INTEGRATED VULNERABILITY ASSESSMENT OF KARNATAKA COAST, INDIA: A GEOSPATIAL APPROACH

Thesis

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By

AKSHAYA B. J.

DEPARTMENT OF APPLIED MECHANICS AND HYDRAULICS

NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA,

SURATHKAL, MANGALORE – 575 025

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DECLARATION

By the Ph.D. Research Scholar

I hereby *declare* that the Research Thesis entitled **Integrated vulnerability assessment of Karnataka Coast, India: A Geospatial approach**, which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfilment of the requirements for the award of the Degree of **Doctor of Philosophy** in **Applied Mechanics and Hydraulics Department** is a *bonafide report of the research work* carried out by me. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

AM11F01, AKSHAYA B. J.

(Register Number, Name & Signature of the Research Scholar)

Department of Applied Mechanics and Hydraulics

Place: NITK-Surathkal
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CERTIFICATE

This is to *certify* that the Research Thesis entitled **Integrated vulnerability assessment of Karnataka Coast, India: A Geospatial approach,** submitted by AKSHAYA B. J. (Register Number: AM11F01) as the record of the research work carried out by him, is *accepted as the Research Thesis submission* in partial fulfilment of the requirements for the award of degree of **Doctor of Philosophy**.

Dr. ARKAL VITTAL HEGDE
Professor
Research Guide
(Name and Signature with Date and Seal)

Chairman - DRPC
(Signature with Date and Seal)

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ABSTRACT

Coastal environments are important ecological hotspot for all living organisms. Coastal environments support a large species of indigenous fauna and vegetation with a high biological diversity. Even the human population density in coastal areas is estimated to be three times the global mean. In recent times, increased and the rapid development at the coastal regions has strained the coastal ecosystems in the form of destruction and degradation. Change in globe's atmospheric conditions has also increased the frequency of coastal hazards such as floods, hurricanes and storm surges. The sea level rise due to the global warming, along with the frequent storms, forms a looming threat to our coastlines.

Mitigation of a potential disaster requires a detailed knowledge about vulnerability of the places to various hazards. Such vulnerabilities may be associated with natural or social hazards, or sometimes a combination of both. A systematic vulnerability may be carried out only if the various dimensions involving a hazard are considered. Vulnerability studies generally undertaken skip a very important aspect of human interaction with the nature. Researchers have insisted on inclusion of human interaction as a socio-economic variable in assessment studies. Most of the studies have been carried out using physical variables; Shoreline change rate, Sea-level change rate, Coastal slope, Significant wave height, Tidal range, Coastal regional elevation, Coastal geomorphology and very few studies have been carried out by combining socioeconomic variables along with the physical variables. Also very few studies have evaluated the effect of Tsunami and storm surge as variables for determining CVI.

Most often CVI is calculated using the USGS equation. However, researchers have highlighted that the equation has a disadvantage for usage as equal weights has been assigned to all the variables even when the influence of one variable is more than that of the other variable. On the other hand, assigning random weights to variables can also be logically a mistake as weights are influenced by discretion of the individual researcher. In addition, it was found that the CVI calculated using USGS equation underestimates the risk of certain stretch of coast, which is highly prone to erosion. Hence, in the present study, an opinion survey of experts from ocean and coastal engineering discipline was carried out and a weight scheme was formulated using the principles of Analytical Hierarchical Process (AHP). Tsunami vulnerability for regional scale using GIS was also carried out in the present study. Four geospatial variables, *viz.*, topographic elevation, topographic slope, coastal proximity and vegetation were used to create a tsunami vulnerability map.

It was found that Karnataka coast has 71.92 km length of coast in ‘very high vulnerability’ category, while 71.25 km was under ‘high vulnerability’ category. The extent of ‘moderate vulnerability’ and ‘low vulnerability’ was 71.20 km and 80.69 km, respectively. An overlay of the landuse classification on the tsunami vulnerability map showed that habitation (206.403 km2) and cropland (181.103 km2) are the two major classes of the study area, which are in high-risk category. It was also noticed that coast of Udupi and Magaluru talukas were most vulnerable coast of the study area. In addition, the use of AHP for assignment of weights to variables has provided the realistic scenario for the vulnerability assessment. The MCVI developed in the present study evaluated the level of risk on different segments of the coast. The maps developed in the present study are useful to identify areas where physical changes are most likely to occur in case of a coastal hazard, and as well in planning, managing and protecting resources in the study area.

Key words: *Vulnerability, remote sensing and GIS, AHP, socio-economic variables, CVI, Karnataka*

CONTENTS

Appendix-A

Appendix-B

Bio data

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Coastal environments are of vital importance to all living organisms as they have productive ecosystems. Coastal environments comprise of marine, freshwater and terrestrial habitats that support a wide range of indigenous fauna, as well as vegetation with a high biological diversity. Population in coastal areas are estimated to be three times the global mean and it is anticipated that by 2030 about 50% of the world's population will live within 100 km of the coast (Small and Nicholls 2003).An important reason for such substantial human settlement is due to convenience of waterway for trade and commerce with foreign countries and the accessibility to inland through the same.

The coast is a dynamic system under increasing pressure due to human developmental activities (Nicholls et al. 2007). Ever increasing and rapid development has inflicted several pressures on the coastal ecosystems in the form of destruction and degradation. Coastal areas around the globe are being subjected to major threats of infrastructure development, urbanization and coastal development, overfishing, pollution and climate change. Transformation of globe's atmospheric conditions in recent years has increased the frequency of floods, hurricanes and storm surges. The rising sea levels due to global warming along with the frequent storms form an imminent threat to our coastlines (IPCC 2001). Recent research findings show that human actions have deep impacts upon coastal zones (UNEP 2005).

Natural hazards have been considered to be the elements of physical environment which are harmful to humans and are caused by forces unrelated to mankind (Burton et al. 1993). Events like tropical storms and hurricanes induce beach and cliff erosion, resulting in damage of coastal ecosystem and infrastructure, and heavy rainfall causes flooding. One such example was hurricane Katrina in which

1,833 people died and property worth 108 billion dollars was lost (National Hurricane Centre). However, a storm surge does not cause devastating effects on coast, but poses a significant risk. On the other hand, a Tsunami has a potential to bring upon greater damage to coastal zone in terms of both life and property. During these events, significant amount of resource is lost and their occurrence poses risk to coast. These hazards cause imbalances in the natural stability of the coastal system and hence can be considered as risk factors.

Quantifying the degree of risk on a system can be done by carrying out a systematic vulnerability assessment, since measuring vulnerability is a key step towards effective risk reduction (Birkmann 2006). Therefore, identifying the vulnerability of different coastal sectors to the various natural hazards is an important aspect of coastal risk mitigation. Since coastal systems are complex and they vary from sector to sector, the need of the hour is a site specific research, required to realistically predict the extent of geomorphic and ecological changes that will occur with sea level rise (Nicholls and Mimura 1998) and other seaborne hazards.

1.2 COAST

A coastline or seashore is the area where land meets the sea or ocean, or a line that forms the boundary between the land and the ocean or a lake. Coastal environment is one of the most dynamic systems located at the boundary between land and sea. The Fig 1.1 shows typical cross-section of coast.

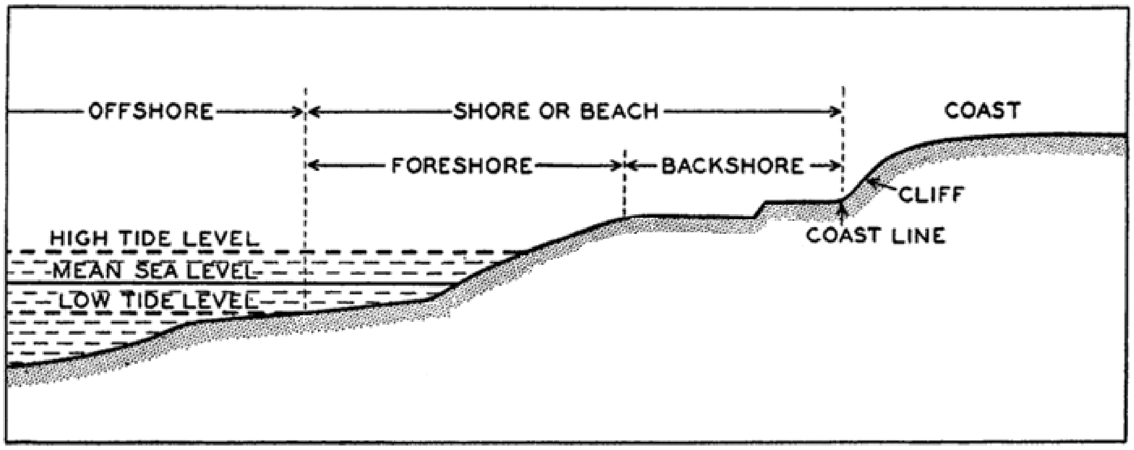


Fig. 1.1 Cross Section of the Coast

The coastal zone is a region of land surface, influenced by marine processes. It extends from the landward limit of tides, waves, and windblown coastal dunes, and seaward to the point at which waves interact significantly with the seabed. The coastal zone is a highly dynamic part of the Earth's surface. The coast sustains rich ecosystems, such as salt marshes, mangroves, seagrass, and coral reefs. The shallow waters, long duration of sunlight, terrestrial and marine nutrients, tidal and wave flushing, and a range of habitat type support the diverse coastal ecology.

1.3 VULNERABILITY

Vulnerability has been defined by the Intergovernmental Panel on Climate Change (IPCC)as a function of exposure, sensitivity, and adaptive capacity (Das 2012). Exposure in present context refers to frequency and magnitude of a climatic event, sensitivity is the degree to which the system under analysis is affected by that exposure and the adaptive capacity, represents the ability of the system to recover from the exposure. 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).

The concept of coastal vulnerability is based on human value judgements concerning risk to various elements of the natural and human environment from a variety of sources(Green and McFadden 2007). Vulnerability of a coast may be understood as the measure of risk that the coast is exposed to. Generally, it is the amount of land resource lost to any hazardous event that takes place along the coast. Modelling coastal vulnerability is vital in order to understand regional and global ecosystem responses towards change induced in them by the environmental and anthropogenic factors and consequently to formulate strategies to mitigate these impacts. Dynamic complexities of coastal system have been an obstacle in predicting the vulnerability of a coast on a quantitative scale. Therefore, simple inundation models, probabilistic frameworks, and coastal vulnerability assessments are some of the tools used in predicting susceptibility of a coast.

1.4 COASTAL VULNERABILITY INDEX (CVI)

Various methods have been proposed to assess coastal vulnerability to climate change. Based on the European Topic Centre on Climate Change impacts, vulnerability and adaptation(Ramieri and Hartley 2011) report, coastal vulnerability assessment can be classified into four main categories:

1. Index-based methods
2. Indicator-based approach
3. GIS-based decision support systems
4. Methods based on dynamic computer models

Development of a vulnerability index involves the identification of key variables representing significant driving processes influencing the coastal vulnerability as the first step. The second step involves quantification of key variables which is generally based on the definition of semi-quantitative scores according to a 1-5 where 1 indicates a low contribution to coastal vulnerability of a specific key variable for the studied area or sub-areas, while 5 indicates a high contribution. Final step involves key variables are integrated in a single index. Main limitation of this method is the inability to address socio-economic aspects.

The Eurosion (2004) project has identified thirteen indicators to support the assessment of coastal erosion risk throughout Europe. The same indicators are generally used worldwide as the vulnerability indicators. The indicators may be changed according the need of the study. In indicator based method of vulnerability assessment, each indicator is evaluated based on a semi-quantitative score representing low, medium and high level of distress expected in future. Finally, sensitivity and impact indicators are aggregated deriving a sensitivity score and an impact score whose product defines the “risk of coastal erosion” which is subdivided in four classes: very high, high, moderate and lower exposure

Among the index based methods Coastal Vulnerability Index (CVI) is the most commonly used method to assess coastal vulnerability. However, last several years have witnessed noticeable increase in the number of vulnerability indices for specific coastal areas (McLaughlin et al. 2002). CVI has been very useful to identify the regions vulnerable to the impacts of future Sea Level Rise (SLR), and has aided coastal management decisions with necessary maps and data(Gornitz et al. 1997; Shaw et al.1998;Pendleton et al. 2010). CVI has the advantage of revealing the combined effect of risk factors on any particular segment of coast over other assessment methods. CVI also provides a simple numerical basis for ranking sections of coastline in terms of their potential for change that can be used to identify regions where risks may be relatively high.

1.5 COLLECTION OF MULTIDISCIPLINARY DATA

Cutter et al.(2000) opined that vulnerability is the threat of exposure, while other researchers state vulnerability as an indicator of the capacity to suffer harm, including resistance, resilience and recovery for a hazardous event. The vulnerability due to a natural hazard is an essentially geographical problem, which demands a spatial solution. Although there is considerable research activity on selected elements of vulnerability (social systems, exposure, risk estimation, infrastructure), we frequently lack the capability to assimilate information across all these domains. Further, vulnerability assessments at the local level are constrained by data availability and the lack of appropriate analytical techniques(Cutter et al. 2000).

Two recent developments in spatial information technologies have made it effortless to carry out global assessments of coastal vulnerability. The first development is the access to spatial datasets for environmental assessment derived from sources such as satellite remote sensing, historical aerial photography, and published socio-economic data. Advantage of remote sensing data is that it can be transformed into information using digital image processing techniques if appropriate logic and methods are used. The second development is the advancement in spatial data processing technologies such as Geographic Information Systems (GIS) and image processing with high performance computers. These developments make it possible to model such changes at varying levels of temporal and spatial scale.

Geographic Information System (GIS) handles spatial information by linking locations with information about that location. GIS has functions and tools required to efficiently capture, store, analyze, and display the information about places and things. The preparation of data and mapping the spatial relationships between natural hazard phenomena and the elements in threat requires the use of GIS. The techniques of remote sensing, GIS and GPS have been proven to provide extremely valuable data for analysis of the scenario and develop management action plans. Studies showed that satellite remote sensing offered high temporal resolution for monitoring of land-use change at lower costs than those associated with the use of traditional methods (El Raey 1988; Jensen and Toll 1982). The advantage of repetitive coverage and synoptic view of the 'region of interest' from various earth observation satellites have supported in generating databases on various aspects of the coastal and marine environment (Nayak 2004).

1.6 COASTAL VULNERABILITY ASSESSMENT IN INDIA

The Indian coast is subject to severe weather events, such as cyclones and super-cyclones at an average of nine cyclones per year (ICZMP 2010). Research on coastal processes gained importance post tsunami event of 2004 (Sudha Rani et al. 2015). In this regard, many studies have been conducted in India for developing vulnerability index and to assess vulnerabilities along the cost. East coast has been the region of interest more often in studies as it is subjected to higher events of natural hazards in comparison to the west coast of India. Following section lists out some of the important studies in India.

Coast of Andhra Pradesh was analysed by Rao et al. 2009 and a CVI was constructed for eustatic sea-level rise for the Physical variables. Kumar et al. (2010) developed CVI for coastal areas of Orissa considering eight relative risk variables representing coastal natural hazards. The data were collected from different sources including remote sensing satellites, insitu measurements and from numerical models. Sheik Mujabar and Chandrasekar(2013) assessed coastal Tamil Nadu for erosion hazard using geological and physical variables assembled from remote sensing and Geographic Information System (GIS). Mahendra et al.(2011) conducted the vulnerability analysis for Cuddalore, Nagapattinam and Pondicherry coast following Hazard Risk-Exposure approach using Remote Sensing and GIS tools. Arun Kumar and Kunte (2012) developed CVI for the Chennai coast while Mariappan and Devi (2013) studied the part of south Chennai coast. In the west coast of India, previously D. P. K. Kumar (2006) carried out an assessment for Cochin coast of Kerala. Hegde and Reju (2007) and Dwarakish et al. (2009) had assessed the vulnerability for the Mangaluru and Udupi coast of Karnataka. Kunte et al. (2014) studied the coast of Goa and evaluated CVI which is a combination of physical as well as socio-economical variables. Mahapatra et al. (2015) carried out study for coast of Gujarat. Even after such assessment, nation's rapidly growing population in coastal regions, their demand for reliable information regarding the vulnerability of coastal regions and increased episodes of natural hazards have created a need for developing vulnerability index.

1.7 NECESSITY OF PRESENT WORK

In the recent times, there has been an increase in the number of sea-borne hazards. Mitigating the effects of a potential disaster requires a detailed knowledge about vulnerability of the places to a wide range of hazards. Since vulnerability may be associated with natural or social hazards, or sometimes a combination of both, various dimensions involving a hazard must be taken into account to effectively carry out a vulnerability assessment (Parthasarathy and Natesan 2014). Coastal zone of Karnataka is one of the highly urbanized and better-developed geographical areas of the State with a high degree of economic development and population density. Literatures revealed that a comprehensive study on vulnerability factors of complete Karnataka coast was lacking. Hence, the present study aims to develop a vulnerability index that provides an understanding about the vulnerability of the Karnataka coast to natural hazards.

Study intends to make use of new spatial information techniques and currently available global data-sets to assess the current status of vulnerability for the coast of Karnataka. The study attempts to identify main driving forces affecting coastal environment using the application of remote sensing and GIS. In addition, study also aims at aiding policy options for coastal planners and authorities with regard to prioritizing coastal areas for mitigation.

1.8 OBJECTIVES OF THE STUDY

1. To quantify the vulnerability of various physical and socio-economical variables such as population, infrastructure, land use and land cover on the coast of Karnataka.
2. To develop a model for calculation of CVI.
3. To determine CVI for the coastal stretch of Karnataka.

1.9 ORGANIZATION OF THE THESIS

The thesis comprises of seven chapters, list of references and annexure. A brief explanation about each chapter is presented here.

Chapter 1 provides an introduction and need of the present research work and also lists out the objectives of the study.

Chapter 2 presents the literature review of the previous works on coastal vulnerability assessment, problem formulation and specific objectives and the scope of the present study.

Chapter 3 describes the study area, vulnerability variables, datasets used in this study along with methodology adopted.

Chapter 4 details the analysis of vulnerability variables pertaining to the study area.

Chapter 5 provides the results and discussion of the analysis.

Chapter 6 provides details about tsunami vulnerability mapping of the study area.

Finally, **Chapter 7** provides conclusions, limitations and scope for further research.

CHAPTER 2

LITERATURE SURVEY

2.1 GENERAL

Coastal ecosystem is exposed to natural hazards such as storms, tsunamis, river flooding, shoreline erosion, and sometimes, also to bio-hazards such as algal blooms and pollution (IPCC 2001). Degree of resistance offered by the entity to the hazard amounts for the vulnerability of that entity. Vulnerability has various definitions for itself as it has a multi-dimensional aspect (Sudha Rani et al. 2015). From natural hazard's perspective, risk could be the probability of occurrence of a hazardous event (Boruff et al. 2005) 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 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). The risk assessment study involves four components, namely, environmental vulnerability, social vulnerability, hazard potential and mitigation capacity.

One of the most common vulnerability assessments is carried out using indicators which are combined together to form a composite index. Normally, coastal environments are exposed to multiple threats and hence vulnerability assessment in such environments has led to the construction of composite indices, with a common index known as the Coastal Vulnerability Index (CVI). Various methodologies have been developed to assess the vulnerability of coastal areas to environmental hazards. CVI stands out among these as the simplest method of assessment. CVI classifies the coastline into units exhibiting similar attributes or characteristics based on relative risk posed by the natural and anthropogenic factors. A focused research work has been carried out in determining indices for coastal zone. Following section lists various studies carried out in this aspect. The majority of researchers have used multidisciplinary data for their study.

2.2 GLOBAL CVI STUDIES

Early studies on CVI were carried out by Gornitz (1990). The study assessed the vulnerability of the East coast of the United States with primary consideration on future Sea-level rise. A coastal hazards database was constructed in the study considering mean elevation, local subsidence trend, geology, geomorphology, mean shoreline displacement, maximum wave height and mean tidal range as the variables. A ranking system ranging from 1 to 5 was assigned to these hazard influencing variables based on relative risk factor. The rankings were later combined to derive an index.

Gornitzet al.(1994) improved upon the former CVI (Gornitz 1990). A coastal risk assessment database was developed for use with geographic information system. The database was used to identify the coastal areas at risk due to erosion or accretion, probabilities of tropical storm occurrence and maximum storm surge for the Southeast Coast of U.S.A. These variables were grouped into three categories using factor analysis. Each category was then weighted based on its perceived importance in determining the relative risk of an area to erosion or inundation. These weighted factors were used to calculate a risk index. This index classified approximately 30% of the Gulf Coast and 15% of the East Coast as being at very high risk to inundation or increased erosion from Sea-level rise. Study defined High risk coastlines of Southeast U.S.A. characterized with low coastal elevations, erodible substrate, present and past evidence of subsidence, histories of extensive shoreline retreat, high wave/tide energies, and high probabilities of being hit by tropical storms, hurricanes, or extra tropical cyclones. One or more of the above-mentioned features were present in high-risk coast lines.

Huan et al. (1997)studied and assessed the vulnerability of the entire coastal zone of Vietnam to the impacts of accelerated Sea-level rise due to global warming. The project was conducted by employing the Inter-governmental Panel on the Climate

Change (IPCC) Common Methodology framework. In the study, extensive data on physical, socio-economic and institutional characteristics of the coastal zone were the basis for GIS analyses for determined areas with different land use types inundated under various flood scenarios. Further analyses provided loss and risk figures for land use types, population and capital value.

Thieler and Hammer-Klose (1999) made studies on U.S. Atlantic Coast. The CVI estimated was similar to that used by Gornitz et al. (1994), as well as to the sensitivity index employed by Shaw et al. (1998). Study was carried out using coastal slope, geomorphology, relative sea-level rise rate, shoreline change rate, mean tidal range, and mean wave height as variables. Study considered that macrotidal coastline is at a low risk which was in contradiction to previous and related studies (Gornitz, 1990; Shaw et al. 1998). The reasoning for this assumption was based primarily on the potential influence of storms on coastal evolution, and their impact relative to the tide range. Researchers opined that a microtidal coastline is essentially always “near” high tide and therefore always at the greatest risk of inundation from storms. The coastal vulnerability index was calculated as the square root of the product of the ranked variables divided by the total number of variables;

$$\mathrm{CVI}_5 = \sqrt{\frac{a*b*c*d*e*f}{6}} \qquad (2.1)$$

where a = geomorphology, b = coastal slope, c = relative sea-level rise rate, d = shoreline erosion/accretion rate, e = mean tide range, and f = mean wave height. A total of 23,384 km of shoreline was ranked in the study area. Of this total, 27% of the mapped shoreline was classified as being at very high risk due to future sea-level rise.

Belperioet al. (2001) used 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. They claimed that regional scale distributed coastal process modelling may be used as initial assessment of coastal vulnerability to sea-level rise in tide-dominated, sedimentary coastal regions. The study emphasised that distributed coastal process modelling provides suitable basis for assessment of coastal vulnerability to sea-level rise, results of which do have adequate accuracy for effective coastal management.

Dominey-Howes and Papathoma (2003) applied a new tsunami vulnerability assessment method to categorize Building Vulnerability (BV) by considering the worst case of tsunami scenario as the event of 7th February 1963, for two coastal villages in the Gulf of Corinth, Greece. This study considered the identification of the inundation zone without taking into consideration the tsunami source and offshore bathymetry. Study showed clearly that the vulnerability of buildings to tsunami flooding is not uniform within the inundation zone. Study concluded vulnerability is a complex factor that depends on a number of parameters.

Pendleton et al.(2005) assessed the coastal vulnerability of Golden Gate National Recreation area to SLR by calculating 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 study showed that 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. They concluded that geomorphology, regional coastal slope, and mean significant wave height play the largest role in determining the spatial variability of the CVI. The CVI is one of the ways in which authorities can objectively assess the natural factors that contribute to the evolution of the coastal zone.

Diez et al. (2007)assessed the coastal stretches in the Buenos Aires, Argentina. The study was duly concentrated on Buenos Aires province coast since it has a representative geomorphology of complete Argentinean coastline. The aim of the study was to evaluate the response of two coastal vulnerability equations to determine their suitability at national scale. The equations were:

$$\mathrm{CVI}_5 = \sqrt{\frac{\mathrm{X}_1 * \mathrm{X}_2 * \mathrm{X}_3 * \mathrm{X}_4 * \mathrm{X}_5 * \mathrm{X}_6 * \mathrm{X}_7}{7}} \qquad (2.2)$$

$$\mathrm{CVI}_6 = 4\mathrm{X}_1 + 4\mathrm{X}_2 + 2(\mathrm{X}_3 + \mathrm{X}_4) + 4\mathrm{X}_5 + 2(\mathrm{X}_6 + \mathrm{X}_7) \qquad (2.3)$$

where$X_1$is Elevation (m), $X_2$is Sea-level rise (mm/y), $X_3$is Geology,$X_4$is Geomorphology,$X_5$is Shoreline erosion/accretion of the coastline (m/y), $X_6$is average wave height (m) and $X_7$is Mean tide range (m). A single index value for each grid cell was calculated. The data were later classified through the method of natural breaks as low, moderate, high, and very high hazards and then mapped.On verifying the equations, CVI_6 was found to be more appropriate for the analysis of coasts with different morphologies.

Szlafsztein and Horst Sterr (2007) studied north-eastern coast of Pará, Brazil for natural and socio-economic vulnerabilities using Geographical Information Systems (GIS) and developed composite CVI for the study area. In spite of the data problems and shortcomings, the CVI score was computed to classify weight and combine sixteen separate natural and socio-economic variables to create a single indicator. The indicator offered five different classes among regions and communities that are exposed to similar ranges of hazards. The results were presented in three maps referred to as Natural, Socioeconomic and Total Vulnerability. The confidence associated with the results obtained, the need of other variables, and updating the ones used already were analyzed and discussed.

Snoussi and Niazi (2008)carried out a study on Mediterranean coast of Morocco for the scenarios for future sea-level rise ranging from 200 to 860 mm. Assessment of the potential land loss by inundation was carried out using empirical approaches for a minimum inundation level of 2 m and a maximum inundation level of 7 m. The socio-economic impacts were studied for scenarios; one is the ‘worst-case’ scenario obtained by combining the ‘economic development’ with the maximum inundation level, and scenario two is the best-case scenario obtained by combining the sustainability scenario with the minimum inundation level. Their results revealed that most severely affected sectors would be the residential and recreational areas, agricultural land, and the natural ecosystem. The study also proposed a few strategies to mitigate the impact by undertaking wetland preservation, beach nourishment at tourist resorts, and the afforestation on the beach dunes.

Similar CVI was developed for coastal location of Alaska (Gorokhovichet al. 2014), the Canary Islands (Di Paolaet al. 2011), China (Yinet al. 2012), Ghana (Addo 2013), Greece (Doukakis 2005; Gaki-Papanastassiou et al. 2010; Karymbalis et al. 2012), Philippines (Clavano 2012), South Africa (Hughes and Brundrit 1992; Palmer et al. 2011), Thailand (Duriyapong and Nakhapakorn 2011), and Turkey (Ozyurtand Ergin 2010; 2009). Most of these studies made use of same geologic and physical variables as used by Thieler and Hammer-Klose (1999; 2000a, b). Some of these studies were also constrained by the availability of the data. The primary focus of these studies was to assess coastal vulnerability only to Sea Level Rise (SLR) based on geologic and physical parameters.

The major drawback of the listed studies was that in these studies the influence or the weights for each variable on the vulnerability of a coast were deduced arbitrarily or using an individual’s discretion (Manimurali et al. 2013). As developing CVI involved multiple variables non-relative to each other, Analytical hierarchical Process (AHP) has been considered for calculating weights based on expert opinions. AHP had been previously used in several studies involving landslide hazard zone delineation, flood mapping and soil erosion hazard mapping (Phukonet al. 2012;Bhattet al. 2010; Sinhaet al. 2008; Rahmanet al. 2009). Its use for coastal vulnerability has been very limited although.

Sinagaet al.(2011) described a GIS based multi-criteria analysis of tsunami vulnerability for the Jembrana Regency in Bali, Indonesia. Study made use of multiple geospatial variables; topographic elevation and slope, tsunami direction, coastal proximity, and coastal shape. Study applied Analytic Hierarchy Process (AHP) to construct a weighing scheme for the geospatial variables. Study suggested GIS based analyses to aid in disaster assessment and assist in regional planning for management and mitigation of natural disasters such as tsunamis.

Le Cozannet et al.(2013), in their study assessed applicability and usefulness of multi-criteria decision-mapping method (AHP) to map physical coastal vulnerability to erosion and flooding for two regions in France: the coastal zones of Languedoc-Roussillon and the island of La R´eunion. The results showed higher vulnerability of sand spits, estuaries and low-lying areas near to coastal lagoons. Authors found that the application of AHP provides a flexible framework to represent and aggregate existing knowledge and to support long-term coastal zone planning.Study detailed the advantages, disadvantages and uncertainties involving AHP and coastal vulnerability extensively.

Bagdanavičiūtė et al., (2015) developed an updated set of indicators of coastal vulnerability that characterise relatively low-lying coastal segments with negligible tidal range but are affected by significant amount of storm surges. The study area was 90 km long Lithuanian coast. The study derived CVI for the study area using AHP based approach incorporating experts' evaluation to indicate the weights of each criterion. The geological parameters taken into account were shoreline change rate, beach width and height, underwater slope, sand bars, and beach sediments. Only significant wave height was the direct physical parameter. The selected criteria were integrated into CVI for two cases. One, all criteria contribute equally. Second, each criterion may have a different contribution. Based on weights and scores derived using AHP, vulnerability maps were prepared highlighting areas with very low, low, medium, high and very high vulnerability. CVI calculation for case 2 highlighted 32% of the coast being of very high-to-high vulnerability, 22% of moderate vulnerability and 41% of low to very low vulnerability.

2.2.1 SOCIO-ECONOMIC VARIABLES IN COASTAL VULNERABILITY ASSESSMENT

Socio-economic changes are frequent and are more rapid than physical process. The vulnerability of coastal region cannot be comprehensive without the amalgamation of social, economic, built-environment, and physical characteristics(Boruff et al. 2005).Many of the studies which have developed a physical variable based CVI agreed that the inclusion of socio-economic variables would construct a more policy useful index (Clavano 2012; Diez et al. 2007; Gornitz et al. 1994).

Hughes and Brundrit (1992) did not consider socio-economic variable in their study, but acknowledged that economic value of an area would increase with increase in population. They concluded that further studies should focus on population dynamics and the effects of increasing urbanization. Gornitz (1990) also did not consider population in the study, but noted that further studies should take into account coastal populations to help in ranking vulnerable areas and population is to be viewed as an "economic" variable as people in densely populated areas act to protect their properties from erosion.

McLaughlin et al.(2002) carried out a study on Northern Ireland coast considering socio- economic variables: population; cultural heritage; roads; and land use. This study investigated the assimilation of socio-economic variables into a GIS based coastal vulnerability index for erosion due to waves. A socio-economic sub-index was developed which contributed for one third of the overall index score, while the other components were of coastal forcing and coastal characteristic sub-indices. All variables were ranked on a scale of 1 to 5 with five being most vulnerable. The variables were merged within sub-indices and then the sub-indices were combined to produce the overall index. They concluded that inclusion of socio-economic variables in coastal vulnerability indices is extremely important. They also commented that, socio-economic variables are usually omitted from indices, probably due to the difficulties in obtaining and ranking the data.

Nichollset al.(2008)suggested that, in assessments, socio-economic scenarios are needed to be coupled with impact scenarios to provide more complete description of the range of possible future coastal conditions. They also argued that an integrated coastal assessment is a multidisciplinary problem crossing many areas of human knowledge, and future assessments need to integrate engineering, natural and social sciences.

Ozyurt and Ergin (2009) considered seven anthropogenic factors (reduction of sediment supply, river flow regulation, engineered frontage, natural protection degradation, coastal protection structures, groundwater consumption, land use pattern) along with physical variables for selected coastal areas of Turkey. A coastal vulnerability matrix and a corresponding coastal vulnerability index for the region to SLR were developed. During the development, indicators of impacts of SLR, which make use of commonly available data, were used. Thus developed coastal vulnerability assessment model was used to determine the vulnerability of three different coastal areas of Turkey to verify the sensitivity of the model to regional properties. The study revealed that local properties could also be incorporated in model with the expected impacts of Sea-level rise. They concluded that integration of geographical information systems and application of fuzzy logic would increase the accuracy of prediction.

McLaughlin and Cooper (2010)investigated the effect of spatial scale in depicting coastal hazard risk. Coastal vulnerability indices were developed at national (Northern Ireland), local authority and site levels. Variables were separated into three sub-indices: a coastal characteristics sub-index concerned with the resilience and susceptibility of the coast to erosion; a coastal forcing sub-index to characterize the forcing variables contributing to wave-induced erosion; and a socio-economic sub-index to evaluate the infrastructure at risk. The three sub-indices were merged into a overall index. It was observed that some of the important local variations in vulnerability were cloaked by simplifications at the national scale. It was also noted that spatial resolution of the study directly influenced the completeness of information for some of the variables, while for others it became obsolete as data are of insufficient resolution to differentiate real variability at more detailed scales. The study results highlighted the importance of spatial scale in developing indices of vulnerability.

Orencio and Fujii(2012) constructed a Coastal Community Vulnerability Index (CCVI) to evaluate the vulnerability of coastal communities in the municipality of Baler, Aurora, Philippines. Index was combination of weighted averages of seven vulnerability factors namely geographical, economic and livelihood, food security, environmental, policy and institutional, demographic, and capital good. Among the factors evaluated, economic and livelihood, policy and institutional and food security contributed to CCVI across communities. Only small variations on CCVI values were observed as factor values cancelled out one another during combination process. The highest CCVI was contributed mainly by geographical and demographic factors. This technique to determine factors that influenced communities' vulnerability can provide information for local governments in enhancing policies on risk mitigation and adaptation.

2.3 COASTAL VULNERABILITY ASSESSMENT STUDIES IN INDIA

Indian subcontinent has a coastline of 5,400 km and around 250 million people live within 50 km of the coastline of India (ICZMP 2010). In spite of the various policies and regulatory frameworks, India‘s coastal and marine ecosystems are under threat due to multiple stresses (Sudha Rani et al. 2015). The event of December 2004 tsunami brought importance of studying natural hazards and coastal processes along the Indian coast(Nayak et al. 2007). Various vulnerability assessments were carried out in India after the December 2004 tsunami. Such works have been listed in this section to ascertain the position of India in terms of vulnerability assessment.

Rajawat et al.(2006) delineated the hazard line along the Indian coast using data on coastline displacement, tide, waves, and elevation. Dinesh Kumar (2006) used SLR scenario to calculate the potential vulnerability for coastal zones of Cochin, southwest coast of India. Study concluded that climate induced sea-level rise will bring profound effects on coastal zones. Study also revealed that the mean beach slope and relief play a vital role in land loss of the region. The local relief of coastal zone would decrease as Sea-level would rise, thereby increasing the percentage of land above mean sea level to periodic inundations.

Hegde and Reju (2007) developed a coastal vulnerability index for the Mangaluru coast using geomorphology, regional coastal slope, shoreline change rates, and population. A detailed study of erosion and accretion rate was carried out to calculate shoreline change rate. Study area was divided into transects of equal length and each transect was analyzed. CVI for coast was determined as the mean of variables considered. They opined that with inclusion of physical parameters like wave height, tidal range, probability of storm, etc., could improve the quality of the CVI.

Dwarakish et al. (2009) carried out a study on Udupi coast using geologic variables like historic shoreline change, geomorphology and coastal slope. They also included as physical variables mean tidal range, mean significant wave height and global SLR. Study used both conventional and remote sensing data for evaluating effects of variables. Method used was same as that used by Gornitz et al. (1994) and Thieler and Hammar-Klose (1999). Land or the beach loss due to coastal erosion and coastal inundation were the two types of physical impacts considered in this study. A total of 95 km of the shoreline was ranked in the study area. They found out that 42.19 km^2 and 372.08 km^2 of the land area would be submerged by flooding at 1 m and 10 m inundation levels respectively. They concluded that most severely affected sectors can expected to be the residential and recreational areas, agricultural lands and the natural ecosystem.

Srinivas Kumar et al.(2010) carried out a study for coast of Orissa using Shore-line change rate, Sea-level change rate, Coastal slope, Significant wave height, Tidal range, Coastal regional elevation, Coastal geomorphology, and Tsunami run-up. They suggested that the mean of the long-term tidal records has a tendency to suppress the effect of episodic inundation hazards of tsunamis and hence tsunami run-up has to be considered as a parameter to calculate the CVI. Multidisciplinary data involving remote sensing satellite data, long-term in situ measurements or data generated from numerical models were used for the study. The method of computing the CVI in the study was similar to that used in Pendleton et al.(2005); Thieler (2000); and Thieler and Hammar-Klose (1999). Zones of vulnerability to coastal natural hazards of different magnitude were recognized and revealed on a map.

Mujabar and Chandrasekar (2011) carried out a study on southern coast of Tamil Nadu using five physical variables, namely, coastal geomorphology, coastal slope, shoreline change, mean spring tide range, and significant wave height. The erosion and accretion at different parts of the study area were measured and analyzed. The coastal vulnerability index (CVI) was used to map the relative vulnerability along the study area. Study ranked both geological and physical variables in terms of their physical contribution to sea-level rise and vulnerability. Study revealed that vulnerability is due to a complex interaction of various natural and human-induced coastal processes. The natural processes due to geology and geomorphology, the combined action of waves and currents, variations in sea level, tectonics and storms affect the vulnerability. A coastal vulnerability index was prepared by combining the weighted rank values of the five variables, based on which the coastline is segmented into low, moderate, high, and very high risk categories.

Jana and Bhattacharya (2013) conducted a study around Midnapur-Balasore Coast, West Bengal. Coastal erosion vulnerability was assessed by combining coastal retreat with landuse type and population density in this study area using simple vector algebraic technique. Zones of vulnerability of different magnitude were identified using shoreline change rate, landuse, human activities and population density as parameters. They opined that coastal vulnerability map produced using the methodology followed in the study can identify broad indication of threats to people living in this coastal zone.

Manimurali et al. (2013) applied Analytical Hierarchical Process (AHP) based approach to coastal vulnerability studies first time in India. The study derived AHP based weights for seven physical–geological parameters namely slope, geomorphology, elevation, shoreline change, sea level rise, significant wave height and tidal range along with and four socio-economic factors: population, landuse/landcover (LU/LC), roads and location of tourist areas. The study area was the coast of Puducherry. The authors opined that AHP allows experts to convert their individual judgments into quantitative weights and therefore AHP has advantage in vulnerability assessments where there is a shortage of a purely deterministic method due to the large quantity of data involved from different sources. Based on the weights and scores derived using AHP, vulnerability maps were prepared to demarcate areas with very low, medium and high vulnerability. The study found that 50% of the Puducherry coastline was under high vulnerability while zones of medium vulnerability and the low vulnerability were 25% each of the total coastline. The authors stressed that results obtained from the study may be employed in identification and prioritization of the more vulnerable areas of the region. Also, it can further be used to assist the government and the residing coastal communities for better coastal management and conservation.

Saxena et al. (2013) derived comprehensive habitation vulnerability assessment framework for 42 km coast of Cuddalore District of Tamil Nadu by combining Geophysical–Natural factors with Socio-Economic-Institutional factors responsible for causing vulnerability at habitation levels and to construct composite vulnerability index and dimensional indices. Composite vulnerability index for 17 habitations in the study area was developed on a scale of ‘one’ to ‘five’ by considering nine dimensions of vulnerability; geographic, demographic, institutional, natural, social, safety infrastructure, physical, livelihood and economics. They were of the opinion that sensitivity and resilience of the exposed population decides the magnitude and risk of coastal disasters caused by natural hazards. They also concluded that an index provides a qualitative rating to prioritize key issues that are needed to be addressed, and also enhances the analysis of subjective traits and is useful in summarizing and communicating the vulnerability assessment results to decision makers and stakeholders.

Kunte et al. (2014) assessed vulnerability for 105 km coastline of Goa state in West India. Coastal Vulnerability Index (CVI) was developed for the different administrative units of the state (talukas) using seven physical and geologic risk variables; 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. The study provided information aimed at increasing awareness amongst decision-makers to deal with disaster mitigation and coastal zone management, and prioritizing areas for climate change adaptation in view of the projected SLR and increased storm events.

Parthasarathy and Natesan (2014) investigated coastal vulnerability index (CVI) to map the vulnerability of Tuticorin coast towards coastal erosion using remote sensing data and geographical information techniques based on a multi-indicator approach. Beach width was considered as an additional parameter in the study with other parameters as large number of coastal habitations was present adjacent to the beach along the study area. They observed that Coastal erosion, slope and relative sea level rise are the major factors affecting the coastal vulnerability in

Tuticorin. CVI scores were categorized into four classes, *viz.*, low, moderate, high and very high risk. They stated that the approach adopted by them provides an insight to assess the vulnerability and the degree of potential threat to the coastal system to prioritize actions and develop adaptation measures.

Mahapatra et al. (2015)developed an integrated coastal vulnerability index (ICVI) for the Southern Gujarat coast by combining both physical and socioeconomic variables. Five physical variables, namely coastal slope, Coastal landforms or features, Shoreline change rate, Mean spring tidal range, and Significant wave height were considered for calculating Physical Vulnerability Index (PVI), whereas four socio-economic factors such as population density of adjacent coastal villages, land use/land cover, proximity to road network and settlement were considered to assess the Social Vulnerability Index (SVI). Study employed analytical hierarchical process (AHP) method to calculate weights for PVI and SVI. This improvement to the existing methodology of vulnerability assessment is supported by the argument that the variables under consideration do not have equal hazardous effect on the coast. Study also provided suitable logical justification for the argument. Based on the weights and scores derived using AHP, vulnerability maps were prepared to demarcate areas with very low, low, medium, high, and very high risk regions in the study area. Authors found that 52.51% of the coastal segment was with low to very low risk, while 13.47 % of the coastal stretch was under the high to very high-risk category.

Appelquistand Balstrøm (2015) developed a new methodology termed the Coastal Hazard Wheel (CHW) for coastal multi-hazard assessment and management for the state of Karnataka, India. The methodology was designed for local, regional and national hazard screening in areas with limited data availability. The criteria covered in the assessment are the hazards on ecosystem, inundation, salt-water intrusion, erosion and flooding. The study also demonstrated how the CHW framework can be applied at a scale relevant for regional planning purposes using published geophysical and remote sensing data. The study developed regional and sub-regional hazard maps using GIS, and also generated relevant hazard risk data. The study discussed about uncertainties, limitations and management perspectives involved in such assessments. The hazard assessment revealed that 61% of Karnataka's coastline has a high or very high hazard of erosion, making erosion the most common coastal hazard of Karnataka. It was also found that flooding and salt-water intrusions were also comparatively prevalent. About 39 % of Karnataka's coastline has a high or very high inherent hazard for both flooding and salt water.

Maiti et al. (2015) assessed social vulnerability to climate change of 29 eastern coastal districts across 4 eastern coastal states of India. The assessment was based on secondary data, like socio-economic and bio-physical indicators, collected from several authenticated sources; and weightage of these indicators were assigned by using Principal Component Analysis. Vulnerability was calculated as the net effect of exposure and sensitivity on the adaptive capacity. Pudukottai district of Tamil Nadu was found to be the most vulnerable district, while East Godavari district of Andhra Pradesh was the least vulnerable. The net effect was found to be negative in 10 districts: South 24-Parganas of West Bengal; Bhadrak of Odisha; Prakasam of Andhra Pradesh; Thiruvallur, Villipuram, Thanjavur, Thoothukkudi, Pudukottai, Ramanathapuram and Cuddalore of Tamil Nadu.

2.4 SECONDARY DATA ASSIMILATION AND OBSERVATIONS ON VARIABLES

Datasets are the primary requirement to assess the vulnerability since it involves many driving parameters. Studies mentioned previously have carried out vulnerability assessment using limited data and spatial information, due to lack and limitations of data availability. Two types of data are the essential prerequisite to perform the exercise. One is conventional data, and the other spatial data. The former comes from the ground observations and field reconnaissance survey, while the later could be obtained from spatial sensors. In the following sections, the studies that have provided limited secondary data have been listed.

Church (2004) studied the regional distribution of Sea Level Rise (SLR) over the period 1950–2000. TOPEX/Poseidon satellite altimeter data were used to estimate global empirical orthogonal functions that were then combined with historical tide gauge data to estimate monthly distributions of large-scale sea level variability. They observed that global-averaged sea level rise from the reconstructed monthly time series is 1.8 ± 0.3 mm per year.

Unnikrishnan et al. (2006) estimated mean sea level rise made from archived tide gauge data at selected stations along the coast of India. They observed that a rise of slightly less than 1 mm per year. They also advised that vertical land movement's correction must be applied to SLR estimates.

Kumar et al. (2011) studied the tidal variation along the near shore waters of Karnataka. Three locations along the near shore waters of Karnataka, west coast of India, were selected for study. The characteristics of tidal constituents were described for the near shore waters of Karnataka. They observed that the tidal variation for the locations along the coast varied between 2.1 to 1.58.

Gaughan et al. (2013) prepared high resolution population distribution dataset and using landuse and population count data. Study opined that for assessment of any natural hazard these datasets provide accurate description of human distribution, and hence more accurate mitigation strategies can be adopted.

Vinayaraj et al.(2011) investigated the coastal erosion and deposition at four stations of the study area: Karwar, Honnavar, Kundapura, and Malpe,covering a period of almost thirty years, along the Karnataka, west coast of India. Both erosion and deposition were observed at all the four stations. It was observed that erosion was spatially irregular and at isolated stretches all along the coast. Comparatively larger erosion was observed at the river mouths of Devbag (north of Kali River), at Pavinakurve (north of Sharavathi River) and at Kundapura. They also found that coastline at Malpe (Udupi) was almost stable with negligible erosion and deposition. Considerable loss of land was observed mainly at the river mouth due to the sediment erosion from the banks because of complex interactions between river flow, waves and the tides.

Thieler and Danforth (1994) developed a method for mapping historical shorelines from maps and aerial photographs. Digital Shoreline Analysis System (DSAS) was developed to calculate shoreline rates-of-change from a series of shoreline data residing in a GIS. Four types of rate change statistics could be calculated (end-point rate, average of rates, linear regression and Jack Knife) at a user-specified interval along the shoreline. Coast of Punta Uvero, Puerto Rico was used for assessing the errors associated with the source materials as well as the accuracy of computed shoreline positions and erosion rates. The study opined that the process yielded an accuracy tolerance of 9.25 m with all sources of error being considered and is sufficient to identify the short-term trend of shoreline changes.

Kuleli (2010) undertook a study for the coastal zone located in the Cukurova Delta in Mediterranean Sea. In the study, coastline changes were analyzed by using radiometrically and geometrically corrected multi-temporal and multi-spectral data from Landsat Multispectral Scanner dated 1972, Thematic Mapper dated 1987, and Enhanced Thematic Mapper dated 2002. The image processing steps to carry out coastline extraction, and application of the Digital Shoreline Analysis System (DSAS) to calculate rate of coastline changes were thoroughly discussed in the study.

Kumar et al. (2010) investigated changes in shoreline positions and morphology of spits along the southern Karnataka coast, western India, for the period from 1910 to 2005. In the study, rate of change in shoreline position has been estimated using the statistical linear regression method. Also they opined that short-term investigations (less than 10 year period) are more reliable in estimating the shoreline positions for the regions affected by anthropogenic interventions; and long-term (more than 20 year period) studies can be used for reliable estimates of relatively stable or unaffected regions. The study suggests that multi-dated satellite data along with statistical techniques can be effectively used for prediction of shoreline changes.

2.5 SCOPE OF PRESENT WORK

In the recent times, there has been an increase in the number of sea-borne hazards. Mitigating the effects of a potential disaster requires a detailed knowledge about vulnerability of the places to a wide range of hazards. Since vulnerability may be associated with natural or social hazards, or sometimes a combination of both, various dimensions involving a hazard must be taken into account to effectively carry out a vulnerability assessment (Parthasarathy and Natesan 2014). Coastal zone of

Karnataka is one of the highly urbanized and better-developed geographical areas of the state with a fair degree of economic development and higher population density. Earlier studies lack a comprehensive study on vulnerability factors along the coast of Karnataka. The present study, therefore, aims to develop an index that provides an understanding about the vulnerability of the Karnataka coast to natural hazards and the broad scope of the study is as follows:

1. The study intends to carry out a comprehensive vulnerability assessment of Karnataka coast by considering the physical, geological and socio-economical variables.
2. The data requirement is of large spatial extent and the study intends to utilize new spatial information techniques (remote sensing and GIS) to develop a vulnerability database for the coast of Karnataka.
3. The study identifies the main driving forces affecting the vulnerability of Karnataka coast. The coast is divided into definite number of stretches for the analysis and the driving forces are integrated to a form of index, which gives the risk posing on the coast.
4. One of the primary objectives of the study is to suggest a CVI model for the Karnataka coast. In this regard, study has carried out an opinion survey of experts from ocean engineering discipline for prioritizing the variables considered with regard to their vulnerability. The opinion survey is later converted into weights using the principle of Analytical Hierarchical Process (AHP). The summation of product of these weights with vulnerability score of the variables will yield CVI for the given stretch of the coast.
5. CVI calculated from the present study is used in formulating the suggesting the policy options for coastal planners and authorities with regard to prioritizing coastal areas for mitigation.

2.6 CLOSURE

Vulnerability studies generally undertaken skip a very important aspect, i.e. of human interaction with the nature. Researchers have insisted on inclusion of human interaction as a socio-economic variable in assessment studies. Most of the studies have been carried out using physical variables; Shoreline change rate, Sea-level change rate, Coastal slope, Significant wave height, Tidal range, Coastal regional elevation, Coastal geomorphology and very few studies have been carried out by combining socioeconomic variables along with the physical variables. Also very few studies have evaluated the effect of Tsunami and storm surge as variables for determining CVI.

Further, studies on the same for Indian coast are very few except for Orissa, Tamil Nadu, parts of Karnataka and a very recent study of Goa

CHAPTER 3

MATERIALS AND METHODOLOGY

3.1 GENERAL

Assessing vulnerability involves multi-disciplinary aspects as coastal zone is a complex dynamic system. Indicator-based approaches are best suited for such systems as vulnerability of the coast is expressed using a set of independent elements characterizing key coastal issues involving drivers, pressures, impacts, risk, exposure, sensitivity and damage (Parthasarathy and Natesan 2014). Coastal Vulnerability Index (CVI) has been employed as the most commonly used index for quantifying the vulnerability due to coastal erosion and sea-level rise. This approach provides relative measure to classify the coast based on natural vulnerability to coastal hazard. Index derived in this approach has the relative contribution of natural factors like waves, currents, tides and winds followed by geomorphological characteristics of the shore and sand, changes in relative sea-level.

The procedure adopted in the present study is similar to that formulated by Manimurali et al. (2013). The process results in a classification of coast using simple criteria and yields numerical data that cannot be equated directly with particular physical effects, but shows the region most affected by the hazard. Broadly, methodology involves preparing the database of vulnerability variables, ranking of variables and integrating the variables into single index. The preparation of database involves pre-processing of data which has been covered in following sections. Present study separates the vulnerability due to tsunami from the regular assessment as the reach of tsunami goes beyond the exclusive coastal zone. Hence, a separate tsunami vulnerability mapping has been carried out in the present study. Thus, in the present study, an effort has been made to mathematically express the status of Karnataka coast, in terms of variables influencing the hazardous effect. Present section describes variables, data sources of variables and methodological approach which has been adopted in the study.

3.2 VULNERABILITY VARIABLES

Vulnerability is a quantifiable scale which describes the extent to which any system is likely to be deranged by the impact of a particular hazard. In the present study the variables considered for the assessment are of grouped into three types.

- Geological variables
- Physical variables
- Socio-economic variables

Through a detailed study of literatures, it was found that majority of studies have justified that physical and geological variables are the primary factors influencing the vulnerability. However, inclusion of the socio-economic variables would make the study to be more accurate and complete. Hence, present study employs three physical, four geological and three socio-economic variables for calculation of CVI. Table 3.1 describes the variables considered in the present study with data source. Among the 10 variables of the study, preparation of the data for seven variables involves techniques of remote sensing and GIS. The flow chart in Fig. 3.1 schematises the process adopted in arriving at the preferred data format from the primary data source. The description, importance and vulnerability of the variables on the coast have been explained in the following sections.

Since the magnitude of the above listed variables is the factor influencing the vulnerability, initially a spatial database of the magnitude was assimilated using the GIS package. The magnitude of variables under consideration were assigned a vulnerability ranking between 1 to 5, based on their ability to cause damage on particular stretch of the coastline. The non-numerical variable geomorphology and landuse/landcover variable were ranked qualitatively according to the relative resistance of a given landform to erosion and economical value of the class, respectively. The magnitude was segmented based on their percentiles to assign the ranks. The variable value between lowest and the 20th percentile of the magnitude was assigned the rank 1 since its ability to cause damage is very low. Similarly, other ranks were assigned based on the 40th, 60th, 80th and the highest percentile of the magnitude.

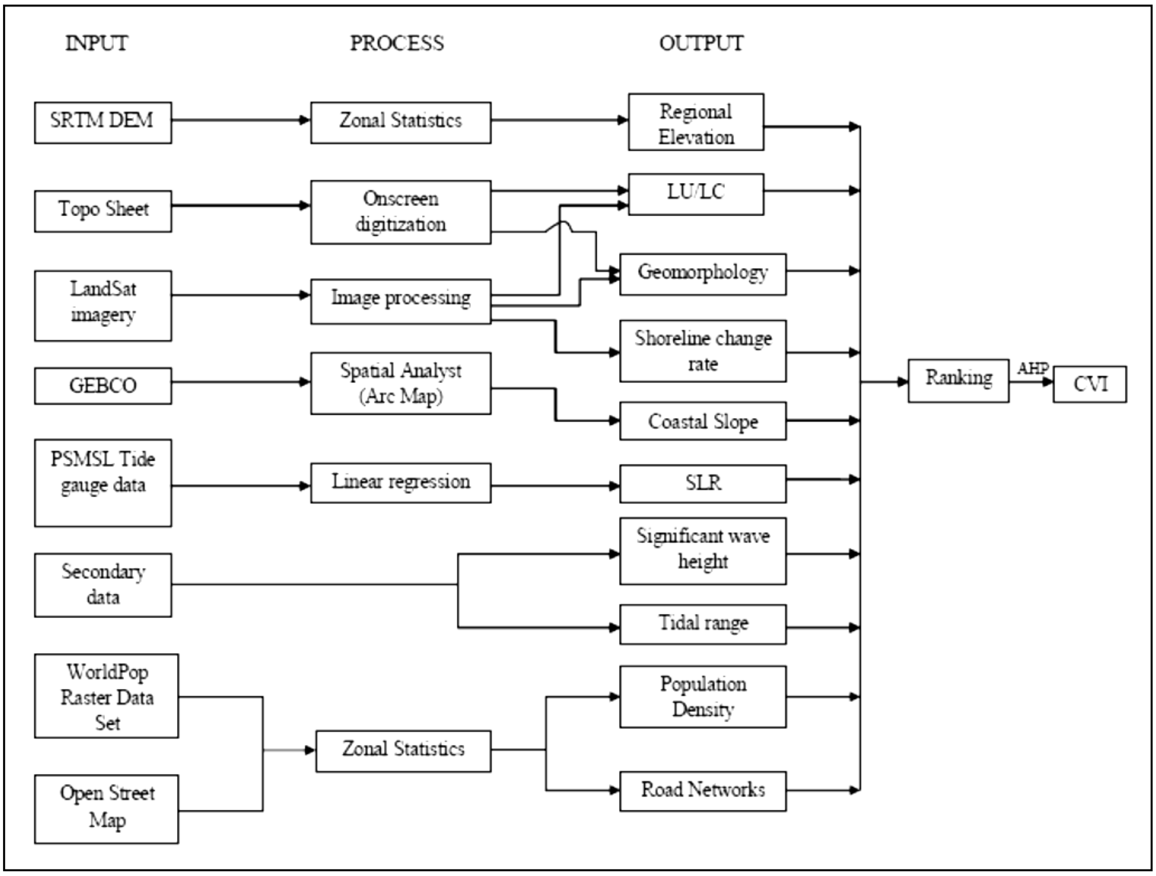


Fig. 3.1 Flow chart of Data preparation

The ranks of the variables were integrated to a single index using the modified CVI formulae. The CVI values were categorised into 4 different classesbased on the relative intensity of risk they impart on the coast. Categories were low, medium, high and very high, with the ranges of each risk-ranking category determined based on index values. The entire coastline was divided into 8 zones based on administrative boundary of talukas as talukas form the smallest administrative units. A grid template of 1.5 km by 1.5 km was used to store data, analyze and display the CVI. The software package ArcGIS 9.3 offers the suitable environment to carry out the process. The variation of each variable within the area was analysed and suitable risk ratings were awarded for each specific data variable and the coastal vulnerability index was calculated.

Table 3.1 List of Variables with their data sources and resolution

Sl. No	Variable	Type	Source of Data	Resolution	Period
1	Shoreline Change Rate	Geological	Landsat MSS, ETM+ and OLI-TIRS satellite imagery	30	1974 to 2014
2	Coastal Slope	Geological	GEBCO bathymetry data	1km	
3	Coastal Geomorphology	Geological	Landsat OLI-TIRS satellite imagery	30	2014
4	Regional Elevation	Geological	SRTM DEM	90 m	
5	Sea-Level Change Rate	Physical	PSMSL Tide Gauge Data	-	1939 to 2006
6	Tidal range	Physical	Secondary data	-	2013
7	Significant Wave Height	Physical	Secondary data	-	2013
8	Population	Socio-economical	Census of India and WorldPop.org	-	1991,2001, 2011 and 2015
9	Landuse/landcover	Socio-economical	KSRSC LU/LC map	-	-
10	Road Networks	Socio-economical	OpenStreetMap	-	2014

3.3 GEOLOGICAL VARIABLES

3.3.1 Geomorphology

Geomorphology is considered to be of primary importance as the geological feature facing the hazard takes the highest impact. It also expresses the relative erodability of various land-form types (Pendleton et al., 2005). The vulnerability of a coast is influenced by their configuration, and their dynamics are influenced by local and regional factors and their geographic location. For example, coast with volcanic boulders and rocky outcrops provides a stable substrate in comparison, offering protection to the landscape for the cases of erosional or depositional processes occurring at the place. On the contrary, beaches with substrates such as fine sand with no protection of rocky outcrops are subjected to increased dynamics with geomorphic and ecological fragility. Features like mudflats, beach terraces, spit, salt pans, sandy beaches, sand dunes and estuaries fall under highly vulnerable geomorphic units to sea-level rise and coastal erosion.

Geomorphologic map for the study area was prepared from the satellite imagery. The Landsat 8 satellite data was employed for the preparation of the geomorphology map. Ortho-rectified satellite images of the study area from the sensors Landsat OLITIRS for the year 2014 was downloaded from USGS Earth Explorer web tool. The image was projected to the Universal Transverse Mercator (UTM) projection system with WGS-84 datum. Using ERDAS Imagine 9.2 software on screen, digitization of various geomorphic classes was extracted using the visual interpretation keys developed by Space Applications Centre.

3.3.2 Shoreline change rate

Coastal shorelines are always under transformation due to coastal processes, governed by wave characteristics and the resultant near-shore circulation, sediment characteristics, beach form, etc. The transformation of the coast in the study area was analysed for a period of 42 years (1972 to 2014), which is regarded as medium term analysis (Crowell et al. 1993; Anfuso and Del Pozo 2009). Ortho-rectified satellite images of study area from the sensors Landsat MSS, ETM+ and OLI-TIRS were downloaded from USGS Earth Explorer web tool. The specifications about the satellite data used in the present study has been listed in Table 3.2. The tidal range along the study region is about 1.5 m and the submergence of the land associated with high tide period is less than 5-6 m (Bhat and Subrahmanya 2000). Hence, no additional corrections are undertaken for the delineation of shoreline other than approximately common acquisition time and period of the year.

The most suitable band for the demarcation of the land–water boundary has been identified as the near infrared band (Maiti and Bhattacharya 2009), and it is used in the study to extract the shoreline from satellite. A binary image was formed using near infra-red band of each image by histogram splicing technique. And these binary images were classified, using unsupervised classification, to form image with complete separation between land and water classes. These classified images were used to extract the shorelines in the form of vector layer using the package ERDAS Imagine 9.2 and ArcGIS®9.3. The digitized shorelines in the vector format of the years 1972, 1991, 1995, 1998, 200, 2006, 2012 and 2014 were used as input in Digital Shoreline Analysis System (DSAS). DSAS is an extension for ArcGIS used to calculate shoreline change rate. DSAS provides necessary features to cast transects normal to shore, spaced at a user defined distance from the baseline. DSAS computes rate-of change statistics from multiple historic shoreline positions residing in a GIS (Thieler et al. 2005). Fig. 3.2 shows the shorelines of various years as well as the baseline and transects for these shorelines. From the perspective of risk, coasts witnessing accretion will be considered as less vulnerable areas as they move towards the ocean resulting in the widening of land areas, whereas areas of coastal erosion will be considered as more vulnerable for the reason that the resultant loss of land and important natural habitats such as beaches, dunes, and marshes. It also reduces the distance between coastal population and ocean, thereby increasing the risk of exposure of population to coastal hazards.

Table 3.2 List of imagery acquisition date, sensor and resolution

Sl. No.	Acquisition date	Sensor	Resolution (m)
1	04-01-1972	MSS	60
2	03-01-1991	TM	60
3	06-12-1995	TM	60
4	17-03-1998	TM	60
5	08-01-2000	ETM+	30
6	11-02-2006	ETM+	30
7	15-03-2012	ETM+	30
8	13-03-2014	OLI-TIRS	30

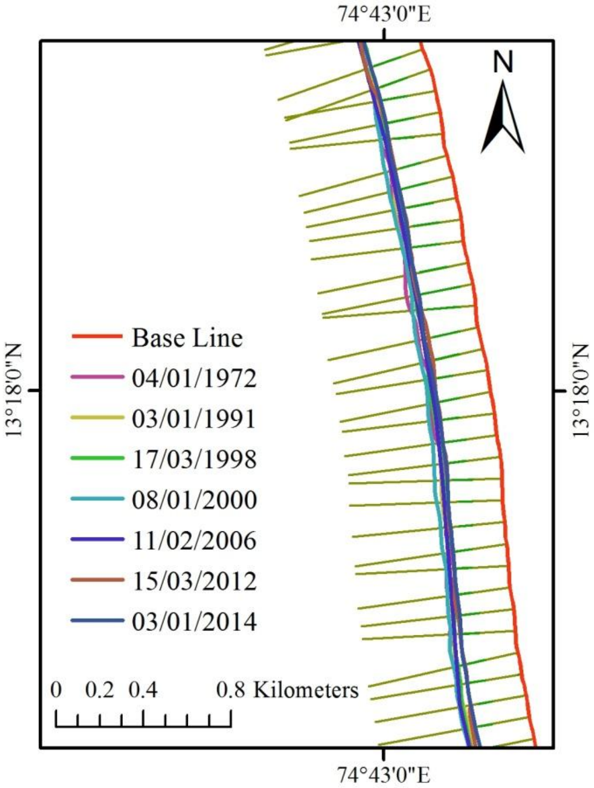


Fig. 3.2 Baseline, Transects and Shorelines

3.3.3 Coastal Slope

The coastal slope is change in altitude for a unit horizontal distance between any two points on the coast. The degree of steepness or flatness of a coastal region determines the susceptibility of coast to inundation by flooding (Thieler and Hammar-Klose 2000). Determination of regional coastal slope identifies the relative vulnerability of inundation and potential rapidity of shoreline retreat because low sloping coastal regions are thought to retreat faster than steeper regions (Pendleton et al. 2005). General Bathymetric Chart of the Oceans (GEBCO) data of 30-arc seconds grid resolution coastal topography and bathymetry has been used to get the regional slope of the coastal area. GEBCO also incorporates land elevations derived from the Global Land One kilometer Base Elevation project data set. GEBCO data sets are useful in deriving the coastal slope values on both land and in the ocean. 3D analyst tool of ArcGIS®9.3 was used in preparing the coastal slope map. Coastal areas having gentle slope were considered as highly vulnerable areas and areas of steep slope as areas of low vulnerability.

3.3.4 Regional elevation

It is important to study the coastal regional elevation detail in the study area to identify and estimate the extent of land area threatened by future sea-level rise. These coastal elevation data are also used to estimate the land potentially available for wetland migration in response to sea-level rise and the sea-level rise impacts to the human built environment (Anderson et al. 2005). From the coastal vulnerability point of view, coastal regions having high elevation will be considered as less vulnerable areas because they provide more resistance for inundation against the rising sea-level, tsunami run-up, and storm surge. Those coastal regions having low elevation are considered as highly vulnerable areas. In the present study, Shuttle Radar Topography Mission (SRTM) data are used to derive the coastal regional elevation. A zonal statistical analysis was carried out using ArcGIS and elevation in each grid cell was determined and risk rating was awarded.

3.4 PHYSICAL VARIABLES

3.4.1 Sea-level Rise (SLR)

Sea-level rise has been identified as a major threat to coastal habitats and communities worldwide. It is considered to be one of the indicators of climate change. Rise in global atmospheric temperature has resulted in a rise of ocean temperature and also melting of glaciers. Both these processes lead to a rise in global sea-level. The immediate effect is submergence and increased flooding of coastal land, as well as salt water intrusion of surface waters. Long-term effects also occur as the coast adjusts to the new conditions, including increased erosion and salt-water intrusion into ground water (Nicholls et al. 2007). According to IPCC (1996), every millimeter rise of sea-level on the coast would result in a shoreline retreat of about 1 m. Present estimates of future sea-level rise induced by climate change, as presented in the IPCC Second Assessment Report (1995) range from 20 to 86 cm for the year 2100, with a best estimate of 49 cm.

The Permanent Service for Mean Sea Level (PSMSL) has been responsible for the collection, publication, analysis and interpretation of sea-level data from the global network of tide gauges. The most familiar application is global and regional sea-level rise and variability. The PSMSL data set is the main source of information on long term changes in global sea-level during the last two centuries.

Mean sea-level changes are estimated by analysing tide gauge data of past years. The data records available from tide gauges are normally at hourly interval and contain data of tidal change. From these data records tides are filtered for the study of long term changes in mean sea-level. In general, monthly mean values of sea-level are used for estimating sea-level rise. In order to determine trends in long-term sea-level changes, desirable length of sea-level data record is greater than 60 years (Douglas, 2001). However, availability of such records in the north Indian Ocean is limited.

Study area consists of two PSMSL tide gauge stations namely Mangaluru and Karwar. The monthly mean sea-level data from 1976 to 2000 are downloaded for Mangaluru station and from 1970 to 2004 for Karwar station from PSMSL web site. The monthly mean values of sea-level recorded at these stations were plotted. A linear best fit line using least squares method was computed for the monthly mean sea-level data to calculate the sea-level change rate. The coast subjected to a high rate of sea-level rise is considered as a highly vulnerable area and high risk rank was assigned for the same.

3.4.2 Tidal range

The tidal range is the vertical difference between the highest high tide and the lowest low tide. From the vulnerability point of view, it is an obvious tendency to designate coastal areas of high tidal range as highly vulnerable. This decision is based on the concept that large tidal range is associated with strong tidal currents that influence coastal behavior. For the current study, coastal areas with high tidal range are considered as highly vulnerable and low tidal range as less vulnerable. Previously, studies have been carried out for calculating the tidal range and have been determined at various locations of the study area(Kumar et al. 2006, Kumar et al. 2011, KREC Study team 1994). This secondary data was also considered for calculations.

3.4.3 Significant wave height

Significant wave height is the average height of the one-third highest waves valid for the indicated 12-hour period. Mean significant wave height is used as a proxy for wave energy that drives coastal sediment transport (USGS 2005). Wave energy is directly related to the square of wave height;

$$\mathrm{E} = \frac{1}{8} \rho \mathrm{g} \mathrm{H}^2 \tag{3.1}$$

where ‘E’ is energy density (J m^{-2}),‘H’ is wave height (m), ‘ρ’ is water density (kgm^{-3}) and ‘g’ is acceleration due to gravity ($m\ s^{-1}$).

The vulnerability study based on wave height is an important step in setting up an all-hazards warning and management system (USGS, 2005). The movement and transport beach/coastal materials are dependent upon the wave energy which varies as the square of the wave height.

With increase in the wave height, and eventual increase in the wave energy, the land is lost and the coast will witness increased erosion and inundation along the shore. Hence, the coastal areas of high wave height are considered as more vulnerable coasts and areas of low wave height as less vulnerable coasts. In the present study, wave heights in the study area were collected from the various other studies conducted primarily on wave characteristics in the study area.

3.5 SOCIO-ECONOMIC VARIABLES

The inclusion of socio-economic variables is of great importance in the development of valid CVI. Coastal management problems have shown that different human and social reactions will reveal themselves according to the size of the population, the economic activity and the prevailing social conditions of the affected area (Doornkamp 1990). The vulnerability of an area is naturally influenced by the presence of houses and infrastructure. Socio-economic parameters, thus, appear to be an essential component in any vulnerability index.

3.5.1 Population

Coastal region has high population density compared to upland areas. Population can also be interpreted as a direct “erosion-inducing” variable because the presence of large number of people near the coast may produce damaging impacts on the coastal area (McLaughlin et al., 2002). Counter argument is that it reduces vulnerability as people tend to have coastal protection structures in order to safe guard their properties. But in the present study area it has been noticed that such structures have negative impact. Hence, presence of human habitation is considered to increase the vulnerability of the study region.

High spatial resolution, contemporary data on human population distributions are a prerequisite for the accurate measurement of the impacts of population growth, for monitoring changes and for planning interventions. Worldpop website provides high resolution, contemporary data on human population distributions for South east Asian countries in raster data format. This raster data was used in the study instead of point based administrative census data. The assemble of the AsiaPop spatial datasets principally follows the methodologies outlined by Gaughan et al. (2013), Linard et al. (2012), Linard et al. (2010) and Tatem et al. (2007). The methods used are designed with full open access and operational application in mind, using transparent, fully documented and peer-reviewed methods to produce easy to update maps with associated meta-data and measures of uncertainty. It aims to provide an open access archive of spatial demographic datasets for Central and South America, Africa and Asia to support development, disaster response and health applications.

3.5.2 Landuse and Landcover

An area will be considered vulnerable only if the area is adequately useful in terms of economics, culture or environment(McLaughlin et al. 2002). The ‘value’ of a land may be defined by monetary terms, aesthetic, or conservation importance. In this regard, land-use type in the region is of importance in determining vulnerability. Study area is an economically important since a major port (New Manglore Port Trust) and B-2 type metropolitan city (Mangaluru) are located. Honnavar and Kundapura talukas of the study area have been considered ecologically vital (as per Institute for Ocean Management, Anna University).

Karnataka State Remote Sensing Application Centre (KSRSAC) Land-use/Land-cover map was used to identify various land-use types of the study area. Suitable risk rating was awarded based on the importance of land-use type. Habitation and built up land was given the highest rank while waste and rocky land were assigned the least ranking.

3.5.3 Infrastructure

Impact of climate and sea-level change driven coastal erosion on coastal communities and infrastructure is being in discussion in recent periods (Hinkel and Klein 2006). In the present study infrastructural components were taken into account so as to accommodate the resilience factor in to assessment. Roads and ports in the study area were considered for the assessment.

With increase in Road Networks, access to the areas increases, there by aiding in the mitigation efforts in the case of a hazard. But in contrast, it can also act as a negative factor for erosion since more access may lead to more human settlements in the area. In the present study, road density has been considered to be a positive factor i.e. an increase in road density decreases vulnerability and vice versa. Spatial data of roads in vector data format from Open-Street-Map database has been downloaded and analyzed in ArcGIS®9.3 for the year 2014.

Open-Street-Map (OSM) is a collaborative project with an aim to create a free editable map of the world. The OSM Foundation supporting the project is an international, nonprofit organization running and protecting the OSM database, and making it available at public domain.

3.6 COASTAL VULNERABILITY INDEX (CVI)

A grid template of 1.5 km by 1.5 km was used to store data, analyze and display the CVI, similar to the procedure adopted by Abuodha and Woodroffe (2010). Each cell of the grid template was assigned with an identification number. The software package ArcGIS®9.3 offers the suitable environment to carry out the process. The variation of each variable within the area was analyzed and suitable risk ratings were awarded for each specific data variable and the coastal vulnerability index was calculated.

After each section of coastline is assigned a vulnerability value for each specific data variable, the coastal vulnerability index (CVI) is calculated as the square root of the product of the ranked variables divided by the total number of variables;

$$\mathrm{CVI} = \sqrt{\frac{a * b * c * \ldots..}{n}} \tag{3.2}$$

where, a, b, c…… = variable ranking and ‘n’ = number of variables.

Researchers have highlighted that the equation has a disadvantage for usage as equal weights has been assigned to all the variables even when the influence of one variable is more than that of another variable. But an assignment of random weights is also logical fault as it is influenced by individual’s discretion (Manimurali et al. 2013). Hence, in the present study, an opinion survey of five experts from ocean and coastal engineering discipline was undertaken. The expert opinion was converted to weights for the variables using the principles of Analytical Hierarchical Process (AHP).

3.7 ANALYTICAL HIERARCHICAL PROCESS (AHP)

Analytical Hierarchical Process (AHP) was developed by Saaty (1977) provides a better understanding of the complex decisions by decomposing the problem into a hierarchical structure. AHP is considered to be more advantageous in the case of a multi-index integrated coastal vulnerability evaluation (Manimurali et al. 2013).

Procedure involves the consideration of expert opinions when the datasets are highly heterogeneous in terms of scale, temporal resolution, etc. which is the case for mapping coastal vulnerability. In addition, pair-wise comparison under taken while calculating weights, allows the prioritization of various parameters relative to each other on a spatial scale. AHP has the consistency test to check the effectiveness of measurements and judgments. The AHP consists of the following steps:

1. Establishing the hierarchy structure: The problem is broken down into a number of factors and is structured into a hierarchical form. In the present study the overall goal is the vulnerability assessment of Karnataka coast subject to the physical and geological variables mentioned in Table 1.

2 Establishing the comparison matrix: A pairwise comparison is undertaken for the using nine point scale given in Table 3.3 as proposed by Saaty (1980).

Table 3.3 Scale of pairwise comparison

Intensity of importance	Description
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values
Reciprocals	Values for inverse comparison

Each pair-wise comparison assigns a numerical value to the pair according to the relative importance of the two factors. The n × n pair-wise comparison matrix, A = [a_{ij}], is mathematically expressed as follows:

$$A = \begin{bmatrix} 1 & a_{12} & a_{13} & \cdots & a_{1n} \\ 1/a_{21} & 1 & a_{23} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1/a_{1n} & 1/a_{2n} & 1/a_{3n} & \cdots & 1 \end{bmatrix}$$

where n is the number of evaluative factors, and a_{ij} is the relative weight determined by the pair-wise comparison to quantify the relative importance of the i^{th} evaluative factor with respect to the j^{th} evaluative factor (i, j = 1, 2, 3, ..., n).

3. Calculating the weights of evaluative factors in each group: If matrix A is not a non-zero matrix, the matrix can be computed by using the following mathematical expression

$$\mathrm{A}w = \lambda_{\mathrm{max}} w \qquad (3.3)$$

and

$$\textstyle\sum_{i=1}^{n} w_i = 1 \qquad (3.4)$$

where w = [w_1,w_2, …, w_n], the weights of evaluative factors in each group and λ_{max} is the largesteigen valueof the matrix A. If the pair-wise comparison matrix is perfectly consistent, then λ_{max} = n and the consistency ratio (CR) is 0.

4. Measuring the consistency of the pair-wise comparison matrix: The consistency of the matrix A is evaluated by the consistency ratio (CR), and w is accepted if CR is 0.1. The CR is measured by the ratio of the consistency index (CI) to the random index (RI). The expression is as follows:

$$\mathrm{CR} = \mathrm{CI}/\mathrm{RI} \qquad (3.5)$$

where CI = (λ_{max} - n)/(n - 1), and RI is the average of CI values of the randomly generated pairwise comparison matrix. The values of RI were described by Satty (1980). The pairwise comparison is said to be inconsistent and result might be a flaw when CR is 0.1 (Saaty 1980).

3.8 STUDY AREA

The study area is the coast of Karnataka state extending from Talpadi to Sadashivgad between Longitude 74°5’22.09” E and 74°51’53.75” E and Latitude 14°53’36.53” N and 12°45’02” N covering a distance of about 280 km (Fig. 3.3). The coast is bounded by the Western Ghats in the east and the Arabian Sea on the west and is intercepted with a number of rivers joining the Arabian Sea. The coastal zone of Karnataka is one of the highly urbanized and better developed geographical areas of the State with a high degree of economic development and density of population (Singh et al., 2014). Coastal Karnataka consists of the entire coastal stretch of Udupi, Dakshina Kannada and parts of Uttara Kannada districts. The three districts consist of 19 Talukas of which 8 are coastal Talukas. As per 2001 Census, the total population of coastal districts is 4,363,617 with average density of 278 per km^2 (Census of India 2011). About 90 beaches have been identified to be suitable for beach tourism (Singh et al. 2014).

Three distinct agro-climatic zones have been noticed in the study area. The region varies with coastal flatlands in the west with undulating hills and valleys in the middle and high hill ranges in the east that separates from the peninsula. There is a narrow strip of coastal plains with varying width between the mountain and the Arabian Sea, the average width being about 20 km. The average height of the hinterland is 70–75 m, but in some places it can be as high as 150 m. Areas near the river mouths along the study area suffer permanent erosion due to natural shifting and migration of the river mouths (Dattatri 2007). The tides are of mixed semi-diurnal type and its range increases towards the north of the state (Kumar et al. 2011). Significant wave height, during the monsoon has been assessed to be greater than 3 m (Kumar et al. 2010) and is normally less than 1.5 m during the rest of the year. Deep water waves approach the coast from south-western and north-western directions (Kumar et al. 2010). The study area falls in Zone III, Moderate Damage Risk Zone (MSK VII) as for as earthquake is concerned.

3.9 SOFTWARE AID

Study needs extensive use of remote sensing and GIS packages. Three software packages that were used in this study are:

- ERDAS IMAGINE®: ERDAS IMAGINE is the raster geoprocessing software used to extract information from satellite and aerial images. The vast array of tools available in it allows users to analyse data from almost any source and present it in formats ranging from printed maps to 3D models, making ERDAS IMAGINE a comprehensive toolbox for geographic imaging, image processing, and raster GIS needs.

- ARC-Info 9.3®: ARC-Info is a geographic information system (GIS) software package for working with maps and geographic information. It is used for creating and using maps; compiling geographic data; analysing mapped information; sharing and discovering geographic information; using maps and geographic information in a range of applications; and managing geographic information in a database.

- PriEsT: Its is an acronym for 'Priority Estimation Tool'. It is an open source decision-making software that implements the Analytic Hierarchy Process (AHP) method. PriEsT can assist decision makers in prioritizing the options available in a given scenario. PriEsT implements the Analytic Hierarchy Process (AHP) which has been widely used in numerous fields, such as health, transportation, telecommunication, and policy decision making.

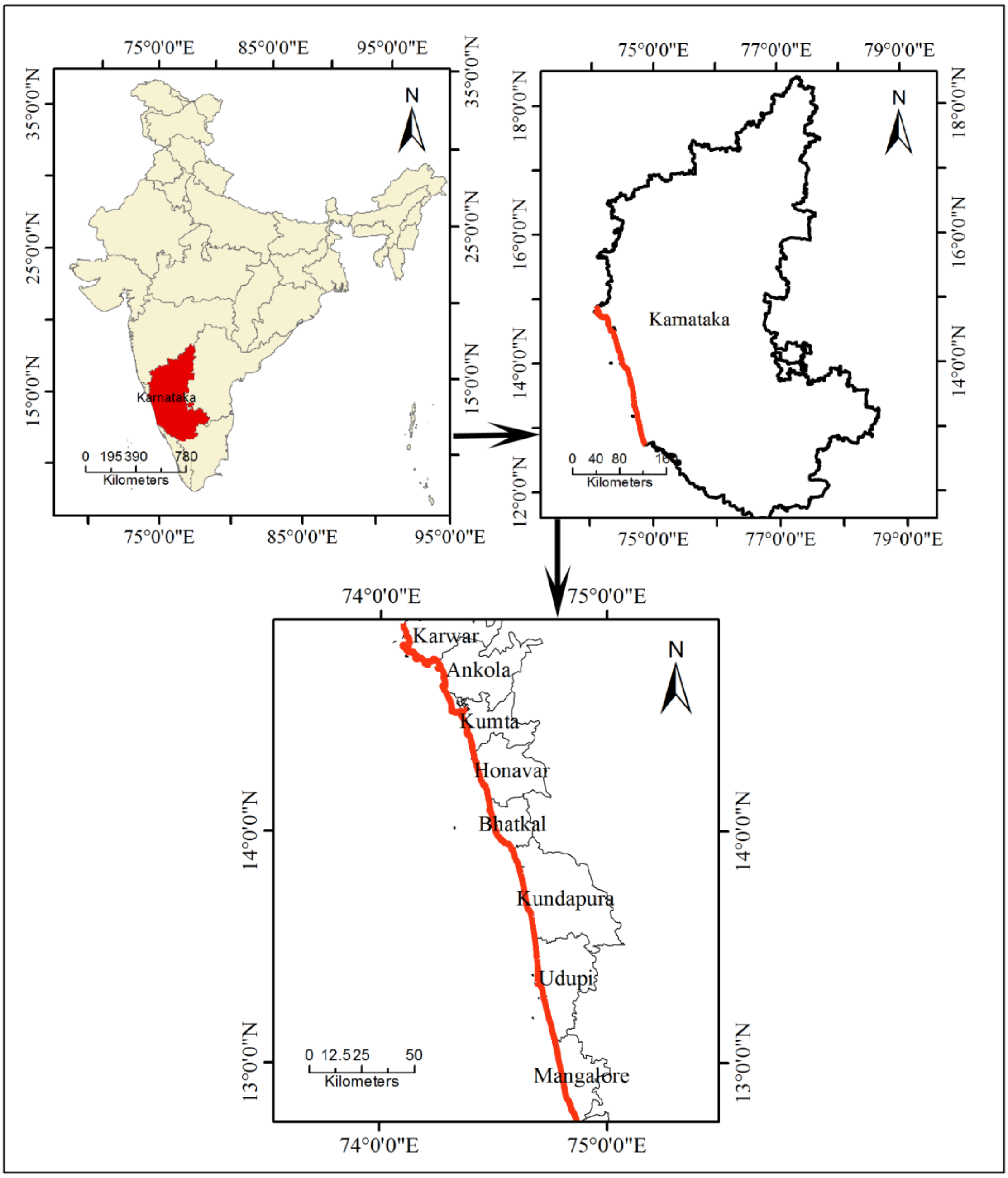


Fig. 3.3 Study Area

CHAPTER 4

ANALYSIS OF VULNERABILITY VARIABLES

4.1 GENERAL

Present study employs four geological, three physical and three socio-economic variables for the vulnerability assessment. Each of the variable has its own contribution to the vulnerability of the coast. While exposure to certain variables increases the vulnerability of the cost, presence of some variables near the coast brings adaptive capacity to the coast. Earlier sections have described the importance, effect and the primary data source of the variables considered in the study. In following sections, the analysis of variables of the study has been carried out on the data of the vulnerability variables.

4.2 ANALYSIS OF THE PHYSICAL VARIABLES

4.2.1 Sea-Level Change Rate

As mentioned earlier, the study area consists of two PSMSL tide gauge stations namely Mangaluru and Karwar. By definition, mean sea level at the coast is the average height of the sea with respect to a local land benchmark, over a long period, such that the fluctuations caused by the waves and the tides are also taken into assessment. Both of the stations have relatively short duration length data with 18.4 years data for Mangaluru and 20.6 years data for Karwar respectively. These records show only change of sea level in the study area for last two decades. Hence, the tide gauge data of Kochi, which is situated 416 km south of the Mangaluru, was verified, as it has sea level data for the last 64 years. It was assumed that SLR in Mangaluru coast followed the similar trend as Kochistation. The SLR at Kochi was observed to be 1.0 mm per year for 64 years.

It was also observed that sea level was rising with a rate of 0.8 mm per year (Fig 4.1) at Mangaluru station, while sea level was falling at a rate of 1.3 mm per year (Fig 4.2) at Karwar station. The SLR obtained is less in comparison with global average rate of about 1.7 mm per year as estimated by Church and White (2006) and Jevrejeva et al. (2008). Unnikrishnan and Shankar (2007) estimated regional average of 1.29 mm per year sea-level rise in north Indian Ocean. Hence, the study area is less vulnerable to sea level rise and lowest ranking of ‘1’ was awarded for the entire coast.

4.2.2 Tidal range

Tidal ranges for the study area were calculated using the WXTide package and for the missing ones, earlier published data from the other studies has been used. Tidal range is ranked such that microtidal (< 1 m) coasts are of very low vulnerability and macro tidal (> 6 m) coasts are of very high vulnerability. Table 4.1 gives the tidal range at various locations in study area and the source of the data.

The study area is characterized by mesotidal coasts as the tidal range is within 6m but greater than 1 m. Entire study area has fallen into two categories, namely, very low vulnerable level (<1.0m) and low vulnerable level (1.0 to 2.0 m). Accordingly, the entire coast was classified into these two vulnerability categories. The vulnerability ranking was assigned to each taluka individually and it was assumed that within the taluka’s reach the tidal range did not change.

Table 4.1 Tidal range for talukas and their source

Sl. No.	Location	Mean Significant wave height (m)	Source
1	Karwar,	2.3	WXTide
2	Ankola and Kumta	1.6	Kumar et al.,(2006)
3	Honnavara	1.9	Kumar et al.,(2011)
4	Kundapura	1	Kumar et al.,(2011)
5	Bhatkal	1.4	WXTide
6	Udupi (Malpe)	1.8	WXTide
7	Mangalore	1.6	WXTide

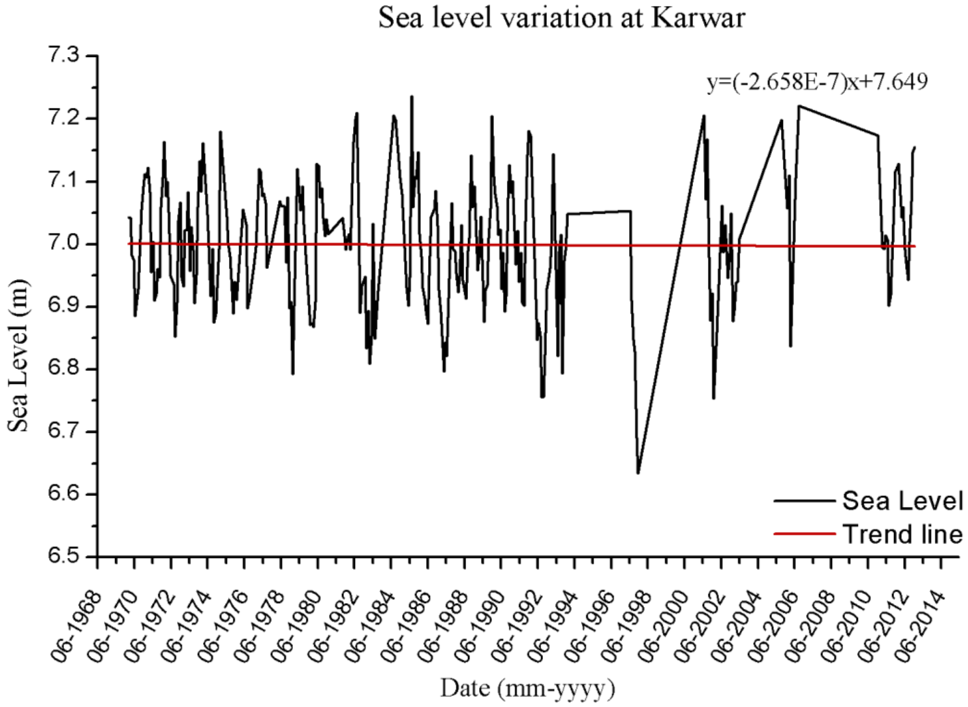


Fig. 4.1 Sea level Variation at Karwar

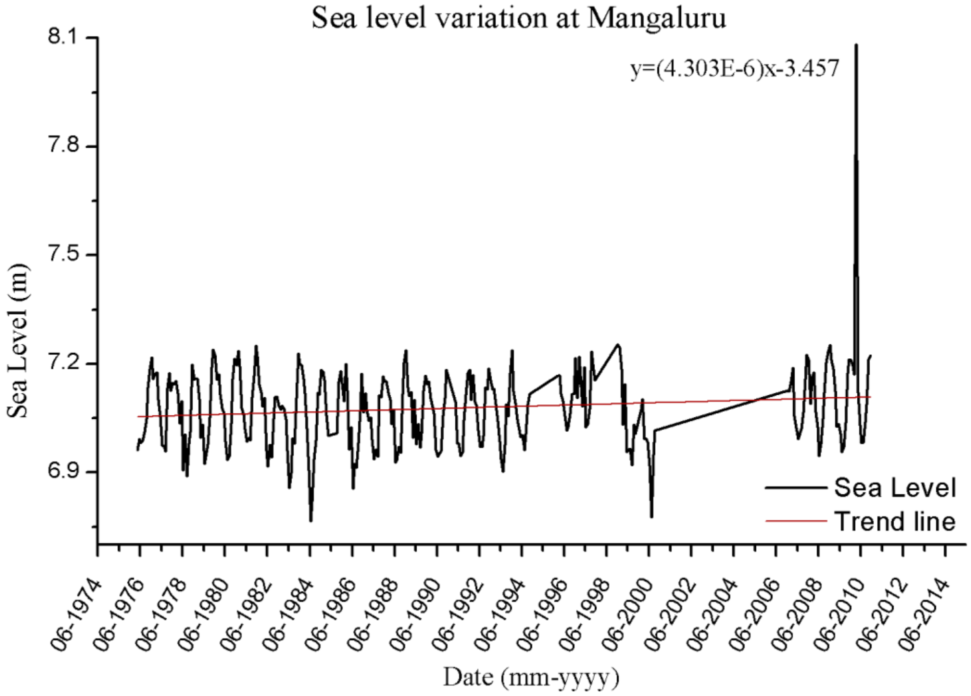


Fig. 4.2 Sea level Variation at Mangaluru

4.2.3 Significant wave height

Table 4.2 shows the mean significant wave heights for various talukas as collected from literatures. The mean significant wave height in the study area is varying between1.0 m to 2.0 m. Accordingly the vulnerability ranking has been given and Table 4.5 shows the ranges for different vulnerability classes of mean significant wave height. The ranges were adopted from the study of Dwarakish et al.(2009) since it has been carried out on a part of current study area.

From the literatures, it was observed that Kundapura had least mean SWH of 1 m while Mangalore had the highest of 2 m. The values presented here are a point value and were generalized to the particular talukas. It was assumed that the mean SWH would not exceed more than the value listed here for that taluka coast.

Table 4.2 Mean Significant Wave Height for Talukas

Sl. No.	Location	Mean Significant wave height (m)	Source
1	Karwar, Ankola and Kumta	1.6	Kumar et al., (2011)
2	Honnavara	1.9	Kumar et al., (2011)
3	Kundapura	1.0	Shanas and Sanil Kumar (2014)
	Bhatkal	1.25	Nayak et al., (2010)
4	Udupi (Malpe)	1.9	Kumar et al., (2011)
5	Mangalore	2.0	NITK Study team (1994)

4.3 ANALYSIS OF THE GEOLOGICAL VARIABLES

4.3.1 Shoreline Change Rate (SCR)

The rate of shoreline change is one of the most common measurements used by coastal scientists, engineers, and lands planners to indicate the dynamics and the hazards of the coast (Savage and Foster, 1989). The various methods are End Point Rate (EPR),Average of Rates (AOR), Linear Regression Rate(LRR), and JackKnife (JK). The LRR was estimated for the study area approach as this approach uses the method of least squares to calculate a best-fit line for the entire sample of shoreline positions and the slope of the best-fit line is an estimate of the shoreline rate-of-change. Linear regression is known to be purely computational and is based on accepted statistical concepts with an easy applicability. In addition, LR uses all the data to calculate the rates. The Figure 1.6 represents the average LRR for each grid in the study area. Shoreline change rate was computed for 42 years using both Liner Regression Rate and End Point Rate methods. In addition, net shoreline movement was calculated. Table 4.3 shows the details of the LRR and Table 4.4 shows details of Net Shoreline Movement (NSM) for the study area. Average accretion for whole of the study area was found to be 1.133 m year^{-1} and average erosion was 0.533 m/yr. In this regard, study also found that the net erosion for the northern talukas is less compared to southern talukas. The SCR estimated previously is localized to the grids used in the study. The values of SCR varied between -3.08 m year^{-1} to 5.74 m year^{-1}. The vulnerability classes were assigned as mentioned in the Table 4.5. Positive values of SCR in the Table 4.5 indicate accretion while negative SCR values indicate erosion.

Table 4.3 Statistical indexes of LRR for the talukas

Sl. No.	Taluka	No. of Transects	Mean LRR	Mean Min. LRR	Mean Max LRR	Mean Var. (LRR)	Mean SD. (LRR)
1	Karwar	617	0.344	-1.921	2.876	3.459	1.256
2	Ankola	268	-4.862	-0.05	30.947	2.316	0.725
3	Kumta	437	-0.107	-1.398	1.157	0.587	0.62
4	Honnavar	280	0.209	-0.737	1.554	0.994	0.675
5	Bhatkal	323	-0.254	-1.716	0.646	0.422	0.56
6	Kundapura	453	0.087	-0.646	0.828	0.251	0.416
7	Udupi	534	0.163	-0.717	0.992	0.427	0.494
8	Mangaluru	401	-0.303	-1.251	0.654	0.644	0.583

Table 4.4 Statistical Indexes of NSM for the talukas

Sl. No.	Taluka	No. Of Transects	Mean NSM	Mean Min.NSM	Mean Max. NSM	Mean Var. (NSM)	Mean SD. (NSM)
1	Karwar	617	13.817	-75.788	115.103	5113.78	50.544
2	Ankola	268	1.406	-54.757	128.706	1994.253	37.525
3	Kumta	437	-0.395	-72.13	71.353	1732.866	32.965
4	Honnavar	280	8.129	-40.28	72.368	1967.028	31.935
5	Bhatkal	323	-4.613	-51.268	43.185	778.275	25.137
6	Kundapura	453	7.436	-31.494	43.601	651.647	21.674
7	Udupi	534	17.476	-19.568	59.241	931.383	22.981
8	Mangaluru	401	-2.516	-47.324	42.094	1273.232	27.364

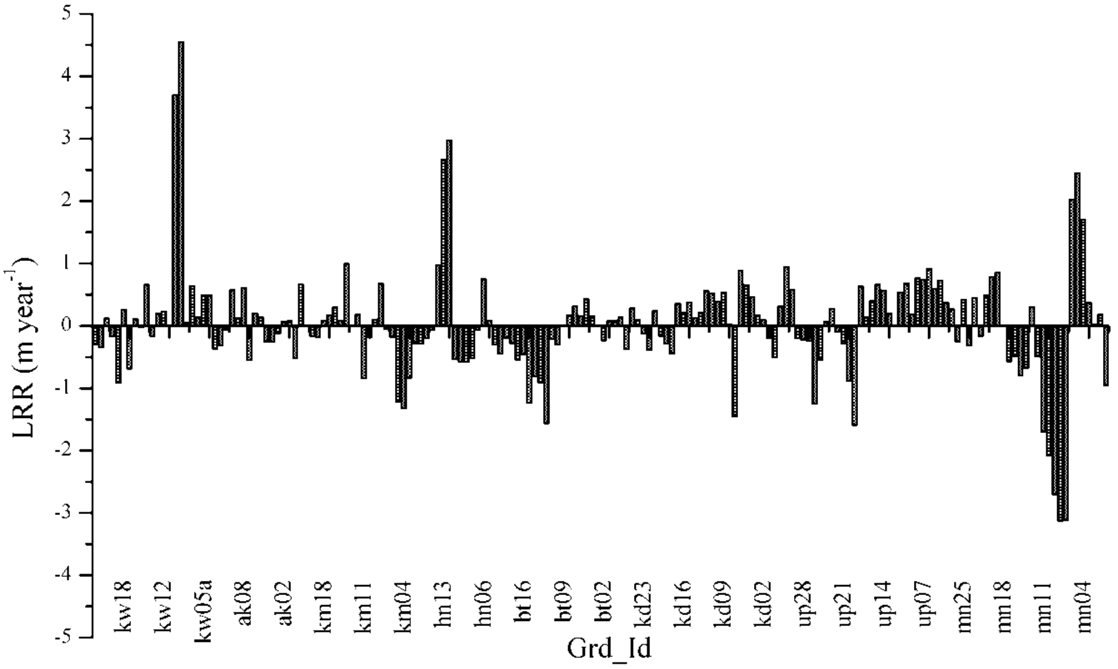


Fig. 4.3 Average Shoreline Change Rate along study area

Temporal variation of SCR showed that during 1972-1991 Karnataka coasts was in relative equilibrium with highest erosion less than 4 m year^{-1} and highest accretion less than 5 m year^{-1}. However, erosion was noticed during the decade 1991-2000 in most of the grid cells and accretion was observed in the same cells during 2000-2012.The time interval considered is approximately 10 years and the technique adopted is EPR due to lack of fair weather satellite images in Landsat platform. Fig 4.4 shows the variations.

4.3.2 Coastal slope

Coastal slope plays an important role in determining the wave run up and its reach. For estimating the impact of sea level rise on a given coast, Coastal slope along with the coastal morphology is to be considered (Rao et al., 2008). In the present study, the bathymetry details were obtained from 30-arc second (1 km) dataset of GEBCO. Fig 4.5 is the bathymetric data of the study area. The regional coastal slope was calculated for a distance of 6 km (3 km both on sea and on land) perpendicular to the shoreline at an interval 1.5 km. The graph shown in Fig 4.6 represents the typical coastal slope of the study area at one of the stations. The slope in the study area varied from 0.06% to 6.38%. Highest value was noticed at Karwar while lowest was found at Kumta.

The variation of slope for different zones is given in the following table. A slope greater than 0.6% is assigned low vulnerability and less than 0.3% is assigned high vulnerability. Karwar and Bhatkal zones did show a significant variation between minimum and maximum slope values. This is because of presence of headlands in the zone.

4.3.3 Geomorphology

Geomorphology and landform database was prepared for the study area using the Landsat 8 imagery and Google earth using visual interpretation. The rocky cliffed coasts which offer higher resistance to erosion were given the least rank value ‘1’ and sandy beaches and mud flats which offer low resistance to erosion were given a high rank value ‘5’. The coastal areas with medium and low cliffs and cobble beaches shared the intermediate rankings.

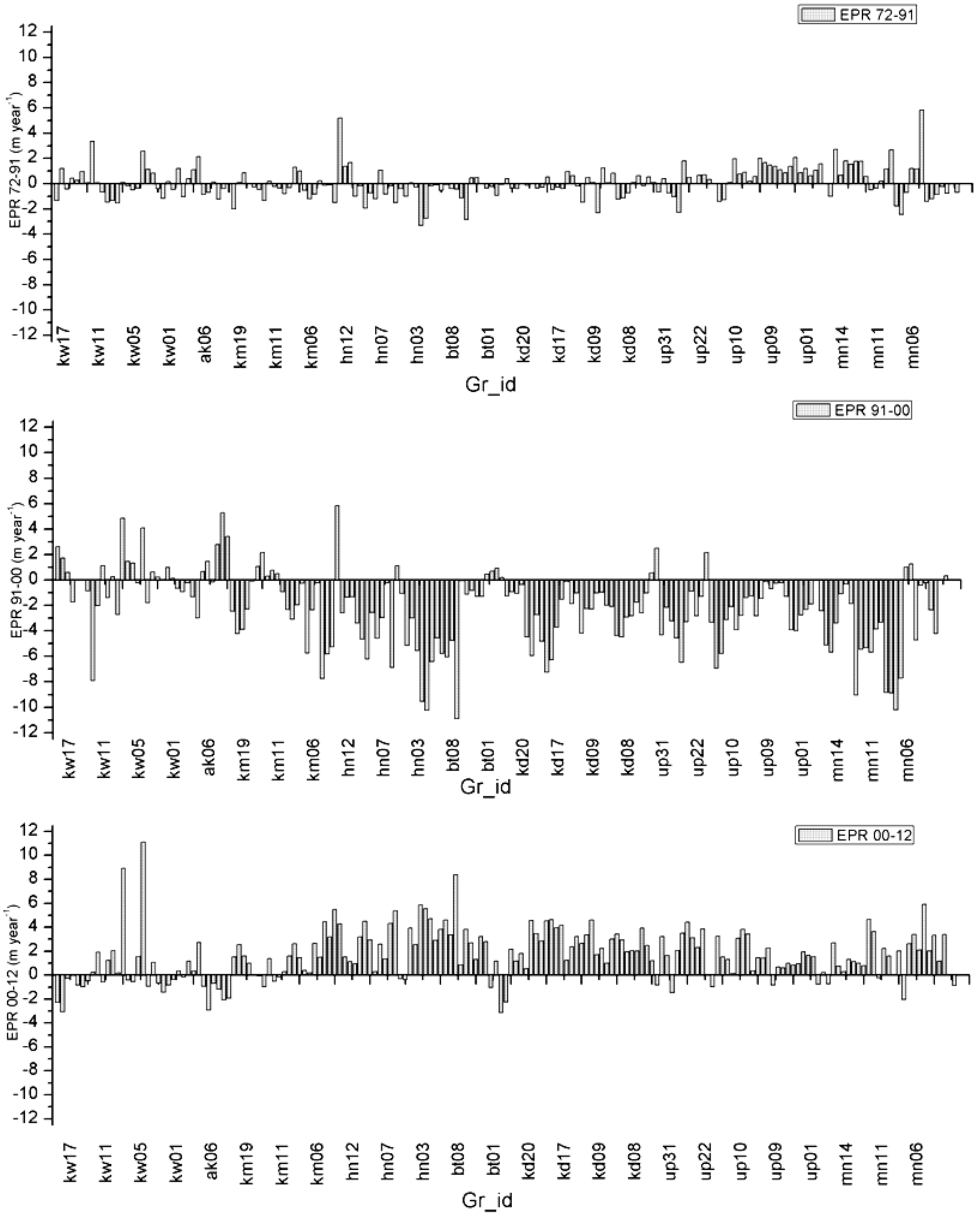


Fig. 4.4 Decadal variation of Shoreline change rate of in the grids from 1972-2012

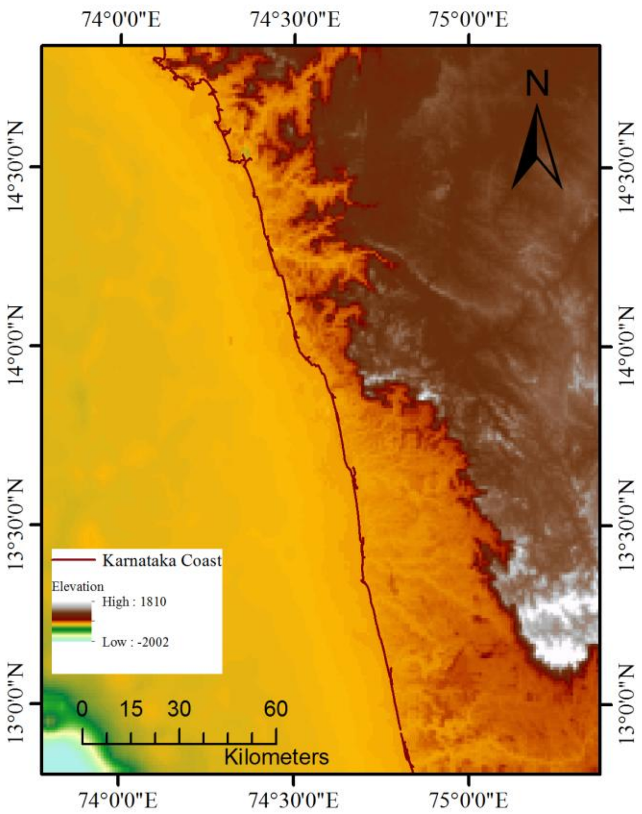


Fig. 4.5 GEBCO Bathymetric map of Karnataka coast

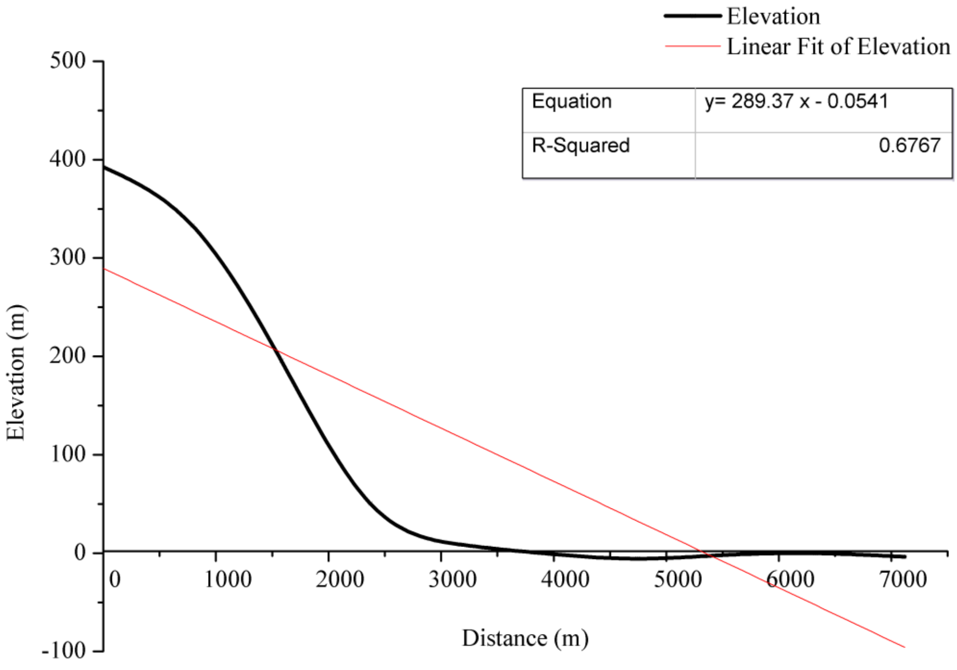


Fig. 4.6 Coastal Slope at Station KW18

Southern part of the study area comprising the coast of Udupi and Mangaluru talukas are more associated with long, narrow and straight open sandy beaches. In addition, we find barrier spits, estuaries, and coastal ecosystems, such as mangroves, coastal forest, and aquaculture ponds in the southern talukas. Northern part of the study area comprising the talukas of Karwar, Ankola and Honnavar are characterized by the presence of beach ridges, coastal alluvial soil, spit and tidal flat. Rocky beaches, lateritic plain, alluvial plain, tidal flat and Channel Islands are the characteristics of Kundapura and Bhatkal talukas. Table 4.5 details the ranking classes of the segments for different geomorphological features.About 157 km length of coast was categorized to be very high vulnerable class and 48 km was of high vulnerable class. About 39 km and 49 km length of coast would fall under low and very low vulnerable category, respectively.

4.3.4 Regional elevation

Those coastal regions having low elevation are considered as highly vulnerable areas. Fig.4.7 shows the elevation map of study area. In the present study, Shuttle Radar Topography Mission (SRTM) DEM data was used to determine the coastal regional elevation. It was noticed that the grid cells enclosing the river mouths showed higher elevation values. Such errors were identified and corrected using visual interpretation technique on the satellite images. A zonal statistical analysis was carried out using ArcGIS package.

Fig. 4.8 and Fig. 4.9 show the low-lying areas along the study grids. Table 4.6 details the total quantity low-lying areas in each of the talukas. It can be noticed that Mangaluru, Udupi and Honnavar talukas have higher amount of low-lying areas in comparison with other talukas. The least quantity of low elevation areas were found in Ankola taluk. This is because geomorphology of Ankola is characterized by rocky headlands and outcrops very close to coast.

Udupi, Kundapura and Honnnavar talukas had higher quantity of low-lying areas. Other zones showed fairly higher elevated areas. Least quantity of low-lying area was found in Ankola due to shorter coastal length. However, Honnavar has higher quantity of low-lying area in spite of longer coastal length. Fig. 4.7 and Fig. 4.8 detail the distribution of low-lying areas in the taluka grids. 'Zero' value in these charts indicates that the particular grid cell is void of the elevation values below 5 m.

Karwar, Honnavar and Udupi have relatively higher value of low-lying areas in the southern grid cell while Ankola and Kundapura have it at the centre. Northern grids of Kumta, Bhatkal and Mangaluru have higher low–lying areas

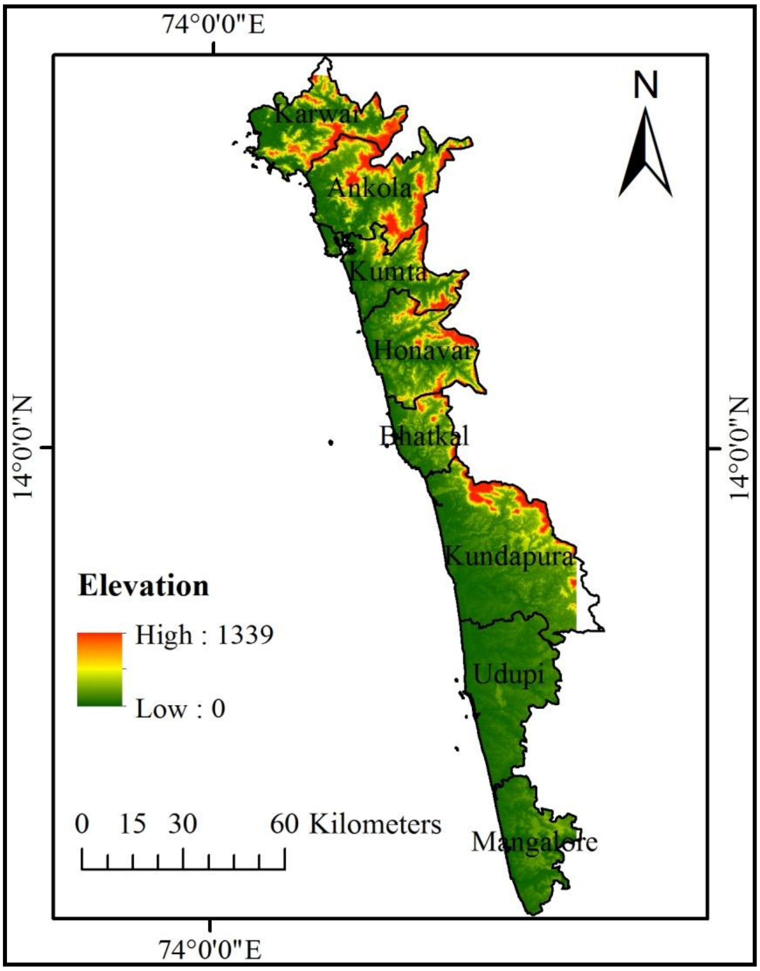


Fig. 4.7 Elevation map of Talukas

Table 4.5 Ranges of variables for Vulnerability Ranking

Sl. No.	Variable	Ranking of Vulnerability				
		1	2	3	4	5
1	Mean tidal range	<1.0	1.0-2.0	2.0-3.0	3.0-4.0	>4.0
2	Mean SWH	<0.7	0.7 to 1.4	1.4 to 2.1	2.1 to 2.8	>2.8
3	Shoreline Change Rate (m)	>0.53	0.53 to 0.17	0.17 to -0.06	0.06 to -0.39	< -0.39
4	Coastal slope (%)	>0.60	0.5 to 0.6	0.4 to 0.5	0.3–0.4	<0.3
5	Low lying areas (km^2)	≤ 0.007	0.008 to 0.022	0.023 to 0.030	0.031 to 0.110	>0.111
6	Geomorphology	Rocky cliffed coasts	Medium cliffs, indented coasts	Low cliffs, lateritic plain	River deposits, alluvial plain	Coastal plain, beach, mud flats
7	Landuse/ Lancover class	Barren, Rocky/ Stony Waste/ Sheet Rock Area	Mining/ Industrial Wasteland	Mixed Vegetation, Forest Plantations	Forest Plantations, wetlands, mangroves	Habitation with Vegetation, In-dustrial Area, Builtup land
8	Population Density (person per grid)	≤ 33	34 to 52	53 to 65	66 to 284	>285
9	Road density(m)	>4793.094	3040.341 to 4793.093	2625.160 to 3040.341	1641.459 to 2625.159	≤ 1641.458

Table 4.6 Low-lying areas in each taluka within the study grid cell

Sl No.	Taluka	Low lying area (km^2)
1	Karwar	1.400
2	Ankola	0.451
3	Kumta	1.492
4	Honnavar	2.418
5	Bhatkal	0.964
6	Kundapura	1.010
7	Udupi	2.419
8	Mangaluru	2.418

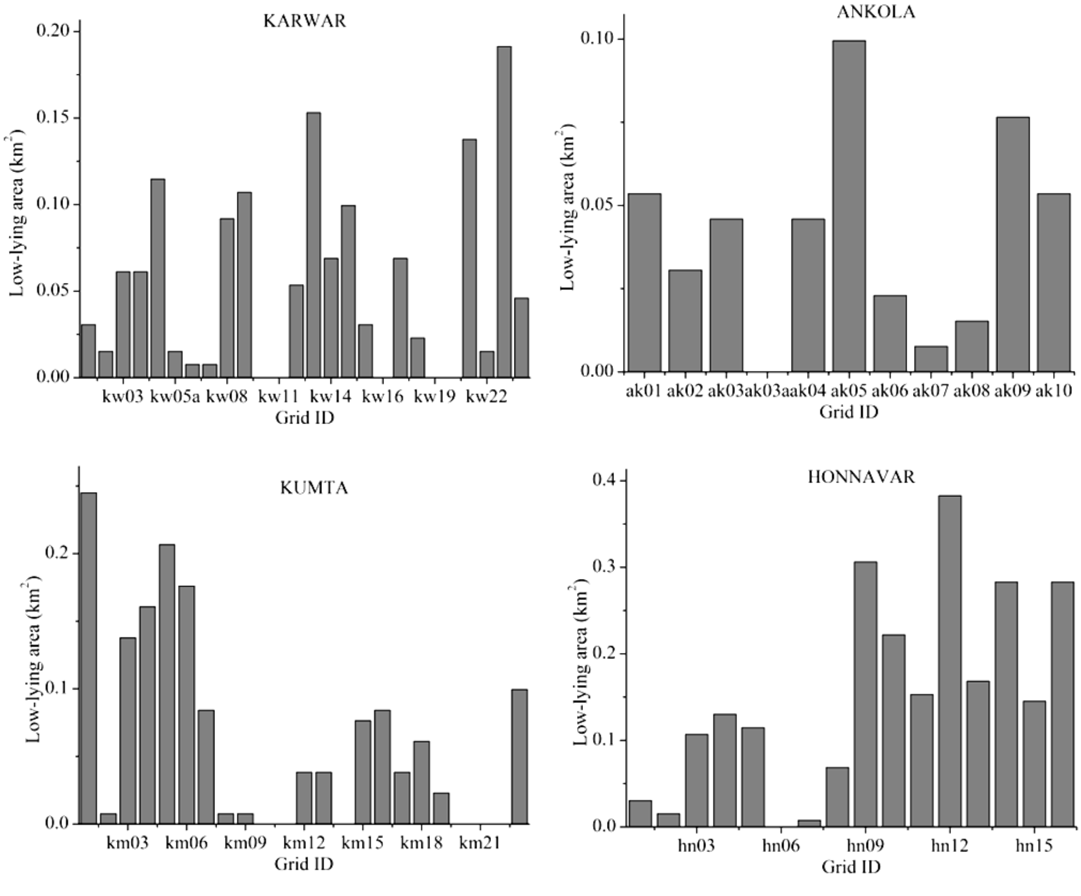


Fig. 4.8 Distribution of Low-lying areas in grids of Karwar, Ankola, Kumta and Honnavar talukas

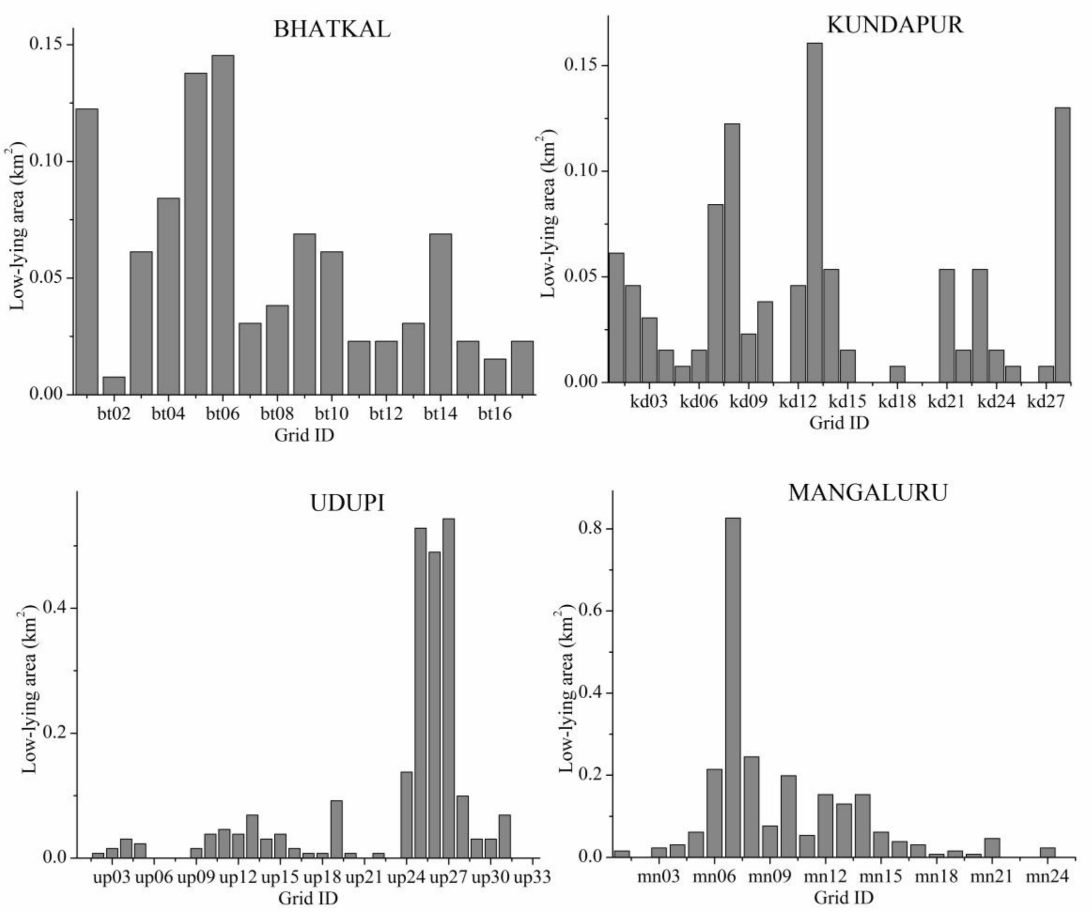


Fig. 4.9 Distribution of Low-lying areas in grids of Bhatkal, Kundapura, Udupi and Mangaluru talukas

4.4 ANALYSIS OF SOCIO-ECONOMIC VARIABLES

4.4.1 Population

High-resolution human distribution raster data downloaded from Worldpop project has data value varying from 0 to 325. Value of ‘0’ indicates no human population within that raster cell and 326 indicate number of persons per cell. Raster data was thus classified into five classes using natural jenks technique (Table 4.5). Fig. 4.10 shows the population distribution in talukas.

Fig. 4.11 and Fig. 4.12 show the population distribution along the grids in each taluka based on the data of Worldpop project. It can be observed from the plots that the population in the study grids of southern talukas is higher than northern talukas. In addition, the peaks in the plots are result of towns and urbanised areas located within the study grids. Coastal grids of Karwar, Udupi, southern Kundapura and Mangaluru show the higher population density, while for other taluka coastal grids are scarcely populated. It was also noticed that in the northern part of study area the population density increased far off from the grids. This particular nature could be attributed to the topography of these grids, which is highly undulating and sometimes flood prone regions. Vulnerability classes were assigned as detailed in Table 4.5.

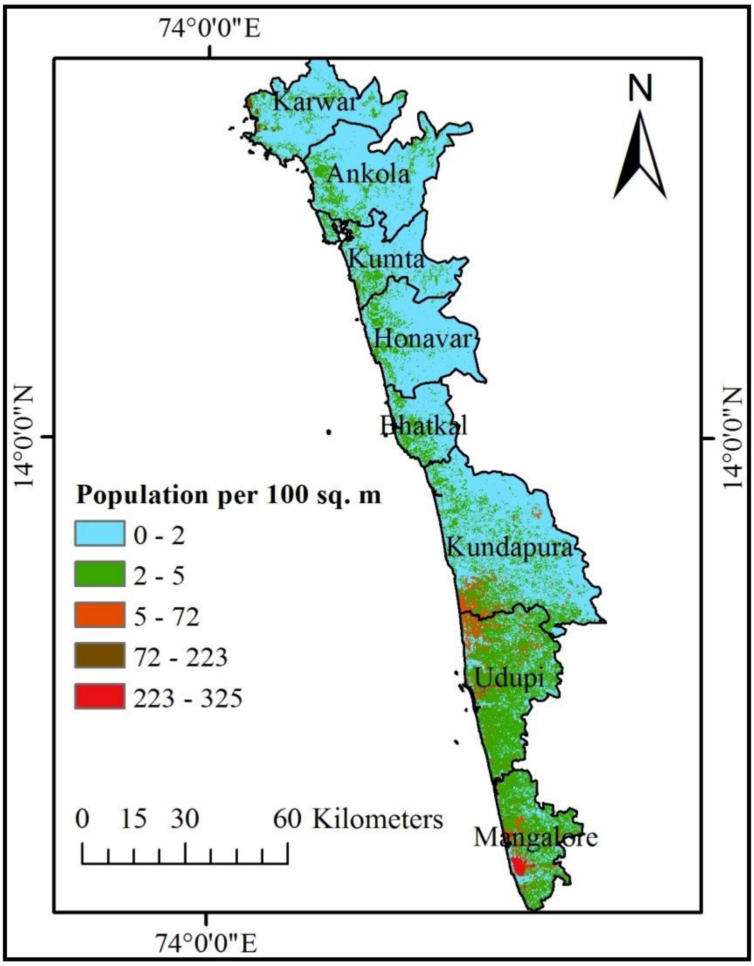


Fig. 4.10 Population distribution in the Talukas

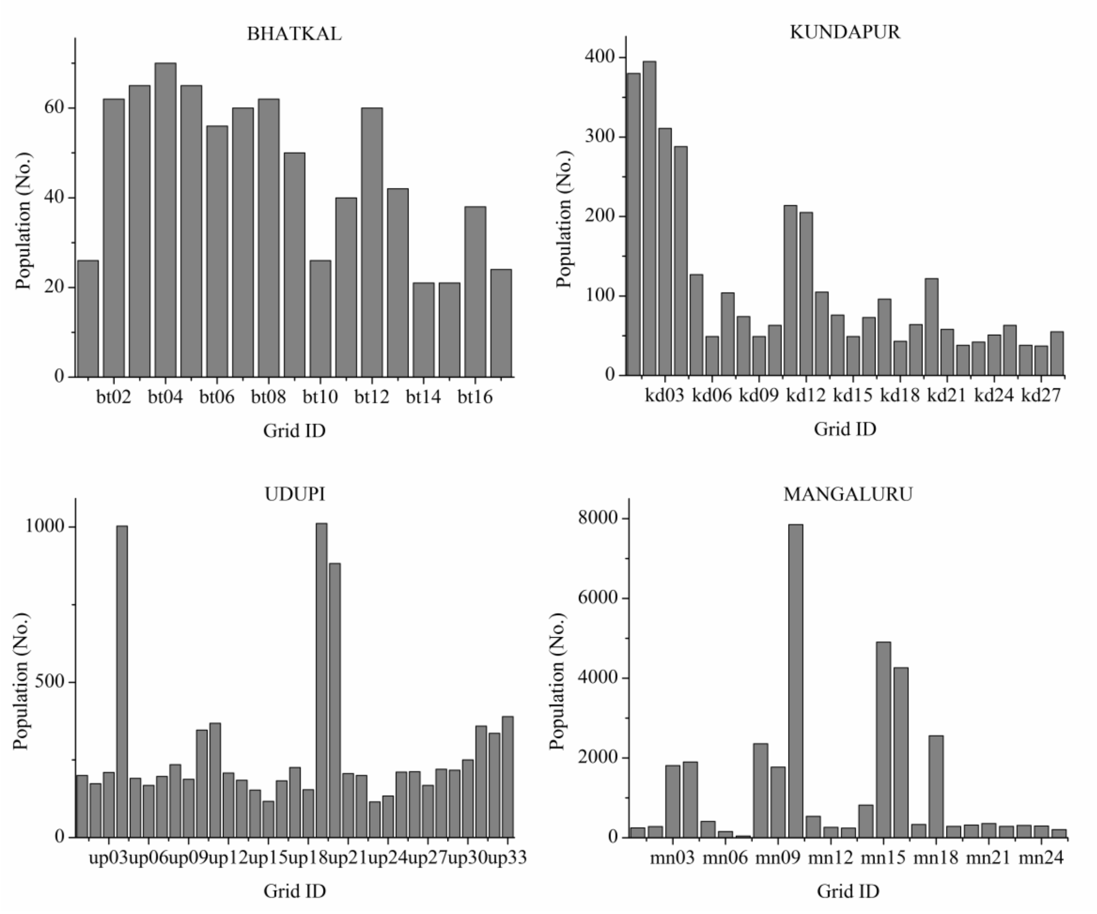


Fig 4.11 Distribution of Population in grids of Karwar, Ankola, Kumta and Honnavar talukas

4.4.2 Landuse and Landcover

The protection of an area, believed to be vulnerable will be considered if the area is sufficiently important in economic, cultural or environmental terms. KSRSAC LU/LC map of 1:50,000 scale was used in the present study for the analysis. The ranking was assigned based on the importance of the class.

Coastal Karnataka was conglomerate of various LU/LC types. ‘Habitation with vegetation’ formed the highest coverage area as the coastal fishing villages covered the majority of the grids. Some urban settlements were also part of the grid cells. In case of conflict, LU/LC type with the higher area coverage was generalized for the grid. Highest ranking was awarded to Built-up land and habitations as these Landuse class are economically valuable than other class, while the wastelands and rocky barren outcrops were ranked least. Table 4.5 details the rank for various LU/LC classes in the study area.

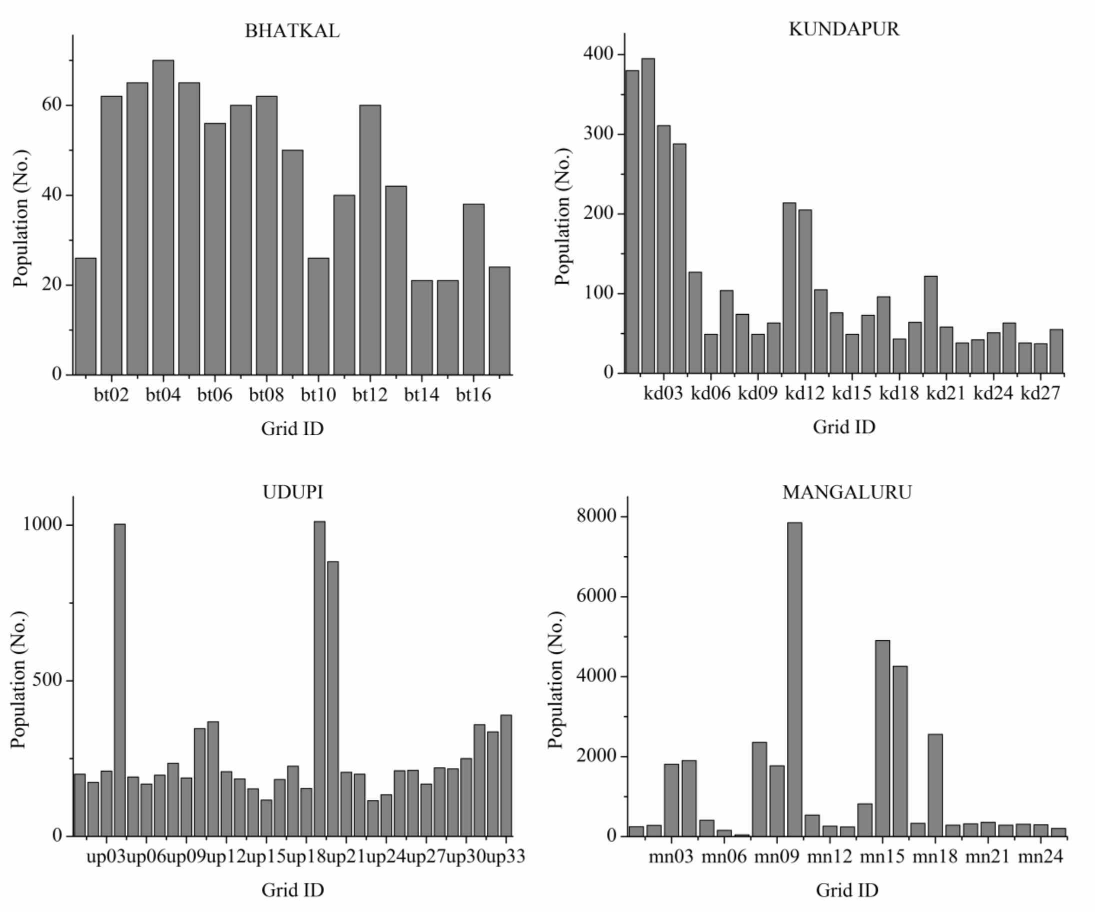


Fig 4.12 Distribution of Population in grids of Bhatkal, Kundapura, Udupi and Mangaluru talukas

4.4.3 Road Networks

Total length of roads in each grid cell was calculated using the GIS. The largest Network length of 14.62 km was found at southern part of Mangaluru while lowest was 0.14 km in northern part of Udupi while in certain cells the road network was absent. Table 4.10 details the amount of road networks in study grids in accordance with talukas. Increase in network length indicates that the particular stretch is more accessible to human population there by increasing the tourist potential as well as increasing the mitigation measures of the stretch.

Table 4.7 Total Road Network in Grids

Sl. No.	Taluka	Road Network (km)
1	Karwar	76.24
2	Ankola	4.32
3	Kumta	68.98
4	Honnavar	40.97
5	Bhatkal	54.20
6	Kundapura	87.60
7	Udupi	98.56
8	Mangaluru	140.43

Ankola taluk has least road network length in its grids cells with value of 4.32 km. While Mangaluru leads with 140 km followed by Udupi and Kundapura with 98.56 km and 87.60 km. Kumta, Bhatkal and Honnavar fall in next consecutive places with 68.98 km, 54.20 km and 40.97 km. Fig. 4.12 and Fig. 4.13 show the road network length in each grid for all the talukas. Two grid cells in Karwar and three grid cells in Bhatkal are deficient of road network while Ankola has road network only in three grid cells.

When satellite imagery was visually verified, it was noticed that some of these grid cells were consisting of geological features such as rocky outcrops, cliffs, headlands and as well comprising of estuaries and aquaculture ponds. These features are also of economically lower importance in LU/LC class. Hence, there are lower human settlements and relatively lower road networks.

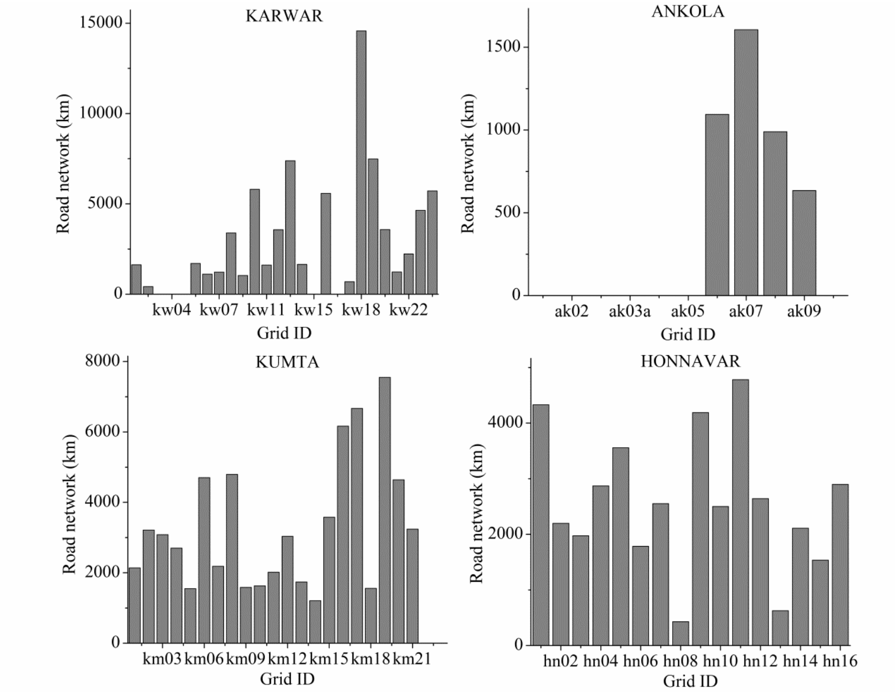


Fig. 4.13 Distribution of Road Network length in grids of Karwar, Ankola, Kumta and Honnavar talukas

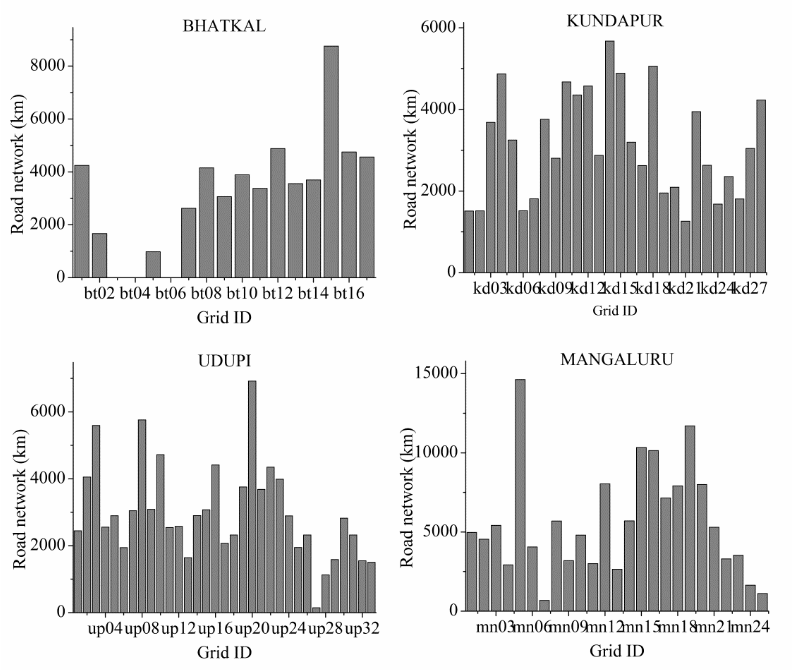


Fig. 4.14 Distribution of Road Network length in grids of Bhatkal, Kundapura, Udupi and Mangaluru talukas

4.5 SUMMARY

The present chapter outlined the situation of Karnataka coast with respect to each of the considered variables. It was observed the Karnataka coast was predominantly affected by the shoreline change than the other variables. Even the SLR was lower than the global mean value. SWH and tidal range were well with in lower limits of vulnerability. Southern talukas were observed to be most socio-economically vulnerable due to higher presence of human settlements. The ranking of each grid cell for various study variables have been included in the Appendix-A at the end of the thesis. In the following chapter the development of CVI for the Karnataka coast along with the derivation of weights for each variable has been discussed.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 GENERAL

Often CVI is calculated using the USGS equation. However, researchers have highlighted that the equation has a disadvantage for usage as equal weights has been assigned to all the variables even when the influence of one variable is more than that of the other variable. In addition, it was found that the CVI calculated using USGS equation underestimates the risk of certain stretch of coast, which is highly prone to erosion. Hence, in the present study, an opinion survey of experts from ocean and coastal engineering discipline was carried out and a weight scheme was formulated using the principles of Analytical Hierarchical Process (AHP).

5.2 USGS FORMULAE BASED COASTAL VULNERABILITY INDEX (CVI)

As a preliminary exercise, coastal vulnerability index (CVI) was calculated in the present study using USGS CVI equation. CVI value from the parameters considered varied from 1.73 to 42.46. The statistical parameters *viz.*, the mean, median and mode of CVI for the entire study area are 12.804, 13.416 and 7.384 respectively. The 25th, 50th and 75th percentiles are 8.48, 13.41 and 15.49 respectively. Table 5.1 shows the mean, median and mode CVI for different talukas.

Table 5.1 reveals that the CVI value of 42.423 for Karwar is the highest, whereas Bhatkal has the least value of 1.732. However, the mean CVI is the highest for Mangaluru with a value of 16.669 and the median and mode values for Mangaluru are very close to the mean value. This implies that CVI for the stretch of Mangaluru is almost uniform there by showing that the complete coast is vulnerable to coastal hazards. For Karwar, only one of the stretch has the highest vulnerability and the other stretches are relatively less vulnerable.

Table 5.1 Statistical parameters of CVI for Talukas

Talukas	Mean	Median	Mode	Maximum	Minimum	Standard Deviation
Karwar	11.55	8.48	7.34	42.42	4.24	8.14
Ankola	13.25	14.69	6.36	22.21	6.36	5.70
Kumta	11.98	13.41	7.348	22.21	6	4.34
Honnavara	9.76	9	7.34	16.47	3.67	3.66
Kundapura	9.58	8.48	15.49	15.49	1.73	2.99
Bhatkal	12.22	13.41	15.49	20	4.89	4.77
Udupi	14.9	14.69	16.43	21.21	9.79	2.12
Mangaluru	16.66	16.43	16.43	28.46	7.74	5.39

As highlighted earlier, variables in consideration have equal importance in USGS formulae. Nevertheless, in practice, the importance of a variable or the weightage for a variable is site specific. Hence, AHP was adopted in the present study to assign the weights to each of the variables of the present study.

5.3 AHP APPLICATION AND CALCULATION OF WEIGHTS

Most of the vulnerability studies have expressed CVI as the square root of the product of the ranking factors divided by the number of parameters considered. However, it could also be expressed in various other expressions. In the present study, CVI has been calculated by using the product of the weighted ranking factors of the variables divided by the number of variables. Weights have been derived only for the various physical and geological parameters using analytical hierarchical process, but not for the Socio-economic variables. This is because socio-economic variables considered in the present study have equal importance with respect to hazard.

In addition, study also used the Pairwise comparison method to integrate expert opinions for calculating the weights for the variables. Based on opinion survey of experts from ocean and coastal engineering discipline the decision matrix was generated. The details of the pair wise comparison have been included in Appendix-B of the thesis. Individual preference of the experts was aggregated and weights were calculated using the PrieSt software. Table 5.2 shows the normalized decision matrix for physical-geological variables.

Table 5.2 Normalized matrix of physical–geological variables

	SCR	**SLR**	**CS**	**CG**	**RE**	**SWH**	**TR**	**Mean**
SCR	0.091	0.492	0.510	0.467	0.453	0.297	0.284	0.370
SLR	0.143	0.022	0.113	0.212	0.133	0.121	0.152	0.128
CS	0.058	0.132	0.042	0.118	0.174	0.185	0.169	0.125
CG	0.352	0.114	0.100	0.050	0.093	0.083	0.073	0.124
RE	0.186	0.105	0.102	0.110	0.034	0.105	0.104	0.107
SWH	0.062	0.136	0.075	0.064	0.031	0.039	0.041	0.064
TR	0.070	0.110	0.130	0.070	0.124	0.064	0.043	0.087

The decision weights calculated were verified for the consistency using afore mentioned equation 3.5. CR was found to be 0.089, which is acceptable as per Saaty and González(1991).

Table 5.3 Showing values of Random Index (RI) (Saaty and Vargas 1991)

n	2	3	4	5	6	7	8
RI	0.00	0.52	0.90	1.12	1.24	1.32	1.41

n = order of the matrix.

Table 5.4 Computation of consistency ratio (CR)

Parameters	**Value**
λ_{max}	7.019
n	7
CI	0.117
RI	1.32
CR	0.089

Such exercise of evaluating the weights for socio-economic variables were exempted in the present study since only three of the variables were under consideration. The weights were assigned in a random but a logical manner for socio-economic variables. Population, LU/LC and road networks were assigned with weights of 0.5, 0.25 and

0.25, respectively. This was based on the logical conclusion that population is the driving force for other two variables and human casualty tops the priority list in any natural hazard mitigation. In case of an event, LU/LC and the road network constitute for the loss of property than the human life. The CVI equation was thus modified to the present study area and the modified CVI equation is given by the equation

$$CVI = PVI + SVI \tag{5.1}$$

where, PVI is Physical Vulnerability Index and SVI is Socio-economical Vulnerability Index, given by

$$PVI = W_1X_1 + W_2X_2 + W_3X_3 + W_4X_4 + W_5X_5 + W_6X_6 + W_7X_7 \tag{5.2}$$

and

$$SVI = W_8X_8 + W_9X_9 + W_{10}X_{10} \tag{5.3}$$

In the equation 5.2 and 5.3, W_n is the weight value of each variable derived by using AHP and X_n is the vulnerability score of each variable. Table 5.5 shows the weights of various variables.

Table 5.5 Weights of various variables employed for calculating the CVI

Sl. No.	Physical and geological variable weights			Socio-economical variable weights		
	Notation	**Variable**	**Weight**	**Notation**	**Variable**	**Weight**
1	W_1	SCR	0.370	W_8	Population	0.500
2	W_2	SLR	0.128	W_9	LU/LC	0.250
3	W_3	CS	0.125	W_{10}	Road network	0.250
4	W_4	CG	0.124			
5	W_5	RE	0.107			
6	W_6	SWH	0.064			
7	W_7	TR	0.087			

5.4 MODIFIED COASTAL VULNERABILITY INDEX (MCVI)

MCVI value from the parameters considered varied from 3.94 to 8.93. The statistical parameters, the mean, median and mode of CVI for the entire study area are 6.35, 6.48 and 7.98 respectively. The 25th, 50th and 75th percentiles are 5.52, 6.44 and 7.14 respectively. These percentiles form the thresholds for the four categories of vulnerability namely; ‘low’, ‘medium’ ‘high’ and ‘very high’. Table 5.6 shows the statistical parameters of CVI for different talukas.

Table 5.6 Statistical parameters of MCVI for talukas

Taluka	Mean	Median	Mode	Max.	Min.
Karwar	5.82	5.63	4.58	8.43	4.07
Ankola	5.73	5.6	-	7.18	4.1
Kumta	5.78	5.82	-	6.94	3.95
Honnavar	5.52	5.43	-	7.72	4.11
Bhatkal	5.62	5.31	-	6.89	4.15
Kundapura	6.7	6.93	7.25	8.12	5.13
Udupi	7.36	7.43	7.56	8.43	6.07
Mangaluru	7.02	6.94	7.81	8.93	5.83

Lowest CVI value of 3.95 was observed at a coastal segment of Kumta while highest was observed at a segment in Mangaluru with a value of 8.93. The highest average CVI was found to be for Udupi taluka and lowest was for Kumta taluka. For Kumta taluka, the mean value is less than the median value indicating that coastal stretches of the taluka are relatively more vulnerable than other talukas. Similar trend is observed for Udupi and Kundapura. The median for Kundapura and Mangaluru are more than the 50th percentile of MCVI, while for the Udupi it is more than the 75th percentile value. This indicates that the more than half of the coastal stretches of Kundapura, Mangaluru are under 'high' vulnerability category, and in Udupi they are under 'very high' vulnerability category.

Vulnerability of the coast decreases from south to north along the study area. This is because of the lesser population density towards north and presence of cliffs and headlands very near to coast, offering high resistance to the erosion in the northern part of the study area. In addition, the extent of open beach is comparatively less in the northern part.

In order to verify the fluctuation of index, bar chart for each taluka was prepared. Fig. 5.1 and Fig. 5.2 shows the variation of the MCVI in Northern and Southern talukas. Honnavar taluka was the least vulnerable with about 62% of its coast in low vulnerable category while Bhatkal and Karwar talukas had about 53% and 46% respectively. Kumta had about only 40% 'low' vulnerability coast and was void of any 'very high' vulnerability coast, a characteristic same as Bhatkal taluka.

Honnavar, Ankola and Karwar too had low quantity of ‘very high’ vulnerable coast (Table 6.1).

Among southern talukas, Udupi and Mangaluru were void of low vulnerable coasts, but respectively possessed about 67% and 40% of very high vulnerable coasts. Table 6.1 details the quantity of vulnerable coast length in each vulnerability category in the study talukas.

The spatial trend of MCVI for Karwar varied from high to low, along north to south (Fig. 5.1). Only three grids out of 24 in Karwar, were observed to be under high and very high vulnerable category. The geomorphology was major factor deciding the vulnerability of Karwar. Rocky out crops, cliffs and Headlands were dominant morphological features in Karwar. Thus, 46% of Karwar coast may be considered as of low vulnerability. For mitigation purposes, priority may be given for three grids under high and very high vulnerability category.

Coast of Ankola was of lowest length among the study talukas with only ten study grids (Fig. 5.2). Of the ten grids, only one of the grids was of very high category and was located at the north of the taluka. Spatial trend of MCVI varied from very high in north to low in south. Similar to coast of Karwar, coast of Ankola too is characterized by the non-erosional geomorphology. About 11% of Ankola coast was found to be of ‘very high’ vulnerability while another 64% of it was in ‘moderate’ vulnerability.

Kumta taluka consisted of 23 grids of which about only four grid cells, contributing to 17% of total coast, were of ‘high’ vulnerability category. ‘Low’ and ‘moderate’ vulnerability were spread over 39% and 43% of the Kumta taluka coast. Spatially, vulnerability trend along coast of Kumta was increasing from north to south.

Coast of Honnavar was found to be more secured with 62% of coast in ‘low’ vulnerability category. Even the ‘high’ vulnerable coastal stretch was about 19%. Two of the northern grid cells in Honnavar taluka were having high value of MCVI. Vulnerability decreased from north to south spatially for Honnavar coast.

Bhatkal was void of ‘very high’ vulnerable coast. However, 30% of the coast was of next vulnerability category, ‘high’. In addition, about 54% of the cost was stable with ‘low’ vulnerability. The spatial trend of vulnerability varied from low to high from north to south (Fig. 5.2). Peak value of MCVI was observed at center of the taluka.

Table 5.7 Quantity of Vulnerable length according to categories in each Taluka

Taluka	**Percent of length (%)**			
	Low	**Moderate**	**High**	**Very high**
Karwar	46.15	26.92	15.38	11.54
Ankola	27.27	63.64	-	9.09
Kumta	39.13	43.48	17.39	-
Honnavar	62.50	12.50	18.75	6.25
Bhatkal	52.94	17.65	29.41	-
Kundapura	7.14	21.43	42.86	28.57
Udupi	-	9.09	24.24	66.67
Mangaluru	-	36	24	40

Converse observations of afore mentioned characteristics were made for the southern talukas, which started from Kundapura. Kundapura had only 8% of ‘low’ vulnerability coasts. However, ‘high’ and ‘very high’ vulnerability category coast were about 43% and 29%, respectively. Jointly, both categories contribute for about 72% of coast of Kundapura may be considered for migration.

Coast of Udupi was the most vulnerable coast of Karnataka. About 67% of the coast was ‘very high’ vulnerability category, 24% of coast was ‘high’ vulnerability category and had no ‘low’ vulnerability coast. Mitigation measures were required for more than 91% of coast. Udupi was characterized by open straight beaches geomorphologically and is densely populated close to shores. Of the 33grid cells, 22 were having MCVI values greater than 7.14. In addition, these 22 cells were well distributed along the cost (Fig. 5.2) confirming that the Udupi coast is the most vulnerable coast in Karnataka.

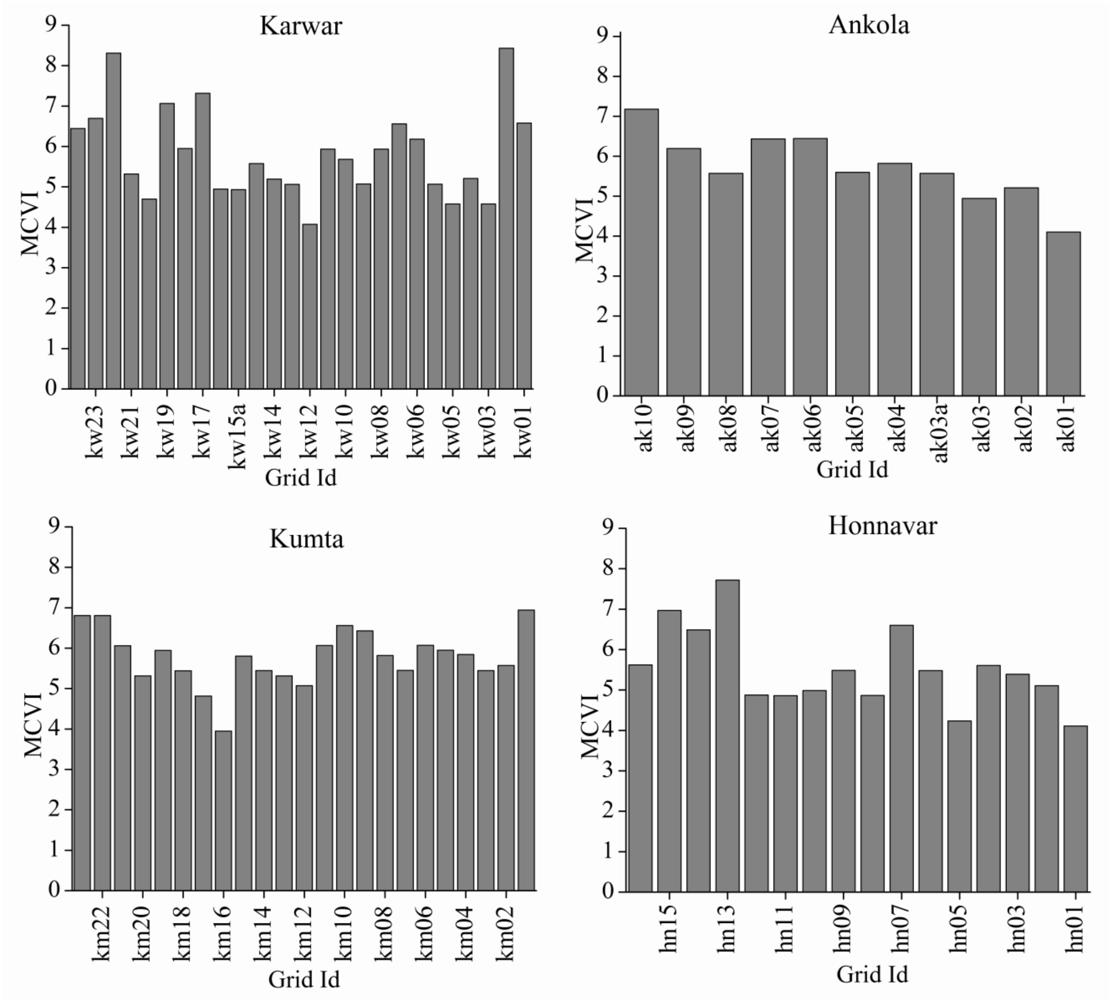


Fig. 5.1 Distribution of MCVI in grids of Karwar, Ankola, Kumta and Honnavar talukas

Coast of Mangaluru takes second most vulnerable coast after Udupi in the present study. It was observed that 40% of the Mangaluru coast was under ‘very high’ vulnerable category and 24% in ‘high’ vulnerable category. However, 36% of coast was in ‘moderate’ vulnerability category. Even with more than one third of coast being moderately vulnerable, Mangaluru coast needs attention since there is no low vulnerability coast present in it.

Based on the present study mitigation priority may be in the following order: Udupi, Mangaluru, Kundapura, Bhatkal, Karwar, Ankola, Kumta and Honnavar. Study also developed taluka level vulnerability maps in the present study, which have been included in the end of the present chapter.

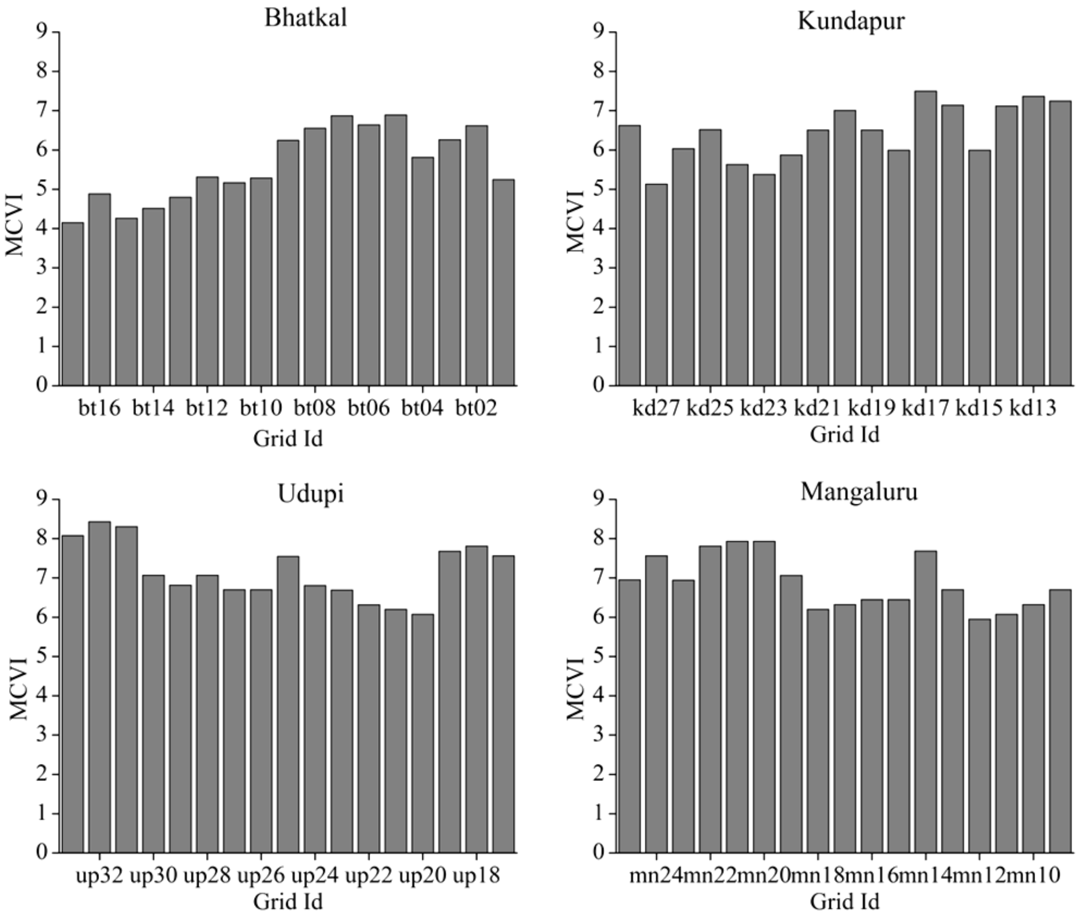


Fig. 5.2 Distribution of MCVI in grids of Bhatkal, Kundapura, Udupi and Mangaluru talukas

5.5 TEMPORAL ANALYSIS OF MCVI

Present study also tried to verify the temporal variation of MCVI, which further strengthens the above prioritization of talukas for mitigation. Among the physical variables considered, Shoreline Change Rate (SCR) was the most dynamic variable of Karnataka coast. Even the opinion survey of experts in the present study also justified the same by providing higher weightage of about 37% to the variable.

Temporal analysis was carried out for three periods 1971-1991, 1991- 2000 and 2000-2012. For these time intervals, the SCR was estimated using the digitized shorelines as mentioned in the methodology chapter. Since sufficient fair weather satellite images were not available to digitize the shorelines, the study was carried out using the End Point Rate (EPR) method of SCR estimation. In addition, due to the unavailability of Socio-economic data in spatial data format for this time period, percentage of increment of variables was considered to extrapolate the data values. Primary emphasis was given to variable population.

National Census study reports contain the Percentage decadal variation in Population at district scale rather than taluka scale. The same values were considered for the taluka within these districts. Increase of population density in the study talukas has been given in Table 5.8.

Table 5.8 Percentage decadal variation in Population if study districts (Source: Census 2011)

Districts	1971-81	1981-91	1991-01	2001-11
Uttara Kannada	26.38 %	13.66 %	10.93 %	6.15%
Udupi	22.31 %	9.42 %	7.14 %	5.90%
Dakshina Kannada	22.72%	15.98%	14.59%	9.80%

Using the values of the Table 5.8 corresponding population in each grid cell was reduced by incremental percentage to arrive at the population for the study periods. Using such population value, the MCVI was computed for the study periods. Table 5.9, 5.10, 5.11 describes the percentage length in various categories.

During the period 1971-1991 Ankola, KumtaHonnavar and Bhatkal did not have any very high vulnerable coastal stretches. Udupi taluka was having about 70% of ‘very high vulnerable’ coast followed by Mangaluru and Kundapura with 52%and 25%, respectively. This is predominantly due to the higher population density and erosion in beaches of the southern talukas during this period. However, the erosion rates were comparatively lower than the erosion rates during the other study periods.

Table 5.9 Quantity of Vulnerable length according to categories in each Talukas for the period 1971-1991

Taluka	Percent of length (%)			
	Low	Moderate	High	Very High
Karwar	34.62	30.77	26.92	7.69
Ankola	27.27	54.55	18.18	0.00
Kumta	52.17	21.74	26.09	0.00
Honnavar	50.00	37.50	12.50	0.00
Bhatkal	58.82	23.53	17.65	0.00
Kundapura	10.71	46.43	17.86	25.00
Udupi	0.00	3.03	27.27	69.70
Mangaluru	0.00	8.00	40.00	52.00

The scenario during 1991-2000 changed with more coastal stretches of northern talukas having the MCVI of 'very high vulnerable' category magnitude. Table 5.10 describes the percentage of length in each category for the period. Udupi consisted of about 42% coast in 'very high' vulnerability category and about 55%in 'high' vulnerability category. Mangaluru possessed 44% length of coast in both 'very high' and 'high' vulnerability categories. This is mainly because of the population growth and the settlements in the study grids during this period and extension of city limits of Mangaluru. In addition, for the same period, stretches of other coastal talukas suffered from erosion and as well had an increase in population. Honnavar and Bhatkal coast were consisting of the highest percentage of 'low' vulnerability coast with about 69% and 65%, respectively. However, Udupi as well as Mangaluru had a contrasting scenario with no coastal stretch with 'low' vulnerability.

During the period 2000-2012, erosion of coast had subsided and accretion was observed resulting in a change of scenario. Ankola, Honnavar and Bhatkal were noticed with no 'very high' vulnerability coast, while Udupi and Mangaluru had respectively about 61% and 52% of 'very high' vulnerability coast. There were no stretches of 'low' vulnerability coast in Kundapura and Udupi for the period 2000-2012, while Ankola was least vulnerable coastal taluka with about 73% coast in 'low' vulnerable category. Table 5.11 describes the percentage of length in each category for the period 2000-2012.

Table 5.10 Quantity of Vulnerable length according to categories in each Taluka for the period 1991-2000

Taluka	Percent of length (%)			
	Low	Moderate	High	Very high
Karwar	26.92	30.77	26.92	15.38
Ankola	18.18	36.36	27.27	18.18
Kumta	39.13	43.48	13.04	4.35
Honnavar	68.75	18.75	6.25	6.25
Bhatkal	64.71	11.76	11.76	11.76
Kundapura	17.86	50.00	17.86	14.29
Udupi	0.00	3.03	54.55	42.42
Magaluru	0.00	12.00	44.00	44.00

Table 5.11 Quantity of Vulnerable length according to categories in each Taluka for the period 2000-2012

Taluka	Percent of length (%)			
	Low	Moderate	High	Very high
Karwar	61.54	19.23	11.54	7.69
Ankola	72.73	9.09	18.18	0.00
Kumta	30.43	39.13	26.09	4.35
Honnavar	31.25	56.25	12.50	0.00
Bhatkal	41.18	41.18	17.65	0.00
Kundapura	0.00	28.57	39.29	32.14
Udupi	0.00	12.12	27.27	60.61
Magaluru	4.00	16.00	28.00	52.00

The temporal analysis in the present study may be viewed to be with high degree of uncertainty. However, such an analysis will provide the preliminary prioritization of most vulnerable coastal stretches. The MCVI in the present study provides insight into the relative potential of Karnataka coast to natural hazard. The data and maps developed here can be considered as a base for developing a more complete catalog of variables influencing the coastal vulnerability. In the following chapter, an assessment of tsunami vulnerability has been carried out to improvise the present vulnerability index.

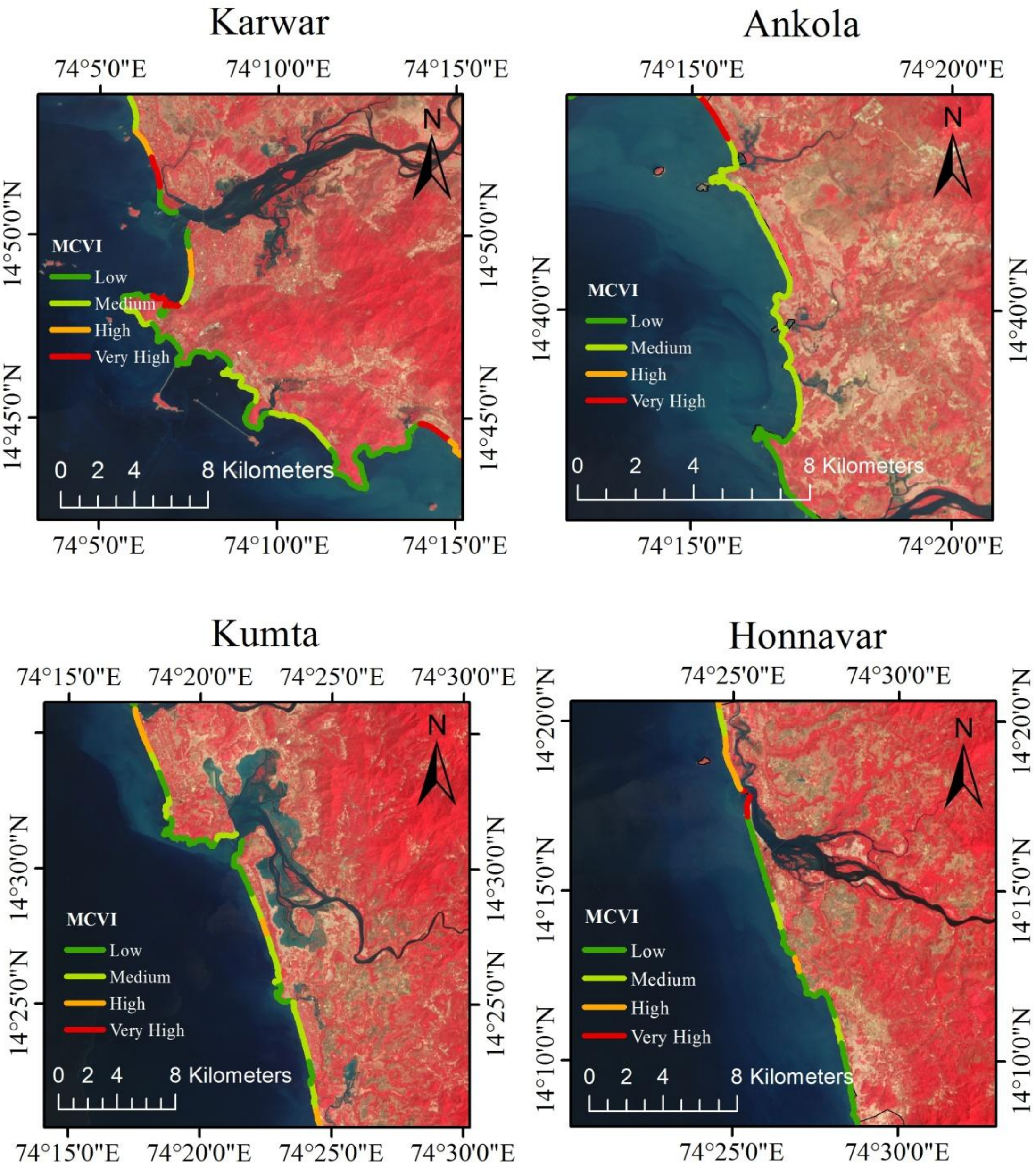


Fig. 5.3 Vulnerability map of Karwar, Ankola, Kumta and Honnavar

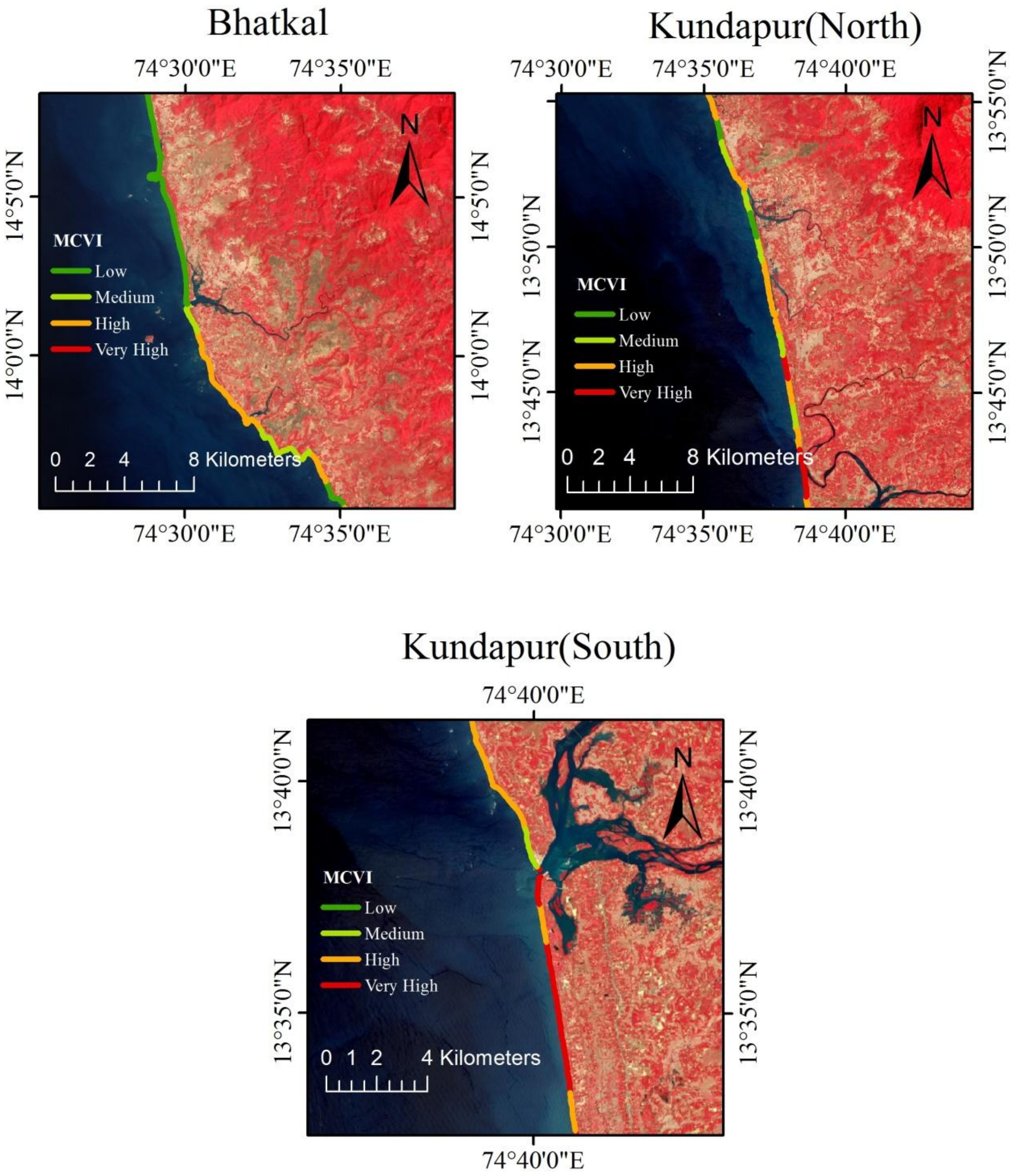
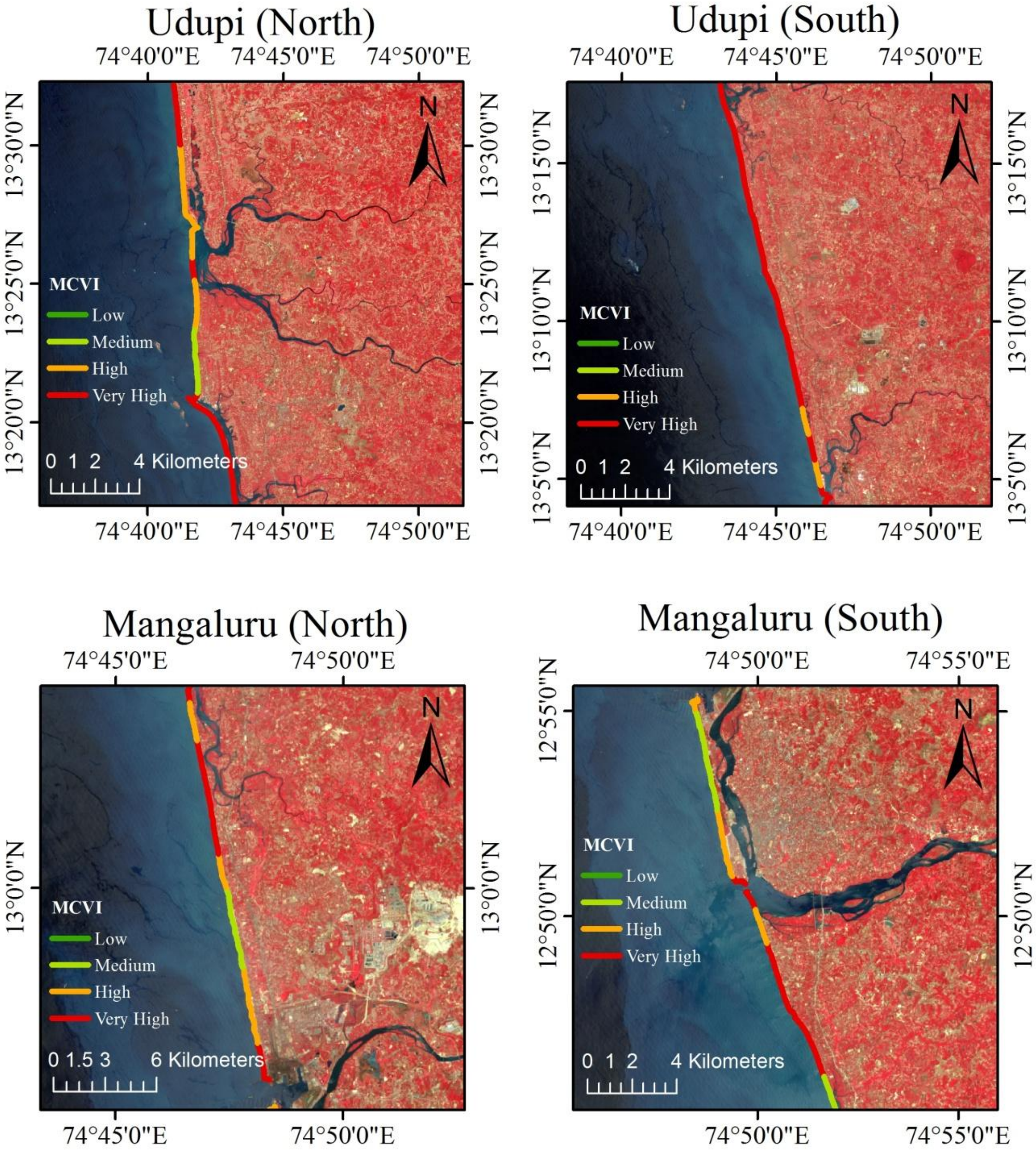


Fig. 5.4 Vulnerability map of Bhatkal and Kundapura


Udupi (North)

Udupi (South)

Mangaluru (North)

Mangaluru (South)

Fig. 5.5 Vulnerability map of Udupi and Mangaluru

5.6 SUMMARY

Recent past has witnessed the higher frequency of coastal hazards. In view of this, the present study assessed coast of Karnataka for vulnerability to coastal hazards. It was noticed that the coasts of Udupi and Mangaluru talukas were most vulnerable in the study area. In addition, the use of AHP for assignment of weights to variables has provided the realistic scenario for the vulnerability assessment. The MCVI developed in the present study evaluated the level of risk on different segments of the coast. The maps developed in the present study are useful to identify areas where physical changes are most likely to occur in case of a coastal hazard, and as well in planning, managing and protecting resources in the study area.

CHAPTER 6

TSUNAMI VULNERABILITY ASSSSMENT

6.1 GENERAL

The coastal zone is a valuable area that supports humans and various ecosystems of high biological and economic importance. However, ecosystems and human settlements in coastal regions can be vulnerable to natural disasters such as tsunamis. The giant Tsunami in the Indian Ocean on 26 December 2004 is a very good example of a disastrous event of Tsunami.

"Tsunami" waves are generated due to the large-scale disturbance of the seabed such as earthquake or volcanic eruption or submarine landslides within a short duration of time. The displacement of seawater during the large-scale seabed disturbance and its return to equilibrium position due to gravity creates a series of oscillations both above and below sea level generating waves that propagate outwards from the source region. The Andaman-Nicobar-Sumatra Island Arc in the Bay of Bengal and the Makran Subduction Zone in the North Arabian Sea have been identified to be tsunamigenic zones threatening the Indian Ocean regions (Nayak and Kumar 2008).

Recent studies have investigated Tsunami vulnerability by analyzing multiple variables that can influence Tsunami damage. These studies have combined variables into a vulnerability index using a weighted mean (Papathoma et al. 2003; Papathoma and Dominey-Howes 2003; Dominey-Howes and Papathoma 2006; Dominey-Howes et al. 2009; Omira et al. 2010), and Dall'Osso et al.(2009) used the Analytic Hierarchy Process (AHP) for computing weights.

The tsunami waves of December 2004 though brought some amount of damage to coast of Kerala, coast of Karnataka was largely spared from the event. However, the presence of Makaran subduction zone in Arabian Sea could be a major threat resulting in a disastrous tsunami. Therefore, a tsunami vulnerability mapping was carried out as part of present study.

6.2 VARIABLES AND METHODOLOGY

Risk due to topographical feature is an integral part of any vulnerability assessment concerning natural hazards and disasters. Especially, while conducting a tsunami vulnerability assessment, it is crucial to determine the areas more likely to be physically affected by incoming waves.

Four geospatial variables, namely topographic elevation, slope, coastal proximity and vegetation were considered in the present study based on the literature review of past tsunami risk assessments. A cell-based spatial analysis was carried out to determine the tsunami vulnerability area. The four variables in their raster data format were classified into five classes of vulnerability based on their raster values. The classification technique used was 'Jenks natural break' method, which lessens the Sum of Squared Difference (SSD) within a group, to form internally homogeneous groups (Sinaga et al. 2011). Rank 5, 4,3, 2, and 1 were assigned to the five classes, "very high", "high", "medium", "low", and "very low" respectively.

A tsunami vulnerability map was prepared for the study area between the coast and 3 km buffer line by overlying all the four variable rasters using ArcGIS 9.3 package. Fig.5.1 shows the flow chart of the process adopted for the tsunami vulnerability mapping. The output map is a raster showing five categories of tsunami vulnerability for the study area. Description of variables and the data used has been detailed in the following sections.

6.2.1 Topographic Elevation

Low elevation coastal zone covers 2 percent of the world’s land area but contains 10 percent of the world’s population and 13 percent of the world’s urban population (McGranahan et al.2007).Therefore, topographic elevation of the region is a primary condition to assess the tsunami vulnerability of a region.

The inundation during a tsunami will differ according to the ground elevation. The safest option for the identification of the potential inundation zone is to define it as the area between the coastline and the contour of the highest recorded tsunami runup. However, the study area has never been subjected to an event of tsunami until date. So, the vulnerability classes were adopted as given by Iida (1963).

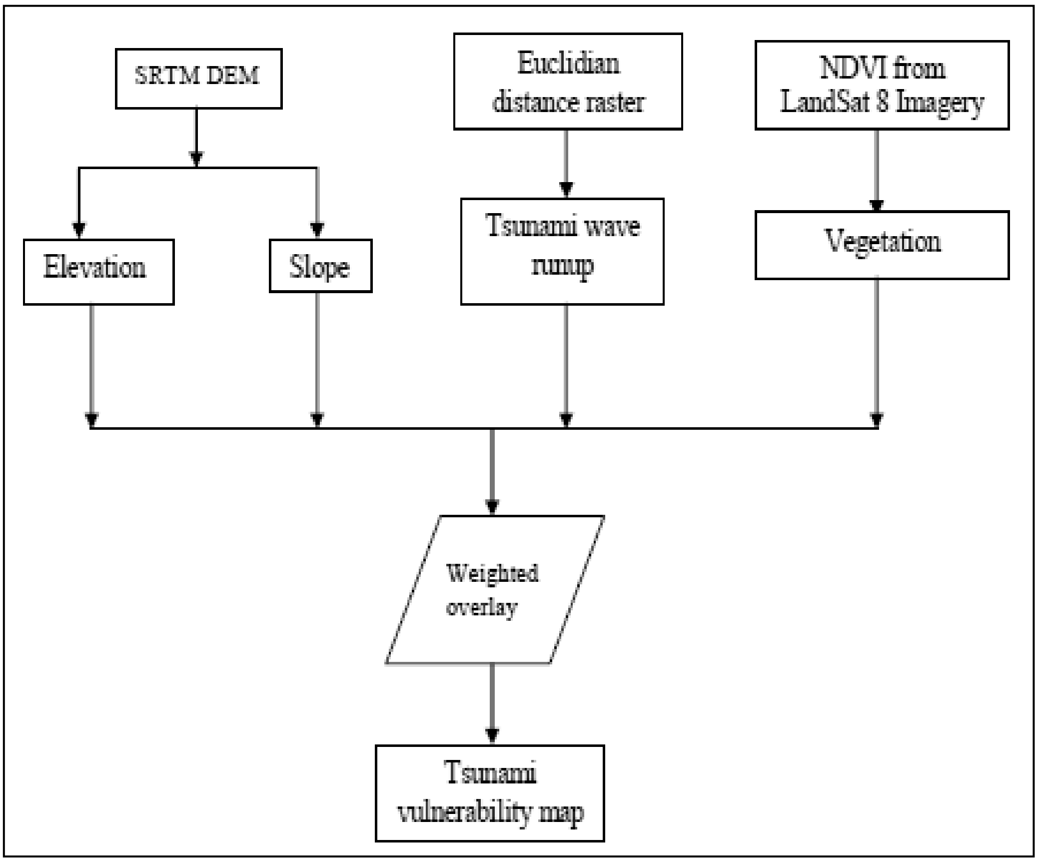


Fig. 6.1 Flow chart of tsunami vulnerability mapping

Present study made use of Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM) to obtain the topographic elevations in the study area and were classified into five groups based on the tsunami runup height at the coast (Table 6.1).

6.2.2 Topographic Slope

Inundation distance and runup wave height are affected by regional coastal slope and bathymetry of the area (Koh et al. 2009). Areas with flat topographic slope experience severe tsunami run-up while hills and steep slopes bordering the beach witness attenuated tsunami runup (Sinaga et al. 2011).

Topographic slope map for the study area was generated using ArcGIS 9.3 package using SRTM DEM. The equation of slope for a grid cell is given by Burrough and McDonnell (1998) as:

$$\mathrm{Slope} = \sqrt{(\partial z / \partial x)^2 + (\partial z / \partial y)^2} \qquad (6.1)$$

Where *∂z/∂x* is the angle for east-west direction, and *∂z/∂y* is the angle for north-south direction. Van Zuidam (1983) slope classification scheme was employedto make vulnerability classes (Table 6.1).

6.2.3 Coastal Proximity

In tsunami vulnerability assessment, tsunami wave height and inundation distance are the most dominant variables. Possible reach of a tsunami wave affecting inland regions isa function of distance from the coastline. Generally, vulnerability increases with increase in coastal proximity. A proximity raster was generated using ArcGIS 9.3package for the study area. To classify coastal proximity, study used equation from Bretschneider and Wybro (1976):

$$\log X_{\max} = \log 1400 + (4/3)\log(Y_0/10) \qquad (6.2)$$

where, X_{max} is the maximum reach of the tsunami over land, and Y_0 is the tsunami height at the coast. According to the above mentioned equation, a tsunami with a 5 m runup would reach up to 556 m from the shoreline. Similarly, runup of 5 to 10 m,10 to 15 m, and 15 to 20 m would reach a distance of 556-1400 m, 1400-2404 m, and 2404-3528 m, respectively, from the shoreline. Table 6.1 describes the ranks for five classes of proximity.

6.2.4 Vegetation

Coastal vegetation belts have been found to be beneficial in mitigating tsunami disasters. Tree belts have been considered "bio-shields" against tsunami wave impact. Several post tsunami disaster field investigations and laboratory experimental results have proved that coastal vegetation belts provide resistance against tsunami runup. Impact of vegetation is dependent upon its presence. Presence of vegetation in front of settlements proves beneficial while beyond settlement has a negative effect (Bayas et al. 2011).

In the present study, Normalized Difference Vegetative Index (NDVI) map prepared from Landsat OLI-TIRS satellite images were used as a proxy for the vegetation data. USGS A NDVI value greater than 0.2 has been considered to be vegetation. This classification was considered from USGS based scheme. Sparse vegetation such as shrubs and grasslands or season crops may show approximate NDVI values ranging from 0.2 to 0.5. Healthy crops at their peak growth stage as well as dense forests (temperate and tropical) might result in high NDVI values (0.6 to 0.9 approximately).

Table 6.1 Range of Tsunami Vulnerablitiy variables

Sl. No	**Variable**	**Rank 5**	**Rank 4**	**Rank 3**	**Rank 2**	**Rank 1**
1	Elevation (m) (*source*: Iida ,1963)	<5	5-10	10-15	15-20	>20
2	Topographic Slope (%) (*Source*: Van Zuidam, 1983)	0-2	2-6	6-13	13-20	>20
3	Distance from the Shoreline (m) (*Source*: Bretschneider and Wybro, 1976)	0-556	556-1400	1400-2404	2404-3528	>3528
4	Vegetation (NDVI)	<0.2	0.2-0.3	0.3-0.4	0.4-0.5	>0.5

6.3 VULNERABILITY ASSESSMENT AND MAPPING

Vulnerability map illustrates the potential area that can be damaged by natural hazards. Tsunami vulnerability describes the possible inundation of habitual area, result of a tsunami wave traveling a long distance. Present study assessed an exposure based tsunami vulnerability assessment for the study area with the aid of GIS. Multi-criteria analysis of regional environmental characteristics was carried out and Tsunami vulnerability map was prepared. Table 6.2 shows the distribution of tsunami vulnerable areas in each taluka.

Table 6.2 Tsunami Vulnerable area distribution among study talukas

Sl. No.	**Taluka**	**Very high (km^2) (Category 5)**	**High (km^2) (Category 4)**	**Moderate (km^2) (Category 3)**	**Low (km^2) (Category 2)**	**Very low (km^2) (Category 1)**
1	Karwar	3.44	31.88	17.52	32.99	1.19
2	Ankola	3.27	20.29	17.06	6.57	0.23
3	Kumta	5.39	34.51	27.78	10.35	0.01
4	Honnavar	3.40	24.73	23.67	12.72	0.09
5	Bhatkal	3.93	32.00	33.25	6.95	0.15
6	Kundapura	7.15	67.96	47.83	5.49	0.00
7	Udupi	4.01	75.63	55.38	1.53	0.00
8	Mangaluru	6.65	44.91	49.33	3.38	0.00

Karwar has about 1.19 km^2 ‘category 1’ and 32.99 km^2‘category 2’ tsunami vulnerable area, both highest among all the talukas. Kundapura, Udupi and Mangaluru talukas are void of ‘category 1’ tsunami vulnerable areas while Ankola, Kumta, Honnavar and Bhatkal have less than 0.5 km^2. This is because geomorphlogy of Karwar taluka has the high-elevated areas and steep slopes very close to the coast. Kundapura has larger category 5 vulnerability area of about 7.15 km^2 followed by Mangaluru, Kumta, Udupi, Bhatkal, Karwar,Honnavar and Ankola with 6.65 km^2, 5.39 km^2, 4.01 km^2, 3.93 km^2, 3.44 km^2, 3.40 $km^2$and 3.27 km^2respectively.

Udupi has highest ‘category 4’ vulnerable area with 75.63 km^2. However, this is the largest area for any category in any of the talukas. Therefore, in formulating mitigation plans Udupi taluka may be given higher priority followed by the Kundapura taluka. Other talukas may be given lesser priority.

Tsunami vulnerability map generated for the study area was overlaid on the landuse/landcover map. The expanse of various LU/LC types in five different risk categories is as in the Table 6.3. It can be observed that habitation (206.403 km^2) and cropland (181.103 km^2) turn out to be major classes of the study area and the both the classes are in high risk category.

Table 6.3 Various LU/LC Classes under Tsunami Vulnerability ranks

		Area under each Risk category (km^2)				
Sl. No.	**LU/LC**	**Rank 1**	**Rank 2**	**Rank 3**	**Rank 4**	**Rank 5**
1	River/Stream	10.736	29.913	3.306	0.134	0
2	Evergreen/Semi evergreen Dense Forest	0.017	0.868	8.858	33.745	1.419
3	Kharif crop	9.76	85.624	31.65	2.162	0
4	Habitation with Vegetation	4.283	103.691	87.169	5.602	0
5	Barren Rocky/Stony Waste/Sheet Rock Area	0.025	1.553	10.486	1.319	0
6	Sandy area	0.342	1.361	0.175	0.008	0
7	Marshy/Swampy Area	0.927	3.198	0.317	0	0
8	Lake/Tanks	0.159	0.726	0.092	0	0
9	Tree Groves	0.134	5.468	14.786	4.057	0
10	Kharif & Rabi (Double Crop)	2.221	34.539	9.017	0.426	0
11	Village	0.109	1.753	2.288	0.075	0
12	Agricultural Plantation	0.225	6.487	8.031	1.319	0
13	Mixed Vegetation	1.002	11.571	19.97	3.949	0
14	Aquaculture pond	1.812	3.54	0.033	0	0
15	Forest Plantations	0.092	1.695	5.719	0.568	0
16	River Island	0.651	7.731	1.394	0	0
17	Town/Cities	0.893	6.17	8.599	0.434	0
18	Moist & Dry Deciduous Dense Forest	0	0.117	1.77	4.066	0.042
19	Scrub Forest	0.008	1.144	9.676	2.989	0
20	Degraded Forest	0.459	3.139	6.762	1.077	0

Sl. No.	LU/LC	Area under each Risk category (km^2) Rank 1	Rank 2	Rank 3	Rank 4	Rank 5
21	Industrial Area	1.077	5.994	2.146	0.109	0
22	Evergreen/Semi evergreen Open Forest	0.017	2.062	10.16	11.596	0.083
23	Fallow land	0.635	2.83	1.636	0.192	0
24	Mining/Industrial Wasteland	0.067	0.209	0.267	0.167	0
25	Land with scrub	0.033	2.154	10.127	1.929	0.008
26	Salt Pans	0	0.058	0.05	0.008	0

It was observed that 36 km^2 area was under 'very high' vulnerability class and 322 km^2 was under 'high' vulnerability class. 'Medium' vulnerability class area was about 264 km^2 ,while 78 km^2 and 2 km^2 area were under 'low' and 'very low' vulnerability class. An administrative unit wise tsunami vulnerability map of the study area was compared with the landuse/landcover map of study area and expanse of various landuse/landcover classes under threat were estimated. The vulnerability maps prepared from the study could be effectively be used for the effective mitigation strategies.

6.4 SUMMARY

Present study evaluated a multi-criteria analysis of tsunami vulnerability for regional scale using GIS environment with geospatial variables. Four geospatial variables, *viz.*, topographic elevation, topographic slope, coastal proximity and vegetation were used to create a tsunami vulnerability map for the Karnataka coast. The study made use of NDVI maps for vegetation. An overlay of the land-use classification on the tsunami vulnerability map showed that habitation (206.403 km^2) and cropland (181.103 km^2) area the two major classes of the study area, which are in high-risk category. Tsunami vulnerability maps for each taluka were generated from the present study, and are enclosed at the end of the present chapter.

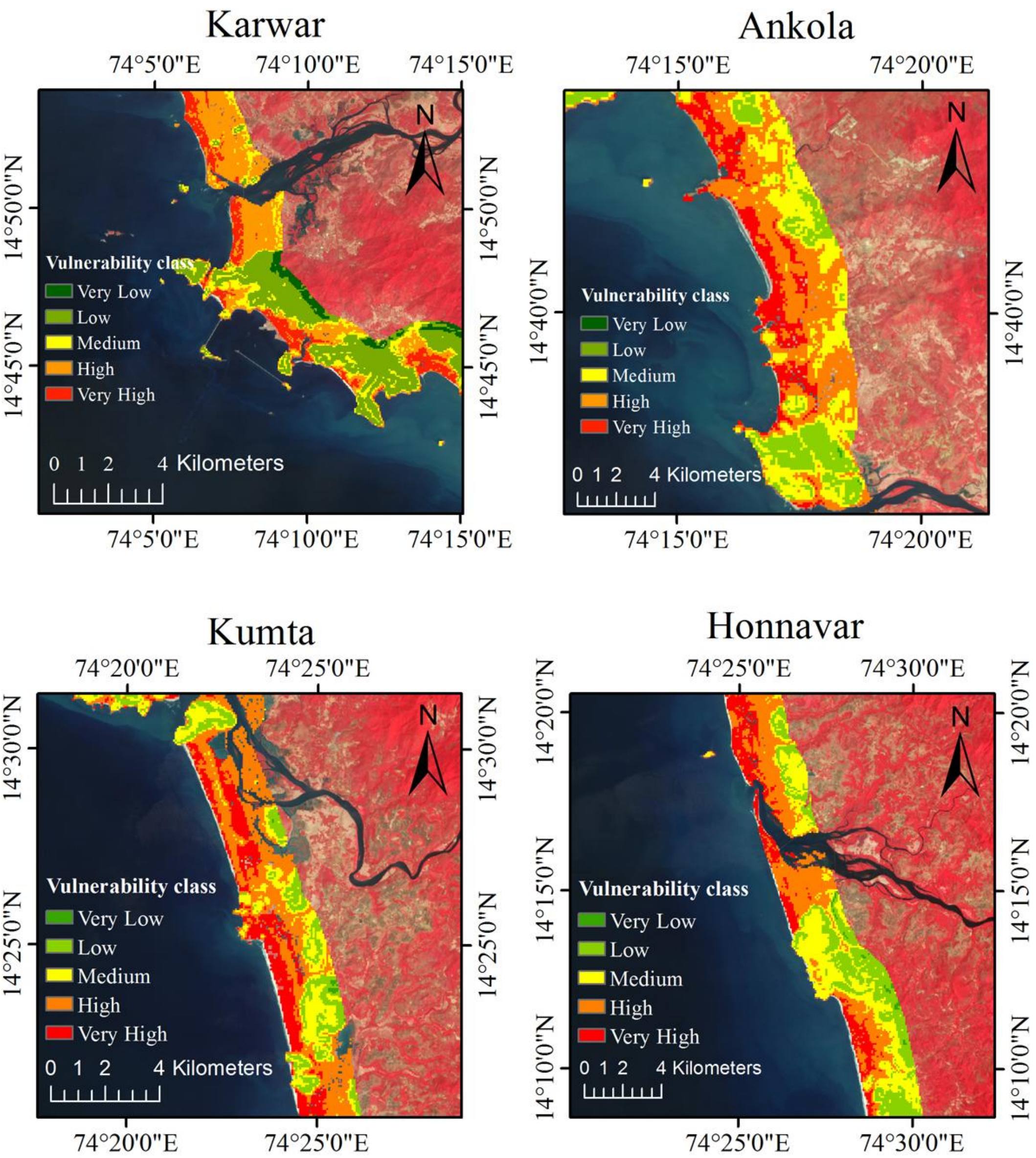


Fig. 6.2 Tsunami Vulnerability map of Karwar, Ankola, Kumta and Honnavar Talukas

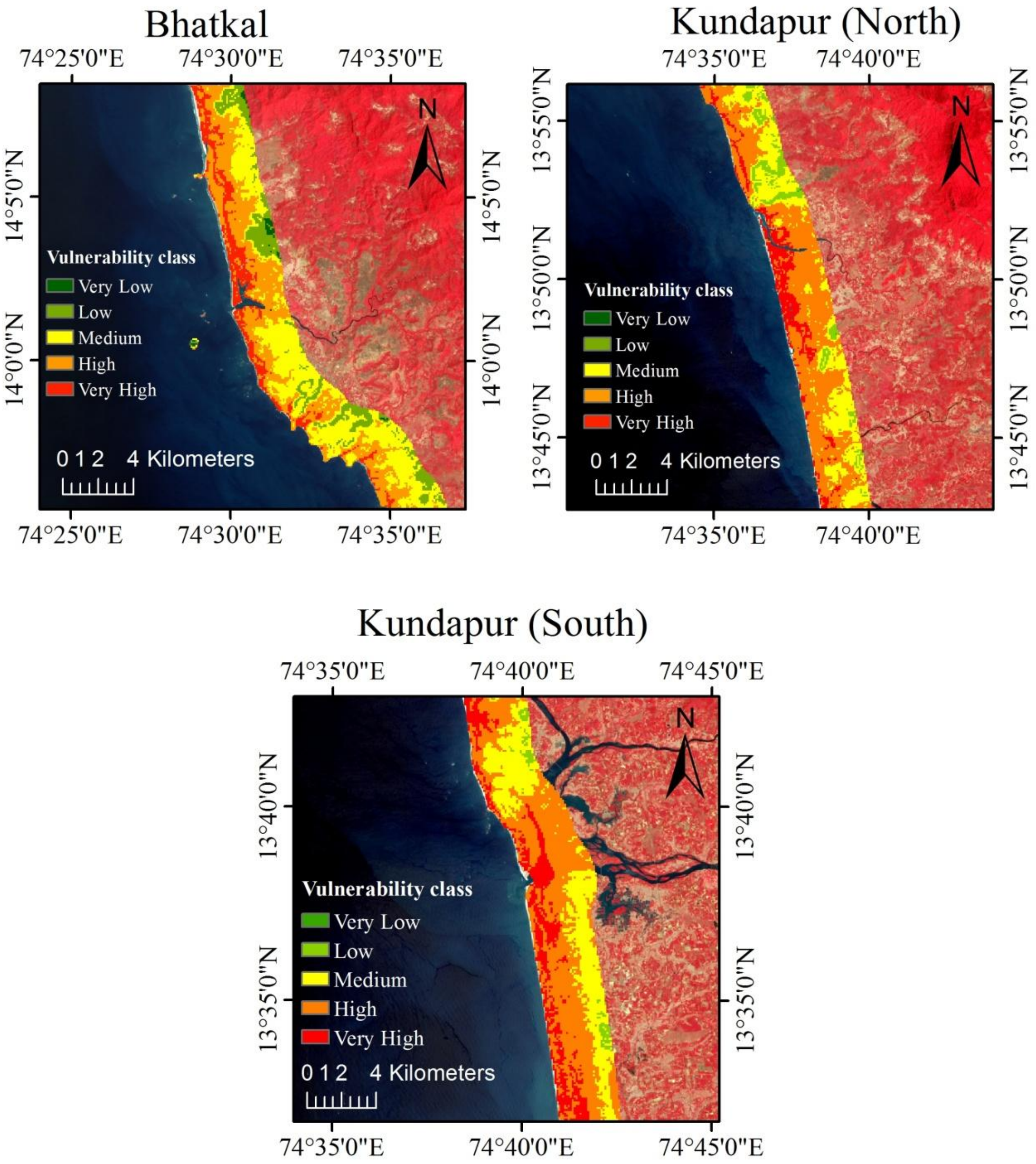


Fig. 6.3 Tsunami Vulnerability map of Bhatkal and Kundapura Taluka

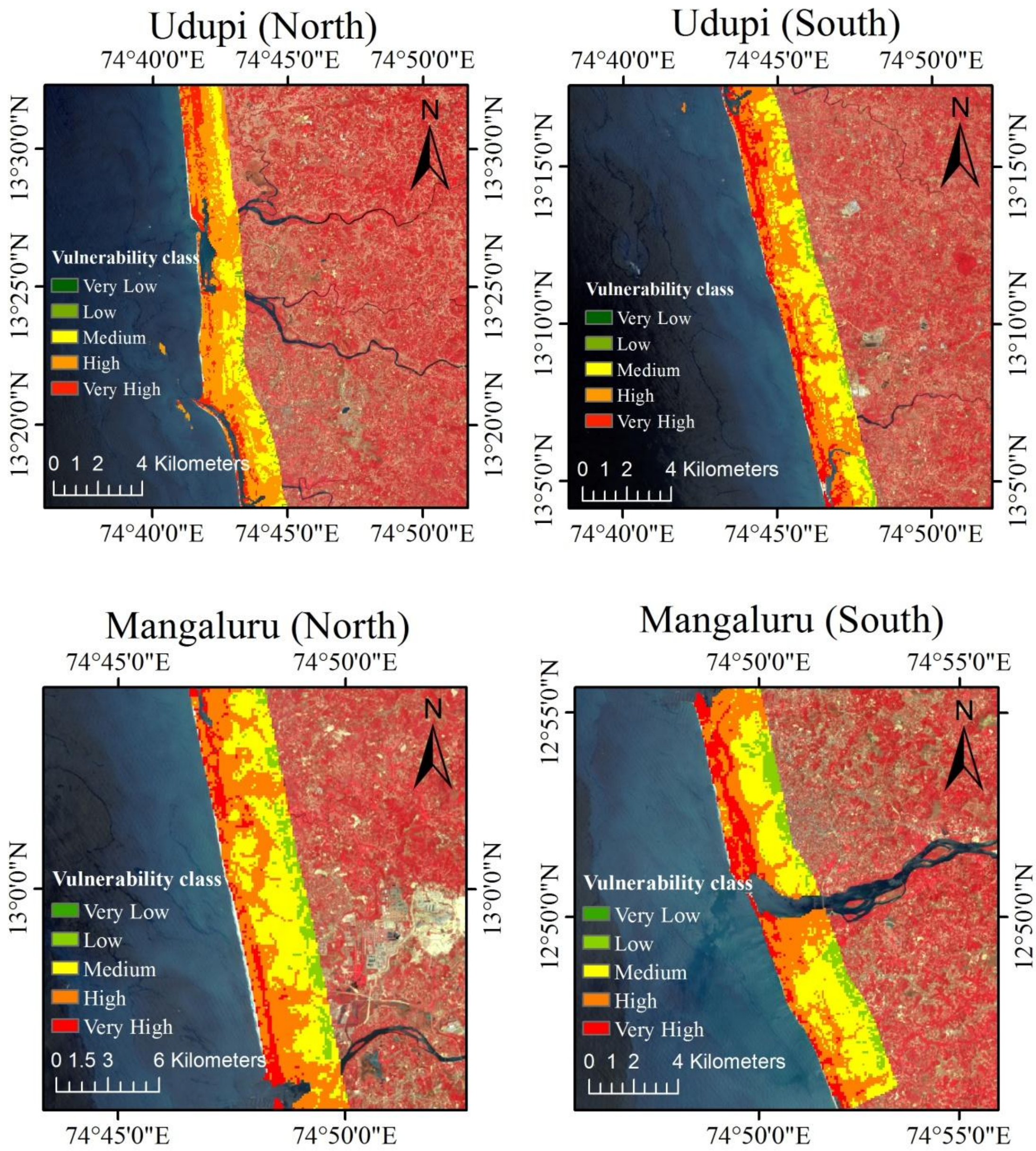


Fig. 6.4 Tsunami Vulnerability map of Udupi and Mangaluru Talukas

CHAPTER 7

CONCLUSIONS

7.1 GENERAL

In the view of the rising sea levels and other coastal hazards, an assessment of coast for its vulnerability to these threats is necessary in order to take suitable actions to protect the people and property. Hence, in the present study, Modified Coastal Vulnerability Index (MCVI) was developed to for the coast of Karnataka with the extensive use of geospatial technologies.

Study of literatures indicated that the majority of vulnerability studies made use of physical and geological variables as the primary factors influencing the vulnerability. However, it was noticed that researchers have stressed on the inclusion of the socio-economic variables would make the study to be more accurate and complete. Hence, present study employs seven physical and three socio-economic variables for calculation of CVI. Later, AHP and pairwise comparison method was used to integrate expert opinions in prioritization of variables to develop MCVI. Present chapter incorporates the conclusion, limitations and future scope of the present work.

7.2 CONCLUSIONS

The major conclusions drawn from the study are listed below:

1. Karnataka coast has 71.92 km length of coast in ‘very high vulnerability’ category, while 71.25 km falls under ‘high vulnerability’ category. The extent of ‘moderate vulnerability’ and ‘low vulnerability’ was 71.20 km and 80.69 km, respectively. Coast of Udupi taluka has 65% of the cost highest in ‘very high’ vulnerability category coast, which is highest for any of the other talukas. Mangaluru taluka has about only 40% in ‘very high’ vulnerability

category. Hence, the prioritization of mitigation actions should be concentrated on coast of Udupi and then Mangaluru. Among the northern taluka coasts, Karwar may be given higher preference as it has about 12% in very high vulnerability category, and also has important defence infrastructure as well as higher density of population.

2. Based on the analysis of 42 years of shoreline data, it was observed that about 4.09 km of Karnataka coastline has a very high erosion risk and 14.25 km of coastline has high erosion risk. Of the remaining length about 267.50 km of coastline was under a moderate risk while 1.5 and 10.66 km stretch were under low and very low risk category respectively. Average accretion for the study area was found to be 1.133 m year^{-1} and average erosion was 0.533 myear^{-1}. It was also noticed that the net erosion in for the southern talukas was 52% more than the northern talukas.
3. Between the years 1972-1991 Karnataka coasts was in relative equilibrium with highest erosion less than 4 m year^{-1} with and highest accretion less than 5 m year^{-1}. However, higher erosion was noticed for the decade 1991-2000 in most of the grid cells and accretion was observed in the same cells during 2000-2012. This may be due to intense urbanization and population settlements in southern coastal talukas of Karnataka.
4. Geomorphologically, about 157 km length of coast was categorized to be of ‘very high’ vulnerable class and 48 km was of ‘high’ vulnerable class. About 39 km and 49 km length of coast would fall under ‘low’ and ‘very low’ vulnerable category, respectively. The coast of Udupi and Mangaluru talukas comprise of erodible geomorphic features like long, narrow and straight open sandy beaches. In addition, barrier spits, estuaries, and coastal ecosystems, such as mangroves, coastal forest, and aquaculture ponds are also found in southern talukas. While, the coast of Karwar, Ankola and Honnavar are characterized by beach ridges, coastal alluvial soil, spit and tidal flats. Coast of Kundapura and Bhatkal talukas comprise rocky beaches, lateritic plain, alluvial plain, tidal flat and channel islands.
5. It was observed that 36 km^2 area was under 'very high' tsunami vulnerability class and 322 km^2 was under 'high' tsunami vulnerability class. 'Medium'

tsunami vulnerability class area was about 264 km^2, while 78 km^2 and 2 km^2 area were under 'low' and 'very low' tsunami vulnerability class.

6. The effect of physical variables on Karnataka coast is very much less in comparison with the geological and socio-economical variables.
7. Mangaluru, Udupi and Honnavar talukas were having higher amount of low-lying areas in comparison with other talukas. The least quantity of low elevation areas were found in Ankola taluka. Other talukas comprised of fairly higher elevated areas. Least quantity of low-lying area was found in Ankola due to shorter coastal length. However, coast of Honnavar has higher quantity of low-lying area in spite of longer coastal length.
8. Coastal grids of Karwar, Udupi, southern Kundapura and Mangaluru consisted of higher population density, while grids of other coastal talukas are scarcely populated. In the northern part of study area, the population density increased far off from the grids due to highly undulating topography and flood prone regions. This has reduced the vulnerability of such grids drastically, once again emphasizing on the influence of geomorphology on the vulnerability of coast.
9. MCVI values obtained in the present study indicate that northern talukas of the state are less vulnerable in comparison to southern talukas. This can be particularly attributed to the lower population density and non-erosional geomorphology of northern talukas.
10. MCVI developed in the present study was more sensitive to the socio-economic variables in the study area than physical or geological variables.
11. The application of Analytical Hierarchical Process (AHP) to multi-criteria vulnerability assessment is more advantageous since such assessments lack a purely deterministic method due to the huge data involved from different sources.

7.3 LIMITATIONS

Some of major limitations of the study have been listed below:

1. The results of MCVI is largely dependent on the quality of the data used and types of data used, which influence the vulnerability of a particular coastal stretch.
2. Availability of socio economical data in temporal scale is limited. Because of this, the temporal vulnerability study is limited largely.
3. Present study evaluated vulnerability of complete Karnataka coast for which some generalizations were made. With increase in size of the study area, such generalization are necessary for the analysis. However, with a smaller study area, such generalization may be avoided and an accurate assessment can be made.

7.4 FUTURE SCOPE

Some of the future scopes for the present study are listed below.

1. Present study identifies only the total risk on the stretch of the coast. A detailed study on the each variable may be required for developing more mitigation plans.
2. In present study, simple AHP was applied to arrive at the weights. Other types of multicriteria assessments, such as ‘Preference Ranking Organization Method for Enrichment of Evaluations’ (PROMETHEE) might well improve the assessment.
3. Use of numerical modeling for the coastal processes such as tidal range and significant wave height might lessen the inadequacy of data for coastal vulnerability assessment.
4. Vulnerability analysis at smaller spatial scale would provide a detailed mitigation plan for the coastal authority.

7.5 CONCLUDING REMARKS

GIS aided analysis are useful for a wide range of disaster assessment, with spatial functionalities such as topographic operations, proximity calculation, buffer creation, raster reclassification, map algebra, and intersection operations. Such approaches can aid in regional planning for management and mitigation of natural disasters, including tsunamis

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1. Akshaya Beluru Jana and Arkal Vittal Hegde, (2016). “GIS Based Approach for Vulnerability Assessment of the Karnataka Coast, India,” *Advances in Civil Engineering*, Vol. 2016, Article ID 5642523, 10 pages, doi:10.1155/2016/5642523
2. Akshaya B. J. and Arkal Vittal Hegde (2017). “Assessment of Coastal Vulnerability to combined effects of Socio-Economical Factors and Erosion on Karnataka Coast with the aid of Integrated Remote Sensing and GIS Techniques” *International Journal of Earth Sciences and Engineering*, Vol. 10 (02), 313-320, DOI:10.21276/ijese.2017.10.0224,

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APPENDIX-A

RANKING OF VARIABLES ALONG THE GRID CELLS

Grid Id	Slope	Shoreline Change Rate	Regional Elevation	Tidal Range	Wave Height	Sea Level Rise	Geomorphology	Population	Land Use	Road Networks
kw24	4	2	4	4	3	1	5	4	5	1
kw23	2	2	4	4	3	1	3	5	5	2
kw22	3	4	4	4	3	1	5	5	5	4
kw21	4	2	4	4	3	1	4	1	3	5
kw20	4	1	4	4	3	1	4	1	5	2
kw19	1	4	4	4	3	1	3	5	5	1
kw18	1	1	4	4	3	1	3	5	5	1
kw17	1	4	4	4	3	1	1	5	3	5
kw16	1	3	4	4	3	1	1	1	3	5
kw15a	1	5	4	4	3	1	3	1	3	1
kw15	1	2	4	4	3	1	1	3	3	5
kw14	3	3	4	4	3	1	3	1	3	4
kw13	1	4	4	4	3	1	3	1	5	1
kw12	1	2	4	4	3	1	3	1	3	2
kw11	3	5	4	4	3	1	3	2	1	4
kw10	3	5	4	4	3	1	3	1	5	1
kw09	2	3	4	4	3	1	1	1	3	5
kw08	1	5	4	4	3	1	1	3	3	2
kw07	1	4	4	4	3	1	3	3	3	5

kw06	1	5	4	4	3	1	3	1	4	5
kw05a	1	4	4	4	3	1	1	1	3	4
kw05	1	2	4	4	3	1	1	1	3	5
kw04	1	1	4	4	3	1	1	3	3	5
kw03	1	2	4	4	3	1	1	1	3	5
kw02	1	5	4	4	3	1	3	5	5	5
kw01	2	4	3	4	3	1	3	3	4	4
ak10	5	5	4	4	3	1	5	1	5	5
ak09	4	4	4	4	3	1	1	1	5	5
ak08	4	1	4	4	3	1	5	1	5	5
ak07	4	4	4	4	3	1	5	1	4	5
ak06	4	4	4	4	3	1	1	2	4	5
ak05	4	2	3	4	3	1	1	2	4	5
ak04	1	2	4	4	3	1	3	2	5	5
ak03a	1	2	4	4	3	1	3	2	4	5
ak03	1	3	4	4	3	1	1	1	3	5
ak02	1	4	3	4	3	1	1	1	3	5
ak01	1	1	3	4	3	1	1	1	3	5
km23	3	5	4	4	3	1	4	1	5	5
km22	3	4	4	4	3	1	5	2	4	5
km21	4	3	4	4	3	1	5	2	5	2
km20	2	3	4	4	3	1	5	1	5	2
km19	1	3	4	4	3	1	1	4	5	1
km18	4	4	4	4	3	1	1	1	3	4
km17	1	4	4	4	3	1	1	2	3	1

km16	1	3	4	4	3	1	1	1	3	1
km15	1	5	4	4	3	1	4	1	5	2
km14	1	3	4	4	3	1	1	2	3	5
km13	1	4	4	4	3	1	1	2	2	4
km12	2	1	4	4	3	1	5	2	5	2
km11	3	2	4	4	3	1	5	2	5	4
km10	5	4	4	4	3	1	5	1	5	4
km09	3	5	4	4	3	1	5	1	4	4
km08	4	3	4	4	3	1	1	4	3	1
km07	4	2	4	4	3	1	1	2	4	4
km06	2	1	4	4	3	1	5	4	5	2
km05	1	1	4	4	3	1	5	4	3	4
km04	1	1	3	4	3	1	5	4	4	3
km03	2	2	4	4	3	1	5	3	3	2
km02	1	2	4	4	3	1	3	4	3	2
km01	4	2	4	4	3	1	5	4	4	4
hn16	4	3	3	3	3	1	5	2	4	2
hn15	4	5	4	3	3	1	5	2	4	4
hn14	4	5	3	3	3	1	4	2	3	4
hn13	3	5	4	3	3	1	4	3	5	5
hn12	4	2	3	3	3	1	4	1	4	3
hn11	3	1	4	3	3	1	5	2	5	1
hn10	4	1	4	3	3	1	5	2	3	3
hn09	2	1	4	3	3	1	5	4	3	2
hn08	2	2	4	3	3	1	1	2	2	5

hn07	1	5	4	3	3	1	1	4	3	3
hn06	1	4	4	3	3	1	1	3	1	4
hn05	1	2	4	3	3	1	3	2	2	2
hn04	4	2	4	3	3	1	5	2	4	3
hn03	3	3	2	3	3	1	5	1	4	4
hn02	2	2	4	3	3	1	5	1	4	4
hn01	1	1	4	3	3	1	5	1	4	2
bt17	2	1	3	4	2	1	5	1	4	2
bt16	3	1	4	4	2	1	5	2	5	1
bt15	4	1	4	4	2	1	3	1	5	1
bt14	4	1	4	4	2	1	3	1	5	2
bt13	4	1	2	4	2	1	5	2	4	2
bt12	4	2	1	4	2	1	5	3	4	1
bt11	4	2	2	4	2	1	5	2	4	2
bt10	4	4	2	4	2	1	4	1	4	2
bt09	5	4	4	4	2	1	5	2	4	2
bt08	4	4	1	4	2	1	5	3	5	2
bt07	4	4	4	4	2	1	5	3	4	3
bt06	5	4	3	4	2	1	5	3	1	5
bt05	4	4	3	4	2	1	4	4	1	5
bt04	1	3	1	4	2	1	3	4	1	5
bt03	1	2	4	4	2	1	3	4	3	5
bt02	2	4	4	4	2	1	5	3	3	4
bt01	3	4	4	4	2	1	5	1	3	2
kd28	3	4	4	4	2	1	4	3	5	2

kd27	2	2	4	4	2	1	5	2	4	2
kd26	1	4	2	4	2	1	5	2	4	4
kd25	1	4	3	4	2	1	4	3	5	3
kd24	3	2	4	4	2	1	4	2	4	4
kd23	2	2	4	4	2	1	5	2	4	3
kd22	2	4	4	4	2	1	5	2	4	2
kd21	4	2	4	4	2	1	4	3	4	5
kd20	4	2	4	4	2	1	4	4	5	4
kd19	4	2	4	4	2	1	4	3	5	4
kd18	3	4	4	4	2	1	5	2	5	1
kd17	3	4	4	4	2	1	5	4	5	3
kd16	3	4	3	4	2	1	5	4	5	2
kd15	3	4	4	4	2	1	5	2	5	1
kd14	4	4	4	4	2	1	5	4	5	1
kd13	4	5	4	4	2	1	4	4	4	2
kd12	3	4	4	4	2	1	5	4	5	2
kd11	2	4	4	4	2	1	5	4	4	2
kd10	3	5	4	4	2	1	5	3	5	2
kd09	4	4	4	4	2	1	5	2	5	3
kd08	4	1	4	4	2	1	4	4	5	2
kd07	4	5	4	4	2	1	4	4	5	4
kd06	4	5	4	4	2	1	3	2	5	4
kd05	3	5	4	4	2	1	5	4	4	2
kd04	3	4	4	4	2	1	5	5	4	1
kd03	3	4	3	4	2	1	5	5	4	2

kd02	3	2	3	4	2	1	5	5	4	4
kd01	4	1	4	4	2	1	5	5	4	4
up33	4	4	3	4	3	1	5	5	4	4
up32	3	5	4	4	3	1	5	5	4	4
up31	4	5	4	4	3	1	5	5	4	3
up30	3	2	4	4	3	1	5	5	4	3
up29	3	2	4	4	3	1	5	4	4	4
up28	4	2	4	4	3	1	4	4	4	5
up27	4	1	4	4	3	1	4	4	4	5
up26	4	1	4	4	3	1	4	4	5	4
up25	4	3	5	4	3	1	4	4	5	4
up24	3	4	4	4	3	1	5	4	3	2
up23	3	3	4	4	3	1	5	4	4	2
up22	3	2	4	4	3	1	5	4	4	2
up21	3	1	4	4	3	1	5	4	5	2
up20	4	1	4	4	3	1	5	4	5	1
up19	4	5	4	4	3	1	4	5	3	2
up18	4	4	4	4	3	1	4	5	4	3
up17	4	4	4	4	3	1	4	4	4	4
up16	4	5	4	4	3	1	4	4	4	2
up15	4	5	4	4	3	1	4	4	5	2
up14	4	4	4	4	3	1	5	4	4	2
up13	4	3	4	4	3	1	5	4	4	4
up12	3	5	4	4	3	1	5	4	5	3
up11	3	5	4	4	3	1	5	4	5	3

up10	3	4	4	4	3	1	5	5	5	1
up09	3	5	4	4	3	1	5	5	5	2
up08	3	5	4	4	3	1	5	4	5	1
up07	2	5	4	4	3	1	5	4	5	2
up06	3	5	4	4	3	1	5	4	5	4
up05	3	5	4	4	3	1	5	4	5	2
up04	2	4	4	4	3	1	5	4	5	3
up03	2	4	4	4	3	1	5	5	5	1
up02	3	2	4	4	3	1	5	4	5	2
up01	3	4	4	4	3	1	5	4	5	3
mn25	4	1	4	4	3	1	4	4	5	5
mn24	2	4	4	4	3	1	4	4	5	4
mn23	2	2	4	4	3	1	5	5	5	2
mn22	3	4	4	4	3	1	5	5	5	2
mn21	3	5	4	4	3	1	5	5	5	1
mn20	3	5	4	4	3	1	5	5	5	1
mn19	2	3	4	4	3	1	5	5	5	1
mn18	1	1	4	4	3	1	5	5	5	1
mn17	2	1	4	4	3	1	5	5	5	1
mn16	3	1	4	4	3	1	5	5	5	1
mn15	3	1	4	4	3	1	5	5	5	1
mn14	4	4	4	4	3	1	5	5	5	1
mn13	3	1	4	4	3	1	3	5	5	3
mn12	3	1	4	4	3	1	5	4	5	1
mn11	2	1	4	4	3	1	5	4	5	2

mn10	2	1	4	4	3	1	5	5	5	1
mn09	3	1	4	4	3	1	5	5	5	2
mn08	3	1	4	4	3	1	5	5	5	1
mn07	4	5	4	4	3	1	4	5	5	5
mn06	4	5	4	4	3	1	5	2	5	2
mn05	4	5	4	4	3	1	5	4	5	1
mn04	3	4	4	4	3	1	5	5	5	2
mn03	3	3	4	4	3	1	5	5	5	1
mn02	3	4	4	4	3	1	5	5	5	2
mn01	3	1	4	4	3	1	4	4	5	1

APPENDIX-B

Pair wise comparison matrix of expert opinion

Expert 1

1	9	5	6	0.200	9	7
0.111	1	0.333	0.250	0.200	0.333	0.333
0.200	3	1	1	5	5	5
0.167	4	1	1	2	3	7
5	5	0.200	0.500	1	6	4
0.111	3	0.200	0.333	0.167	1	2
0.143	3	0.200	0.143	0.250	0.500	1

Expert 2

1	5	7	2	7	9	6
0.200	1	1	5	9	7	9
0.143	1	1	1	7	9	9
0.500	0.200	1	1	1	9	7
0.143	0.111	0.143	1	1	7	9
0.111	0.143	0.111	0.111	0.143	1	1
0.167	0.111	0.111	0.143	0.111	1	1

Expert 3

1	9	7	6	9	3	2
0.111	1	0.25	0.125	0.125	0.125	0.125
0.143	4	1	3	5	0.200	0.167
0.167	8	0.333	1	5	5	0.333
0.111	8	0.200	0.200	1	5	5
0.333	8	5	0.200	0.200	1	0.250
0.500	8	6	3	0.200	4	1

Expert 4

1	9	6	5	7	2	2
0.111	1	0.200	0.143	0.125	0.143	0.167
0.167	5	1	2	0.333	0.200	0.143
0.200	7	0.500	1	2	0.333	0.500
0.143	8	3	0.500	1	0.500	0.333
0.500	7	5	3	2	1	0.333
0.500	6	7	2	3	3	1

Expert 5

1	7	5	5	2	5	6
0.143	1	3	3	3	9	9
0.200	0.333	1	0.200	0.333	7	2
0.200	0.333	5	1	0.250	5	7
0.500	0.333	3	4	1	7	8
0.200	0.111	0.143	0.200	0.143	1	2
0.167	0.111	0.500	0.143	0.125	0.500	1

Expert 6

1	9	7	5	7	7	7
0.111	1	5	4	2	7	7
0.143	0.200	1	3	5	8	6
0.200	0.250	0.333	1	8	4	6
0.143	0.500	0.200	0.125	1	2	4
0.143	0.143	0.125	0.250	0.500	1	2
0.143	0.143	0.167	0.167	0.250	0.500	1

Expert 7

1	7	3	0.167	3	7	8
0.143	1	0.167	4	3	9	9
0.333	6	1	2	4	5	5
6	0.250	0.500	1	2	7	7
0.333	0.333	0.250	0.500	1	4	4
0.143	0.111	0.200	0.143	0.250	1	2
0.125	0.111	0.200	0.143	0.250	0.500	1

Bio-data

Name : Akshaya B J

Cor. Address : Dept. Civil Engineering, 38/1, Mudugurki, Venkatagiri Kote Post, Devana Halli, Bengaluru, Karnataka 56211

Contact : +91-9986870588

E-mail :aksh.jana@gmail.com, akshayabj@ncetmail.com

Nationality : Indian

Date of Birth : 02nd February 1985

Mother tongue : Kannada

Marital Status : Married

Spouse's Name : Manasa S R

Permanent Address : 5-D 'Bhava', Behind 'Sai Nivas' Apartments, Nandanavana layout, Vidyaranyapura, Bengaluru - 560097