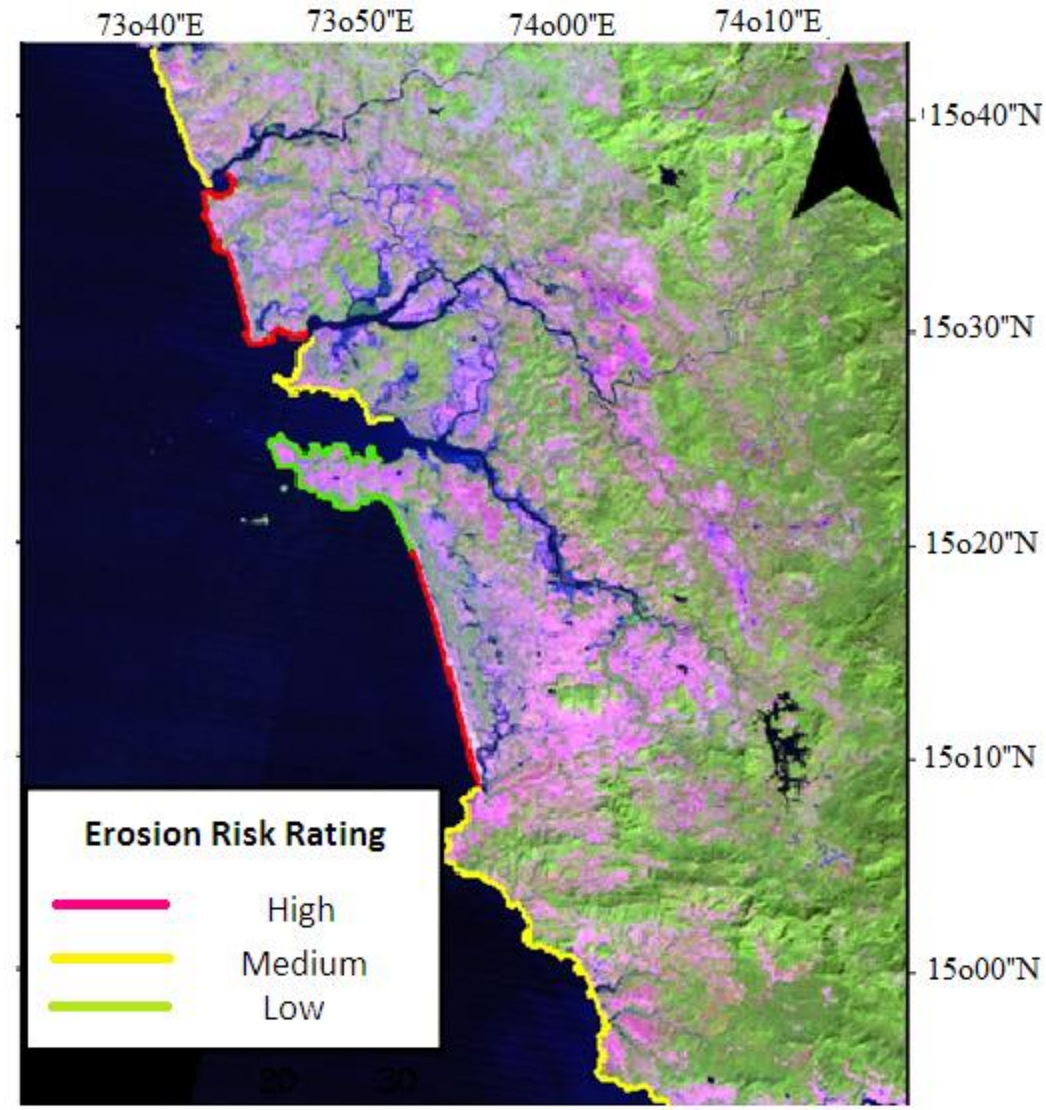

Fig. 5

Figure 6

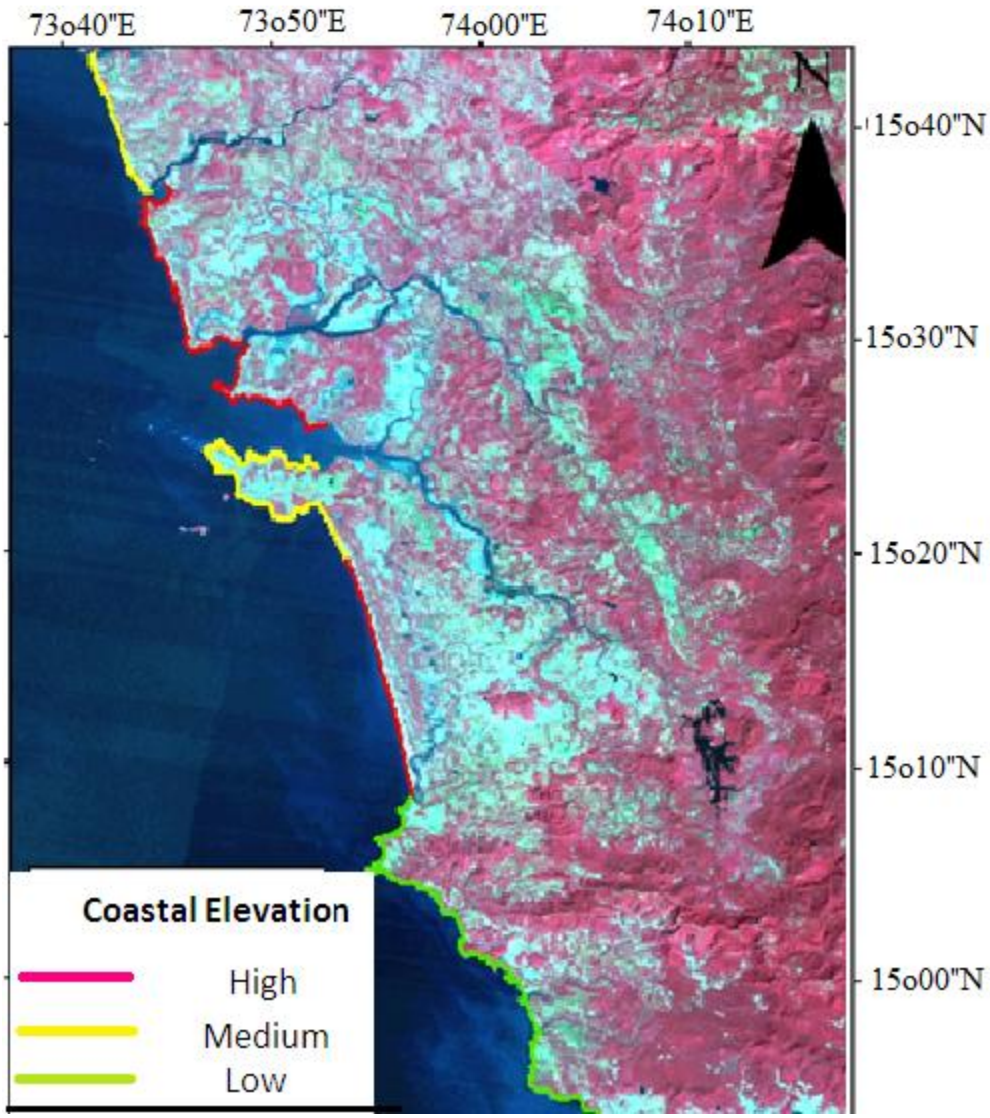

Fig. 6

Figure 7

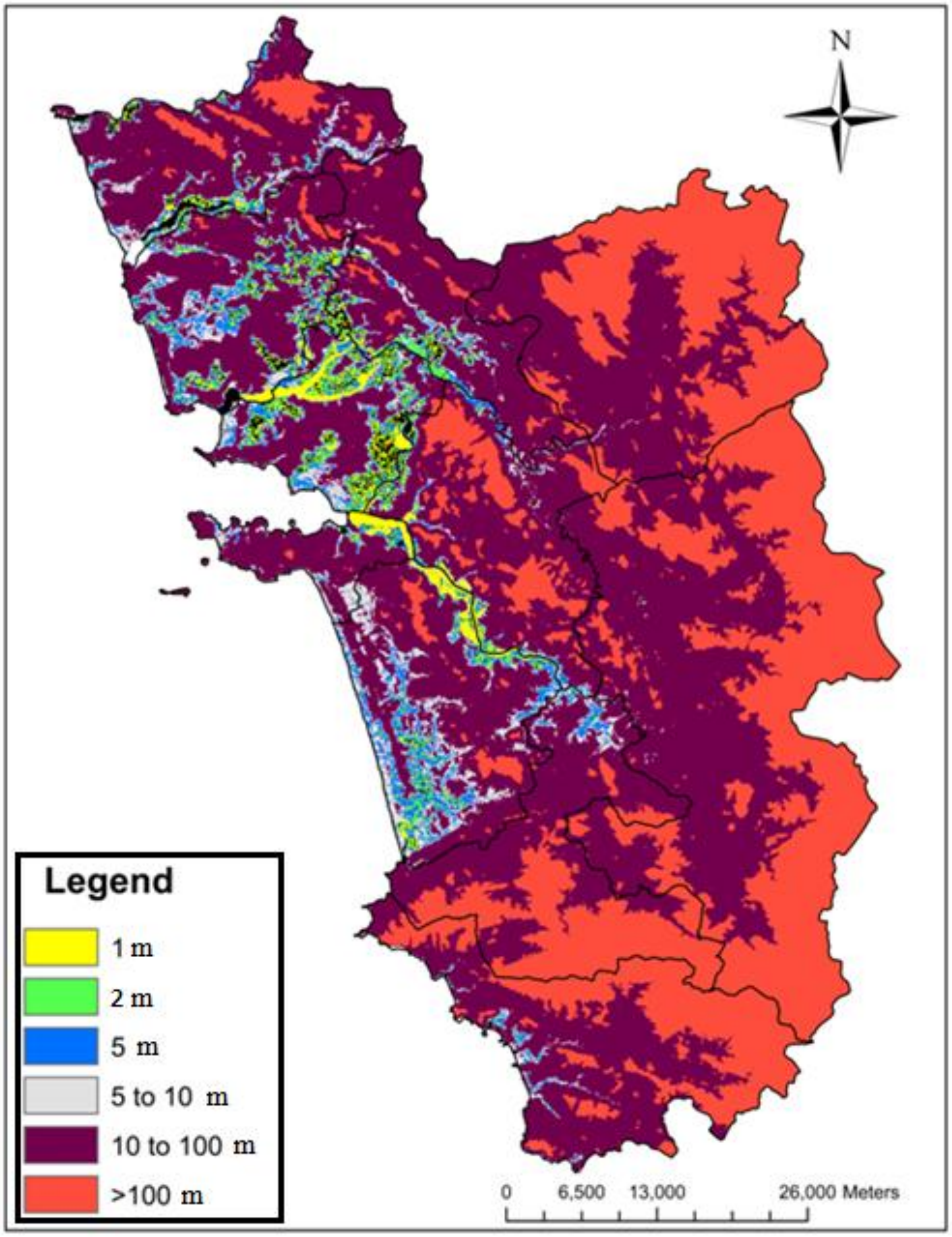

Fig. 7

Figure 8

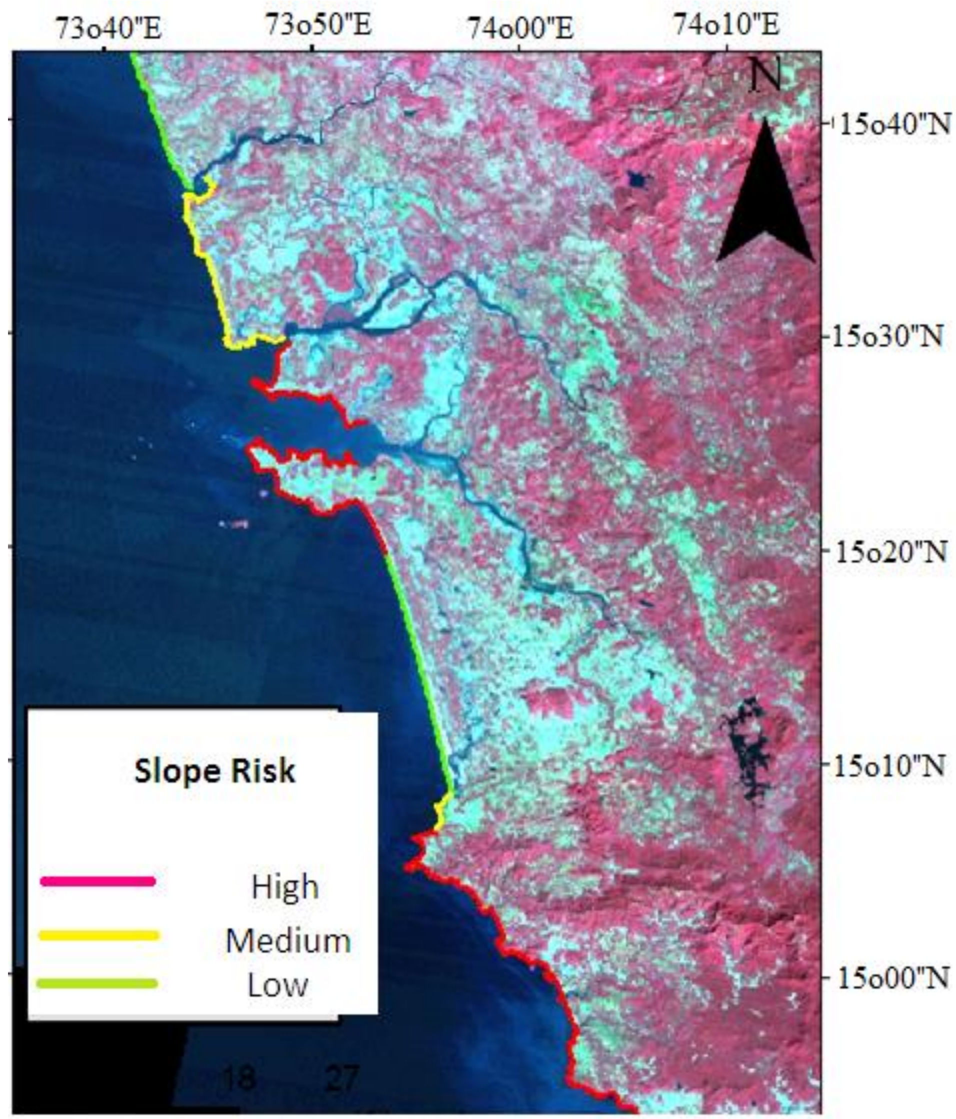

Fig. 8

Figure 9

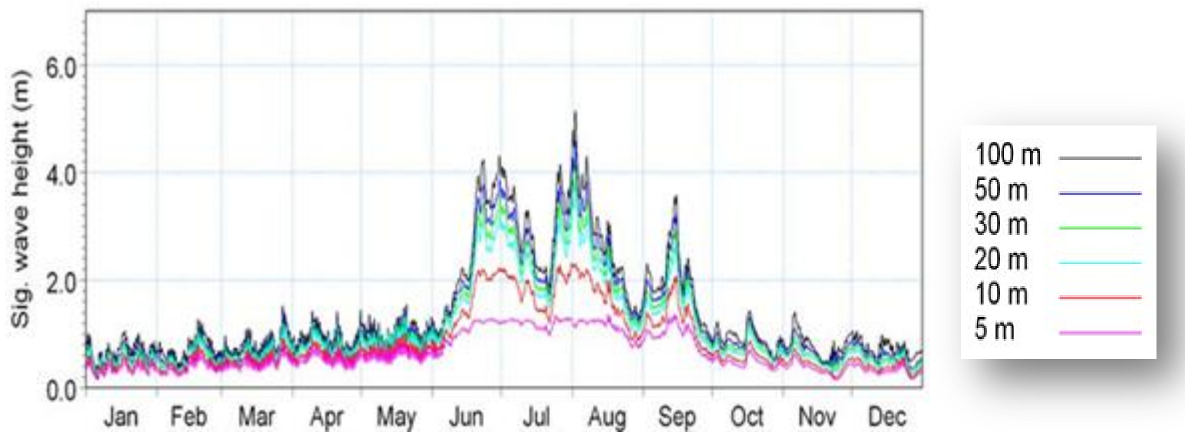

Fig. 9

Figure 10

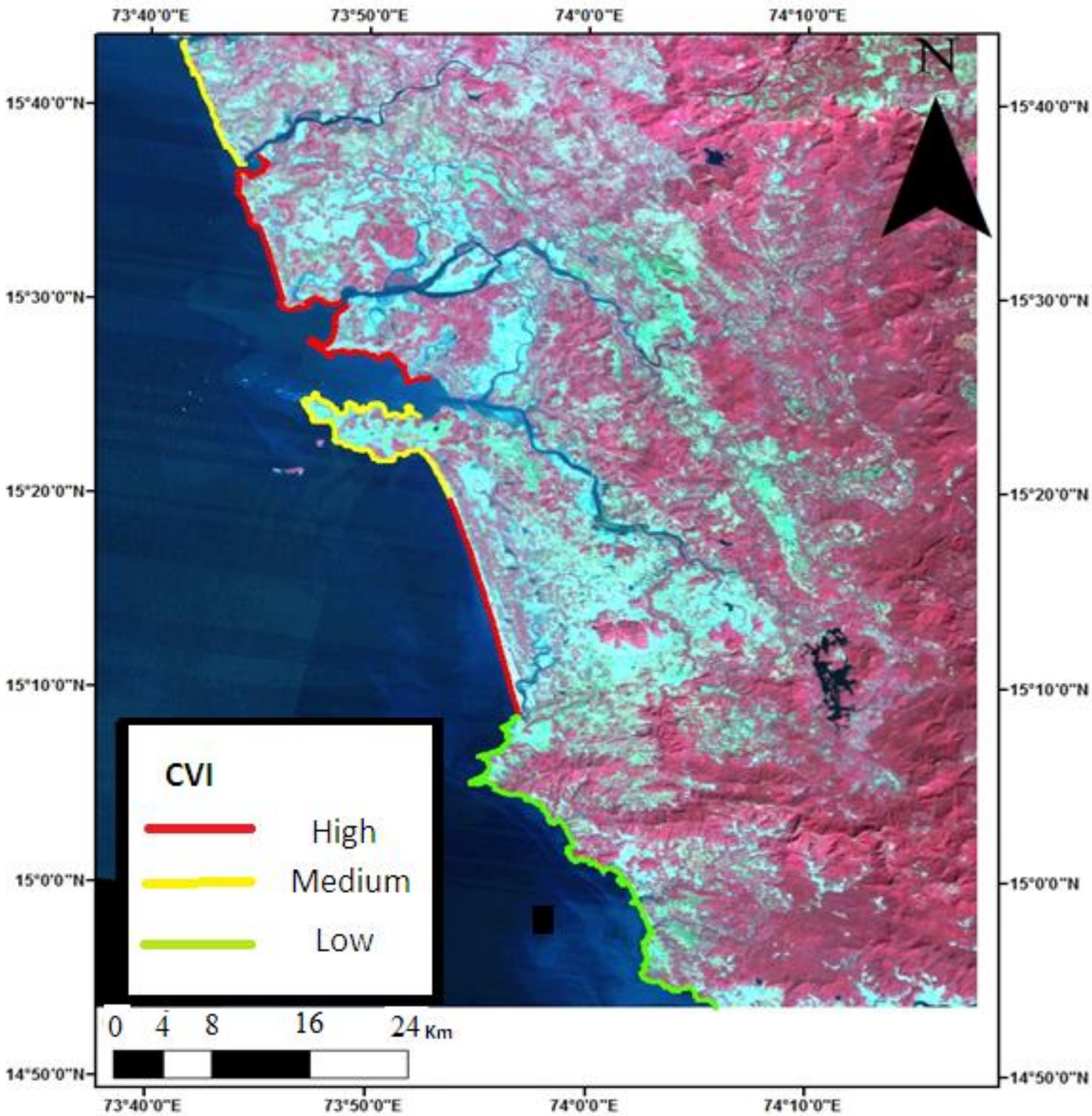

Fig. 10