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A Systematic Review of Coastal Vulnerability Assessment Studies along Andhra Pradesh, India: A Critical Evaluation of Data Gathering, Risk Levels and Mitigation Strategies

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Abstract: The establishment and alteration of any coastal feature is largely dependent upon complex hydrological and geomorphologic processes. Therefore, understanding hazard factors and threat risk level is crucial for mitigating risk in coastal zones. This study examines coastal vulnerability factors and their influence along the Coastal Andhra Pradesh (CAP) region in India. CAP has been exposed to frequent hydrological and meteorological hazards due to variations in the geographical, geological, and bathymetric characteristics. Despite substantial vulnerabilities, the risk to the coastline of Andhra Pradesh has not been rigorously evaluated. The current research systematically reviews the drivers and effects of hazards and vulnerabilities in CAP. Findings indicate that urban cities have a considerably higher risk of cyclones and floods due to their locations on the Bay of Bengal tectonic plate, the topology of this coastal region, and higher population density. The study revealed that the Coastal Vulnerability Index (CVI) data along CAP is mostly gathered using low-resolution satellite data and/or field observation surveys. The study further revealed that there are very few existing mitigation strategies developed or discussed within the obtained results. However, more accurate data gathering techniques for coastal vulnerability factors are available such as Unmanned Aerial Vehicles (UAVs): Air-borne and LiDAR sensors, which provide very high resolution data and low-cost accessibility to physically inaccessible places, making them suitable for vulnerability data collection in coastal locations. These findings are useful for stakeholders seeking to reduce or ameliorate the impact of coastal disasters and their impacts on the CAP economy, environment, and population. The study further helps to reduce the existing shortcomings in the assessment techniques used previously.

Keywords: coastal vulnerability; natural hazards; disasters; coastal Andhra Pradesh; Unmanned Aerial Vehicles

1. Introduction

Coastal environments are particularly vulnerable to the effects of disasters; partly due to denser urbanization and human populations and related economic activities such as agriculture, aquaculture, tourism, industries, trades and transportation in these locations [1–5]. Coastal areas tend to be relatively highly urbanized with higher concentrations of human populations [6,7]. Approximately 40% of the global human population lives within 60 km of the coast [8] and more than 25% of the human population in India lies within 50 km of the coast [9]. Natural processes, particularly those affected by climate change, combined with human activities, are becoming significant factors for coastal vulnerabilities. Risks at coastal regions in India are rapidly increasing; major threats for vulnerability are mean sea level rise, extreme events like flash floods, and cyclone induced storm surges [10–13]. Increased green-house gas emissions, predominantly from human activities, are predicted to expedite climate change and sea level rises that are already making coastal zones vulnerable in the 21st century [14–18]. Warming oceans lead to sea level rises, which in turn provide a source of thermal expansion of sea water, contributing further to intensified and more frequent cyclone-induced storm surges [19–22] addressed the potential climate change impacts owing to drought, floods and cyclone events with more intensity and asserted that India has very high risk levels (class 9 among risk class 0–10). As a result of the changes related to climate change, there are significant challenges for assessing coastal vulnerability and subsequent adaptation and mitigation strategies [23,24]. Systematic coastal vulnerability assessments [25–28] are essential for managing coastal threats. According to Indian Coastal Zone (CRZ) regulations, the buffer zones, also known as active zones, usually cover a region of 500 m from the shoreline; these zones are more usually focused on coastal vulnerability studies. However, coastal areas up to 100 km perpendicular from the shoreline should be considered as vulnerable areas for assessment studies. Coastal vulnerability resistance developments and strategies done to date are limited; they are only applicable to the coastal buffer zone (yet the effects of disasters impact on areas beyond this zone) and mostly concern coastal geomorphology issues but do not pertain to other extreme events such as cyclones and inundation [29–31].

Comprised of different geological, ecological, biological, urban and socio-economic features, the Indian coast is subject to varying degrees of exposure to multiple hazards. In the current scenario, the environmental stresses on coastal zones are increasing significantly in terms of social, physical and economic variables. Social parameters such as population density, drinking water demands owing to over-pumping of fresh-water, communication networks, roads with transportation, drainage, infrastructure, agriculture, aquaculture and industrialization are the prime factors that are providing harmful feedback loops to existing coastal vulnerability. Physical parameters such as sea level rise, slope, cyclones and storm surges are the natural contributing factors (or hazards) for increasing vulnerabilities along the coast. Sand mining is another crucial parameter in terms of coastal vulnerability along this coast. The increasing levels of sand mining along CAP will further result in ecosystem damage in terms of habitat, erosion, riverine system changes, and increased destruction due to extreme events. Therefore, coastal vulnerability assessment techniques require a multi-hazard assessment methodology dependent upon the location at a regional level integrated with global level parameters. Several studies of coastal vulnerability have been conducted at various geographical locations along the Indian coast using a variety of approaches to mapping and data collection methods. Kumar et al. (2006) [32] used mapping techniques to evaluate the potential vulnerability implications, due to sea level variations, along the Cochin coast. Kanakara et al. (2007) [33] used an integrated MIKE-21 model for the estimation of oil spill vulnerability for different locations along the Gulf of Katchchh by using land-use, land cover changes, shoreline changes, rates of erosion and accretion, and sediment transport parameters during pre-monsoon, post-monsoon seasons. Chandrasekar et al. (2011) [34] studied coastal geomorphological vulnerability along the Tamil Nadu coast and revealed that intensive sand mining and coral mining in barrier coral islands are adversely changing beach morphology. Mani Murali et al. (2013) [35] considered a Physical Vulnerability Index (PVI), Social Vulnerability Index (SVI) and calibrated Coastal Vulnerability Index (CVI) for the Puducherry coast. Saxena et al. (2013) [36] developed a composite vulnerability index for coastal hazards along the Cuddlore coast, Tamil Nadu. The parameters considered for this study were erosion mapping, flood hazard mapping, and sea level rise combined together and then integrated with socio-economic influences. Appelquist et al. (2015) [37] proposed a new methodology (adapted from a method initially proposed by Appelquist (2013) [38] to assess and manage the Karnataka coast with a new multi-hazard technique known as the Coastal Hazard Wheel (CHW). The prime focus of this methodology is for screening the coastal area at local, regional and national levels of hazard, mainly in regions where available data is inadequate. These vulnerability assessment studies were mostly conducted using low resolution spatial data; and there were very few mitigation strategies evident. Therefore, it is necessary to adopt a more holistic and integrated approach to overcome these limitations. The concepts' vulnerability, hazard and risks are interrelated, but address distinct issues. According to Gilard (2016) [39], hazards are mostly natural phenomena, whereas vulnerability is associated with socioeconomic parameters affected by hazards and natural processes. For instance, when a vulnerable region is impacted by a hazard, there exists a potential risk that needs to be addressed. The risks are given a rating to estimate the vulnerability level (for example: high, medium, low). Therefore, when a particular coastal vulnerability is estimated, an integrated approach is required that can distinguish between these three concepts.

The main aim of this work is to review the existing coastal vulnerability assessment studies along CAP to identify the vulnerable locations with its main focus on CVI methodology approaches. A systematic literature review of CVI was carried out along the coastal Andhra Pradesh. The literature review for this region was organized according to each of the CVI parameters; including the data-collection technique, the magnitude of the threat, drivers for vulnerability, and the prevalence of mitigation strategies. Furthermore, the current study also identified gaps in knowledge and some recommendations for future research.

2. Snapshot of Coastal Vulnerability Methodologies

The primary technique used to monitor coasts for vulnerability assessments is spatial data with Geographic Information System (GIS). The method for gathering spatial GIS data is satellite imagery; this is due to its relative accessibility, economic affordability, and regular repetitive coverage. GIS-based spatial data is used in a number of different analytical methodologies, which include 'Decision Support Systems' (DSS) and index based techniques. DSS approaches include 'Community Vulnerability Assessment Tool' (CVAT), DINAS-coast, Dynamic Interactive Vulnerability Assessment (DIVA), Digital Shoreline Assessment System (DSAS) and vulnerability assessment [4]. Index-based techniques such as the Coastal Vulnerability Index (CVI) are also used widely across the world [28,40–50] 'Integrated Valuation of Ecosystem Services and Tradeoffs' (InVEST) is an open source software model that has a wide range of models to analyze a range of coastal vulnerabilities, including social, geographical, biological and economic factors [27]. Indian coasts have been studied mostly through the use of CVI methods for physical assessments [51–54] most of these studies required a certain amount of field data for the evaluation, due to limitations in the available spatial and temporal satellite data resolution [55] Remote-sensing approaches evident in the existing literature range from air-born to space-borne data gathering techniques; however, coastal vulnerability studies along the Indian coast were mostly restricted to the use of earth observing space-borne sensors [56–62]. Table 1 illustrates the range of parameters used across India to evaluate coastal vulnerability in diverse circumstances.

Table 1. Vulnerability assessment and parameters considered for different Indian geographic locations (modified from Rani et al. 2015). [3]

Vulnerability Method	Geographical Location	Parameters Considered	Remarks	Reference
CVI due to erosion	Coast between Kanyakumari and Tuticorin, Tamil Nadu	Geomorphology, shoreline change rate, coastal slope, sea level change, mean wave height, mean tidal range	Physical and human intervention processes are major causes of erosion	[63]
CVI due to erosion	Coast between Rasulpur (Midnapur) and Subarnarekha (Balasore), Orissa	Shore line change rate, land use and human activities, population density	Assessment of CVI using socio-economic parameters	[59]
Multi hazard vulnerability	Cuddalore, Pondicherry and Villupuram districts, Tamil Nadu	Probability of maximum storm surge height during the return period, future sea level rise, coastal erosion and high resolution coastal topography	Used multi hazard vulnerability technique	[64]
CVI	Orissa State, East Coast of India	Shoreline change rate, significant wave height, sea-level change rate, tidal range, coastal regional elevation, coastal slope, tsunami run-up and coastal geomorphology	-	[53]
CVI	From Talapady to Surathkal along Mangalore Coast	Geomorphology, regional coastal slope, shoreline change rates, population	Assessment of CVI using socio-economic parameters	[51]
CVI	Udupi coast in Karnataka	Geomorphology, shoreline erosion/accretion, coastal slope, mean tide range, mean significant wave height, mean sea level rise	Considered the CVI due to future SLR	[52]
CRI	Coastal stretch from Kattivakkam to Kovalam, Tamil Nadu	Environmental Vulnerability Index (EVI), Social Vulnerability Index (SVI), Hazard Potential Index (HPI), Mitigation Capacity Index (MCI)	Computed integrated coastal risk index. It is a multi-scale approach. Considered cyclones as indicator coastal risk	[65]
Potential Vulnerability Implications	Cochin	Sea-level variations	Used sea-level-rise scenario as an indicator for vulnerability of Cochin coast	[32]
Gulf of Kachchh, India	Gulf of Kachchh, India	Oil pollution, social and cultural values, scientific values, environmental, and economic values	Used an integrated numerical simulation modelling integrated with GIS	[33]
Coastal geomorphological vulnerability	Coastline between Kallar and Vembar lies in the Gulf of Mannar, Tamil Nadu	Land use/land cover changes, shoreline changes over the years, rate of erosion and accretion, sediment transport during pre-monsoon, monsoon, post-monsoon seasons	Beach morphological changes are influenced by intensive sand mining along the coast and coral mining in the barrier coral islands	[34]

3. Study Area

Coastal Andhra Pradesh (CAP) is located along the Eastern Indian coastline towards the Bay of Bengal at latitude 13°24′ N to 19°54′ N and longitude 80°02′ E to 86°46′ E (Figure 1) and is approximately 966 km in length. CAP has a hot and humid climate and consists of nine coastal districts with an area of 95,442 km^2, which is 60% of the total state area [66]. The Andhra Pradesh (Figure 1) coastline is the second largest shoreline after Gujarat in India. The population is 34 million, which is 70% of the total state population; the major cities are Vijayawada, Visakhapatnam, Guntur, Rajahmundry, Kakinada, Eluru, Nellore, and Ongole [66]. CAP has many hectares of fertile agricultural land due to the Krishna and Godavari deltas. Agriculture and fishing, which are the main fiscal activities in this region, are often disrupted by monsoonal variations, changes in climate, rapid changes in coastal geomorphology, local and sub-local elevations, and the rate of shoreline changes [67].

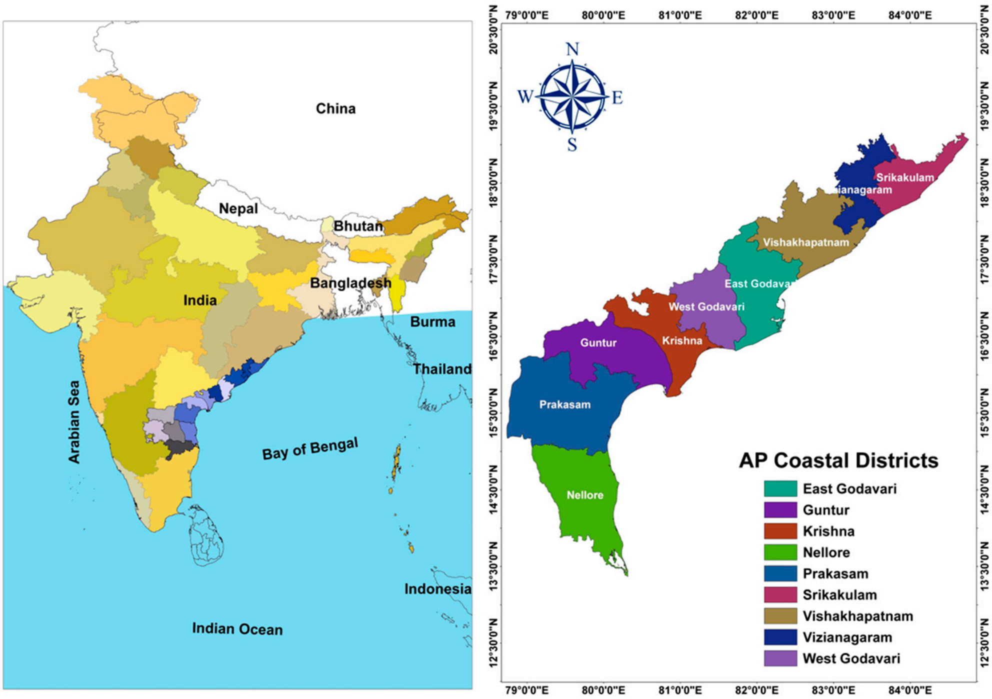

Figure 1. A spatial map of India with CAP indicated.

The rainfall is influenced by both South-West and North-East monsoons and the average annual rainfall along CAP is 1078.0 mm [68]. Andhra Pradesh, particularly coastal Andhra, is prone to cyclones, storm surges and floods. Moderate to high intensity cyclones occur every two to three years. Figure 2 shows the detailed spatial map for Andhra Pradesh coastal districts with the total number of cyclones occurring during the time period of 1951 to 2010. According to UNEP [6], more than 40% of the state is vulnerable to tropical storms, hurricane winds, severe floods and other associated natural hazards. The Godavari and Krishna River floods often contribute to serious disasters in the East and West Godavari and Krishna districts. The death toll and infrastructure damage due to these disasters is higher than other Indian coastal areas. According to the National Disaster Management Authority (NDMA) report (2016) [69], Andhra Pradesh coast is the second-most cyclone affected Indian region after Odisha and second-largest vulnerable region to floods after Kerala. The Ministry of Environment & Forests, Govt. of India (2012) [70] reported more frequent and intensified cyclonic activity and associated storm surges in CAP as a result of the impacts of climate change on air and sea-surface temperatures.

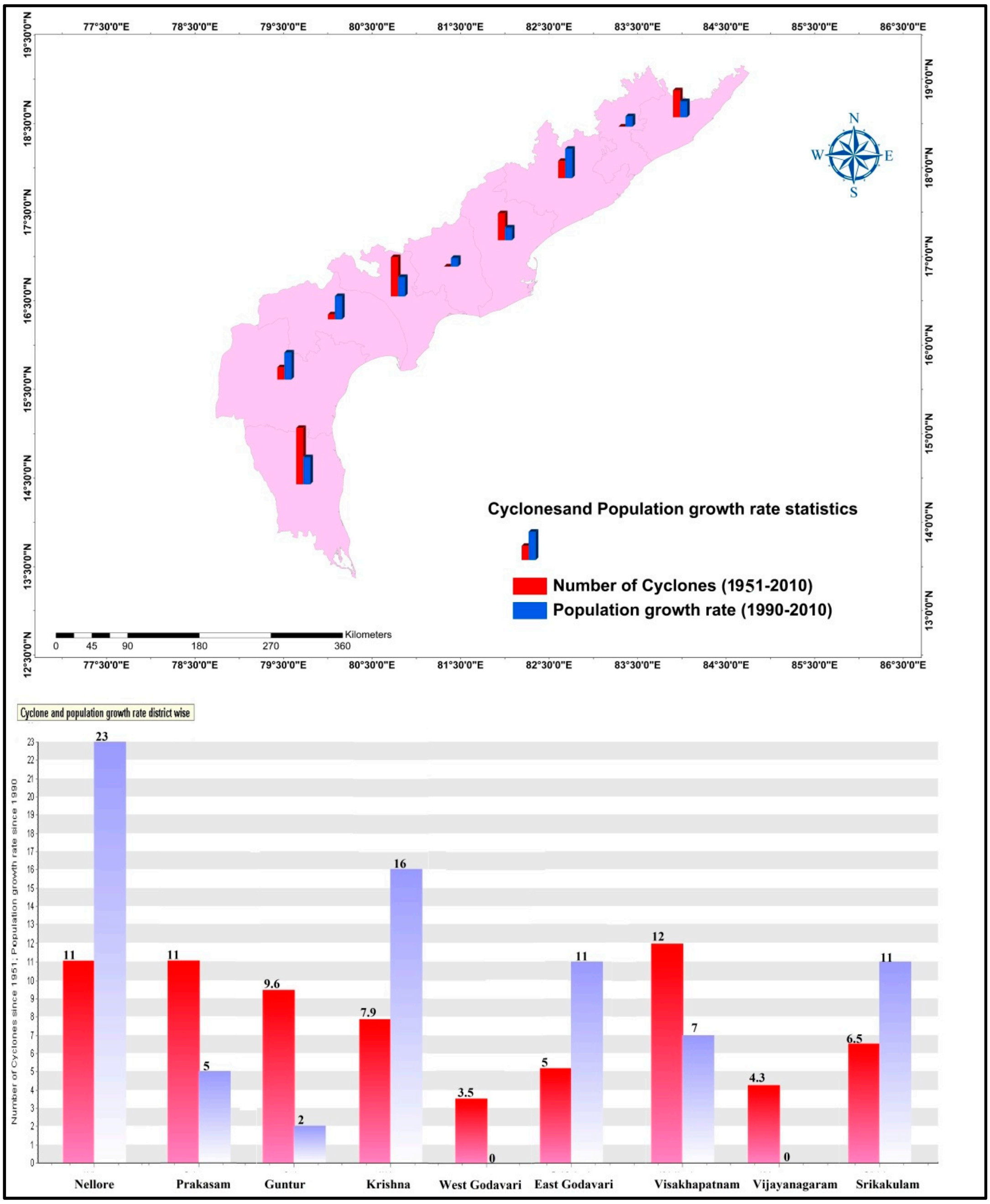

Figure 2. Total number of cyclones and population growth rate. Developed based upon the statistics of Revenue Disaster Management Andhra Pradesh (2017) [71].

4. Methodology

The current study is a systematic review of existing literature on coastal vulnerability assessments of the Indian coastline with emphasis on coastal Andhra Pradesh. The review systematically searched the following databases: ScienceDirect, Google Scholar, Web of Science (WoS), and Scopus to recognise the relevant literature using the keywords *coastal vulnerability, India, coastal Andhra Pradesh, erosion, GIS, spatial analysis*. Before finalising the existing studies to carry out the analysis, the current study performed a scoping exercise to recognise main themes, gaps and trends in the literature on coastal vulnerability studies. The review process comprised three main steps: searching (1), screening (2) finalization and analysis (3) (Figure 3). Initially, the first the review identified 125 articles and documents that met the search criteria. During the screening procedure, the current study applied exclusion and inclusion criteria to the search results to categorize the selected studies. Accordingly, the current study appraised the article titles and abstracts to evaluate their relevance to the study and, consequently excluded 75 articles deemed to be irrelevant. At this stage, 50 articles were selected for the full-text assessment. However, after full text analysis, a further 25 more articles were excluded due to irrelevance. Accordingly, only 25 articles from 125 articles have been finalized for the analysis. The omitted papers discussed coastal vulnerability in general, but their emphasis was not on the Coastal Andhra Pradesh region. Furthermore, other excluded papers examined CVI procedures at some point, but from integrated models' viewpoints, which are not relevant to the current study. In addition, the study also explored various government websites such as AP State of Portal, Government of India National Disaster Management Authority (NDMA), Indian Metrological Department (IMD), Regional Metrological Centre (RMC) and the Mumbai and National Cyclone Risk Mitigation Project (NCRMP) for grey literature. This grey literature was searched and evaluated according to the same criteria used for the selection of journal articles and other associated documents. Accordingly, 32 of these reports have been included for analysis. In total, 57 documents regarding coastal vulnerability studies have been analyzed.

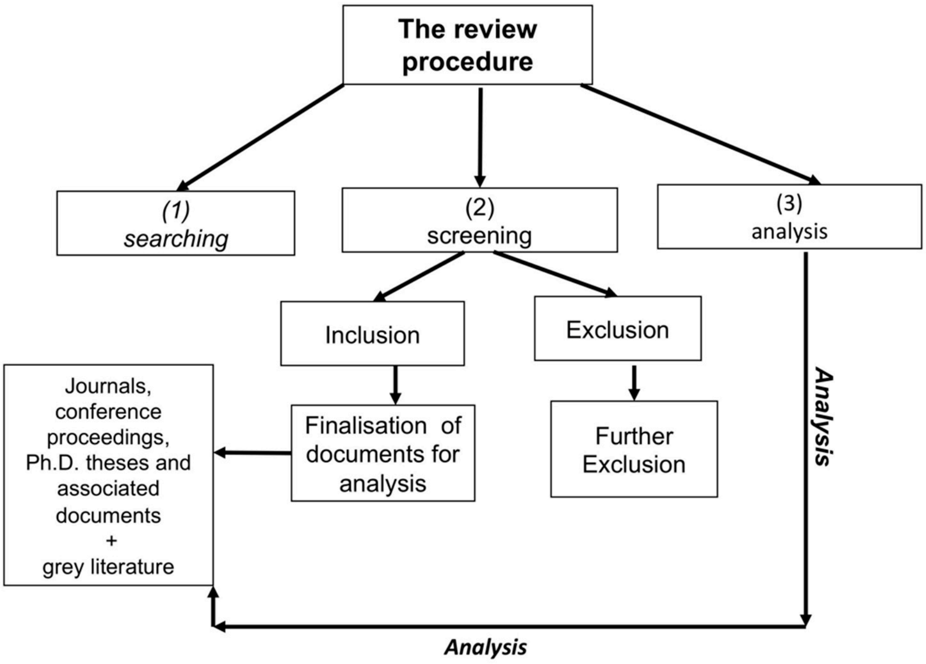

Figure 3. Methodological procedure.

Coastal Vulnerability Index Formulations and Parameters

Several CVI approaches, formulations and parameters are used to evaluate coastal vulnerability. Listed below are the main methodological frameworks and parameters. The first application of CVI (Equation (1)) was developed by Gornitz in 1990 with a focus on sea level rise, which considered the following parameters:

(a) Geomorphology
(b) Shoreline change-rate
(c) Coastal-slope
(d) Relative sea-level rise
(e) Mean significant wave-height
(f) Mean tidal-range

The principal formula for calculating CVI is given as follows:

$$CVI = \frac{\sqrt{a \times b \times c \times d \times e \times d \times e \times f \times g}}{7} \quad (1)$$

The above equation is the standard way to assess coastal vulnerability; however, it is not the only possible way to estimate the CVI quantitatively. Gornitz (1990) [72] proposed various ways to calculate the CVI, though the above equation is most widely used, as the geometric average is the most sensitive to individual parameters. Most of the studies along CAP used the above equation for vulnerability assessment. However, Rao et al. 2010 [73] used a different approach by using the summing of variables with prescribed weightage given to each parameter. For this assessment, five parameters were considered and the equation is as follows (Equation (2)):

$$CVI = 4a + 4c + 2b + f + e \quad (2)$$

where the variables a, c, b, f and e have their usual meanings defined as above.

The majority of studies [32,50–53] focused on basic factors as major drivers for coastal vulnerability along the Indian coast. Krishnan et al. (2018) [74] proposed a cumulative vulnerability index (CuVI) framework to map the coastal vulnerability along the Maharashtra coast. The CuVI is a function of exposure, sensitivity and adaptive capacity and uses the exposure-index (EI), sensitivity-index (SI) and adaptive-capacity-index (ACI). It covers all physical, social, and economic variables cumulatively for the preparation of a spatial decision-making map. Table 2 sets out the data-gathering approaches (in terms of conventional and spatial data) used for various CVI assessments as well as others that can be used. Here, conventional data is defined as point level observations or in-situ data that is collected throughout the year, whereas spatial data is satellite/aircraft based. There are various social parameters such as population, population growth rate, transportation with road networks, mobile-television facilities for each home for hazard warning awareness, age, gender, etc. CVI analyses require the data to be classified into different risk ranges; these are illustrated in Table 3.

Table 2. Different types of data that can be used for CVI studies in India.

Parameter	Data
Spatial	
Shoreline change	Satellite or Aircraft or UAVs
Coastal slope	DEM generated from SRTM or any SAR data
Bathymetry	GEBCO
Sea level change	Satellite altimeter data from TOPEX/Poseidon
Land use land cover change	Satellite data (like LANDSAT 8)
Conventional	
Significant wave height	JASON-1 data or Wintidex software generated data
Cyclones and storm surge	IMD cyclone data
Coastal slope	Elevation measured from point observations
Bathymetry	National hydrographic charts
Sea level change	Tide gauge data from Permanent Service for Mean Sea Level (PSMSL)
Historical floods, water quality	Disaster management reports
Social parameters	Census reports

Table 3. Coastal Vulnerability Index ranges with their risk values considered for CAP. Source: [9,58].

CVI (Coastal Vulnerability Index) Ranking Criteria					
Parameters	**Very Low (1)**	**Low (2)**	**Medium (3)**	**High (4)**	**Very High (5)**
Geomorphology	Rocky coasts	Indented coasts	Beach ridge, high dunes and vegetation	Low fore dunes (<3 m), estuaries and lagoons	Mudflats, mangroves, beaches and barriers/spits
Slope (%)	>1.00	0.50–1.00	0.10–0.50	0.05–0.10	<0.05
Mean sea level change rate (deg)	<1.80	1.8–2.5	2.50–3.00	3.00–3.40	>3.40
Significant mean wave height (m)	<0.55	0.55–0.55	0.85–1.05	1.05–1.25	<1.25
Mean tidal range (m)	<1.00	1.0–2.0	2.00–4.00	4.00–6.00	>6.00

5. Results

Based on the literature reviewed, several of the existing studies evaluated Indian coastal vulnerability. However, very few studies were performed along CAP and most of these studies were based on the conventional CVI technique developed by Gornitz et al. (1990) [72]; however, these studies differ from each other in the selection of parameters.

5.1. Coastal Geomorphology

The coastline of Andhra Pradesh is segregated into three distinct types: a rocky coast starting from North of Godavari delta, a vegetation coast in the Krishna-Godavari deltaic region, and a sandy coast from south of Krishna delta to Pulikat lake (SAC, ISRO report, 2011); a more detailed breakdown of land-use cover is shown in Figure 3, which revels that the entire CAP is predominantly agricultural. The geomorphology of the CAP is very diverse and economically important due to several features such as the Krishna-Godavari river delta, which plays a huge role in agriculture activities; developed/urbanized coastal areas along Visakhapatnam and Machilipatnam port; and ecologically sensitive places like mangroves and mudflats. Pramanik et al. (2016) [75] described the region as sensitive to muddy and soft sand and categorised the entire coast into two risk rates (higher and lower). Rao et al. (2010) [73] used IRS P6 AWiFS (The Advanced Wide Field Sensor) data to map geomorphology and its risk rankings, showing that the Krishna-Godavari deltaic regions are highly vulnerable due to the presence of mud flats, mangroves and the beach ridge complex. Overall, the mangroves and mudflat dominated areas of Kakinada, Mummidivaram, Avanigadda and Repalle were categorised as very high risk.

5.2. Shoreline Change-Rate

Shoreline change rate can be defined as the rate at which shore gets eroded or accreted due to wave-action, sea level-rise or other hazards and processes that affect the land. Although much of this is a natural process, added urbanization, infrastructure development and increased population can exacerbate the process. The CAP region is particularly prone to erosion due to its location and spatial distribution along the ocean. Factors such as sand mining, dredging and hard engineered protection for CAP are making it more susceptible to erosion. Almost all of the studies for the CAP to assess the shoreline erosion used Landsat data. For example, Basheer Ahammed et al. (2016) [76] used Landsat satellite data for the time-period of 1972–2015, and showed that most erosion was observed along the Krishna-Godavari delta and highest accretion was confined to the estuary outlet of the Krishna-Godavari deltaic region. The reason for this accretion could be mostly due to sediment transport from the estuary rather than that of coastal accretion, whereas sand mining could be one of the parameters for extensive erosion patterns. Vivek et al. (2016) [9] used the Landsat data for the period of 1973–2015 and found that some regions, such as Bheemunipatnam, central Chebrolu, Veerappa Konda and south of Tuni, experienced a (maximum) exposure rate of almost 10 meters per year. Rani et al. (2018) [67] used 20 years (1997–2017) of spatial data (Landsat 4 to Landsat OLI) as well as conventional data (such as PSMSL, Survey of India toposheets) and showed that an approximately 2.5 km shoreline shift, in terms of erosion and 1.82 km shift in terms of accretion, was observed along the Vizianagaram–Srikakulam coast. These studies are useful to measure the shoreline erosion statistically; however, there is a need to improve the spatial, as well as temporal resolutions, for more accurate assessment.

5.3. Coastal Slope

Coastal elevation is the degree of steepness of the region with respect to the ocean; its measurement helps to identify the vulnerability of the coast. Rao et al. (2010) [73] used SRTM DEM data to evaluate the coastal slope range and its risk rate. Basheer Ahammed et al. (2016) [76] extracted coastal slope data from GEBCO (General Bathymetric Chart of Oceans) to identify that the lower southern part of CAP has steeper slopes, which leads to higher vulnerability as well as other risks. The available literature revealed different forms of data for coastal slope and its vulnerability mapping: Rani et al. (2018) [67] used ASTER DEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer Digital Elevation Model) data, while SRTM DEM was used by Pramanik et al. (2016) [75] (both SRTM and ASTER DEM have a resolution of 30m for the Indian region). These studies further noted that CAP steep slopes are at high risk due to shoreline erosion and inundation due to storms. One more parameter that can classify the risk along the coastal zone is bathymetry, particularly in relation to wave height. The higher the bathymetry, the higher will be the risk to the coast owing to sea level rise and surge height. Rani et al. (2018) [64] used SRTM DEM with Directorate General of Hydrocarbons (DGH). While Pramanik et al. (2016) [75] used DGH data and revealed that Mummidivaram and Avanigadda zones are under very high risk followed by Pithapuram, Kakinada, Amalapuram and Machilipatnam, lower risk rates were identified for Tuni, Razole and Narsapur.

5.4. Relative Sea Level Rise

According to Unnikrishnan et al. (2007) [77], sea level changes can be due to two phenomena—one is global (mean sea level change) while the other is regional (extreme sea level changes). Therefore, sea level rise is a major phenomenon that combines global and regional processes that affects climate change induced coastal vulnerability along any coast. There are several ways to retrieve data for sea level change, for example from satellites and observations. Vivek et al. (2016) [9] brought together data from GLOSS (Global Sea Level Observing System) and found that the highest sea level rise was 5 cm/year along the Nellore coast and the lowest sea level rise of 0.8 cm/year was recorded in Pulicat coast. Pramanik et al. (2016) [75] used the IPCC global average sea level rise data and found 40% of CAP's population vulnerable to potential flooding by mid-century.

5.5. Significant Wave Height

Significant wave height, when associated with a tropical cyclone-induced storm surge, creates disaster at higher levels and CAP is highly prone to tropical cyclones. CAP wave height records from wave rider buoys were taken from the National Institute of Oceanography (NIO) to calculate the significant wave height [75]. They considered the significant wave height values of the pre- and post-monsoon seasons for 2013, which were found in the range of 0.5 m to 2.5 m. Rao et al. (2010) [73] used the MIKE-21 (Spectral Wave) model to measure the wave height from the European Center for Medium Range Weather Forecast (ECMWF) wind velocity component data. There are other more accurate ways to measure significant wave height, such as Wavewatch III, but this has not been utilized for the CAP region so far.

5.6. Mean Tidal Range, Tropical Cyclone and Induced Storm Surge

The tidal range is the vertical difference between high and low tide. For the CAP region, Rao et al. (2010) [73] used hydrographic chart data. According to the study, the tidal range for CAP varies between 0.7 to 1.4 m, which would be classified as a low vulnerability region. The influence of cyclones and the related induced storm surges are more prevalent along the East coast of India, particularly along Andhra Pradesh and Odisha [78]. Severe cyclones since 1977 are listed in Table 4, while Figure 4 shows land use land cover distribution along CAP. As shown in Figure 4, CAP predominantly suffered from agricultural and the cyclone-induced storm surge and its inundation, which resulted in socio-economic losses. There has been a reduction of risk and loss of life in CAP since 1977, due to improved early warning protection systems that give accurate predictions for cyclonic landfall; however, economic loss has been increasing (Table 4). Surge inundation damages the soil system through penetration of saltwater into the coastal upper aquifer and damages agricultural and biophysical ecosystems. Rao et al. (2010) [73] created a vulnerability map for CAP in the context of storm surges and cyclone winds and determined that Nellore district is at highest risk followed by Srikakulam and Visakhapatnam districts; the lowest vulnerable risk locations are located at Krishna and Guntur districts. Using Expert Decision Support System (EDSS), Matta et al. (2015) [79] concluded that existing CAP cyclone shelters can only accommodate 8% of the rural population, meaning that 92% of the rural populace is still at risk from cyclones. None of the CVI-based systems (that included other parameters) used tropical cyclones as a vulnerability parameter.

Tropical cyclone induced storm surge is a significant threat to CAP, but it has not been rigorously accounted for in CVI assessments previously. One exception is the research by Vivek et al. (2016) [9] who used tsunami run up as one of the parameters for CVI along CAP. Land subsidence, depletion of groundwater, and saltwater intrusion into groundwater are additional parameters that can be incorporated into coastal vulnerability assessments for better results. The resultant CVI categorized Nellore and West Godavari as highly vulnerable. In contrast, low vulnerability ranked areas were observed along the Visakhapatnam region [9,76]. The studies conducted by Vivek et al. (2016) [9] differed because of the inclusion of the parameter 'tsunami' into the CVI studies. The slight differences in the resultant maps from available literature can be accounted for by variations in the parameters and the parameter observation time. Rao et al. (2010) [73] produced a detailed range of risks along CAP, and the analysis shows that over 70% of CAP is vulnerable. Diverse studies evaluated CAP vulnerability by implementing various parameters and techniques under CVI formation; this is shown in Table 5.

Table 4. Severe cyclonic storm and their impact since 1977 along CAP.

Number	Severe Cyclonic Storm/Factor Effected	Maximum Wind (km/h)	Lowest Pressure (mbh)	Fatalities	Economic Loss (million-USD)
1	1977	165	919	14,204	499
2	1990	230	920	967	600
3	1996	145	988	1077	602
4	2014	185	215	124	3400

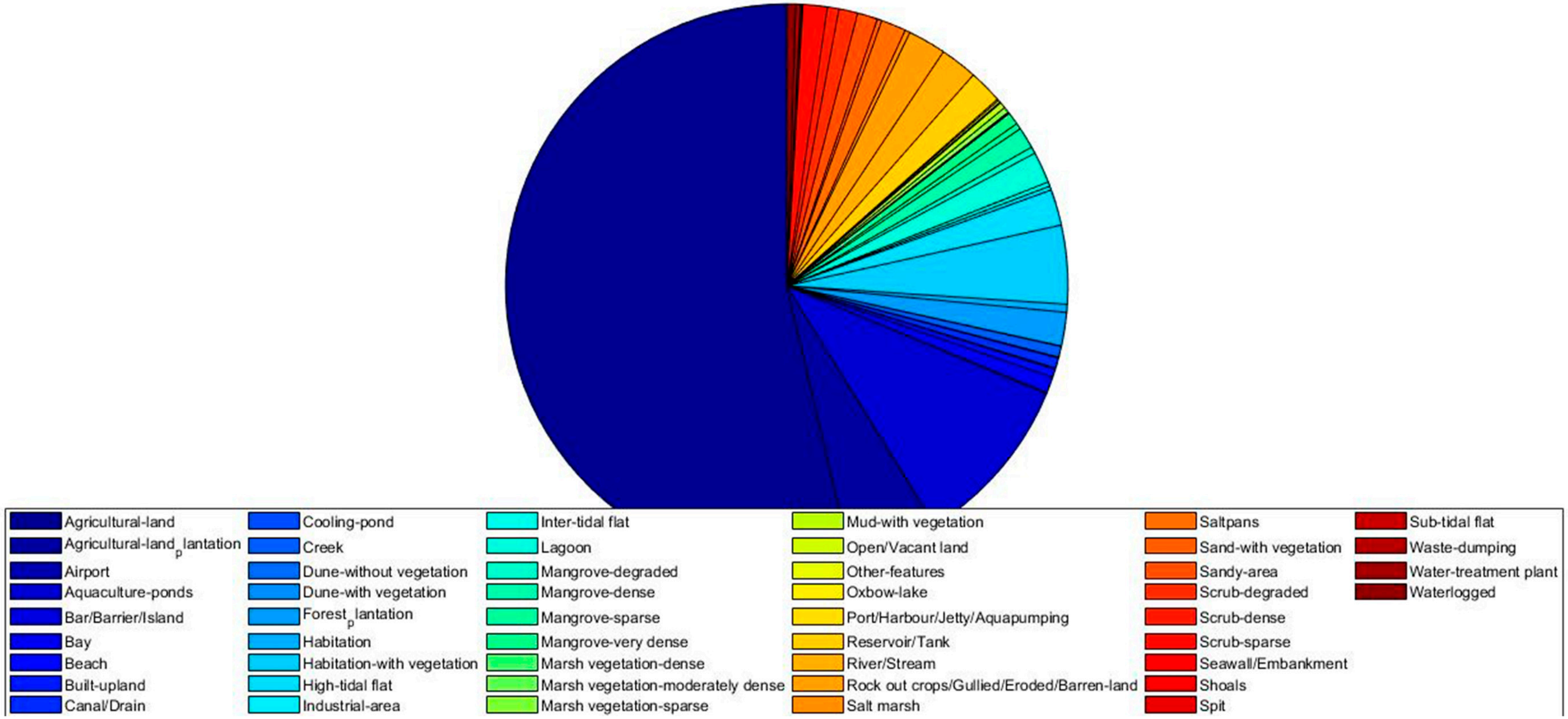

Figure 4. Land use and land cover distribution along the coastal Andhra Pradesh (redeveloped from NRSC, ISRO report 2012–2013 [80].

Table 5. Vulnerability assessment and parameters considered for different geographic locations of Andhra Pradesh.

Vulnerability Hazard	Location	Vulnerability Parameters	Technique	Remarks	Reference
CVI–Square Root of Product (SRoP)	Vijayanagaram-Srikakulam coast, AP	Shoreline change rate, coastal elevation, bathymetry, sea level rise, significant wave height	Remote sensing (space-borne) and GIS	-	[67]
CVI–SRoP	North East-coast of AP	Shoreline change rate, coastal slope, regional elevation, sea level change rate, significant wave height, tidal range, geomorphology, tsunami run-up	Remote sensing and GIS	Parts of Bheemavaram and Visakhapatnam are highly vulnerabble; Nakkapalli and Kancherpulem are at medium risk; Thallapalem is at low risk	[9]
CVI—SRoP	Entire AP coast	Shoreline change, coastal slope, coastal regional elevation, mean sea level, mean tide range, and geomorphology	Remote sensing and GIS	Small stretches in Nellore have very high vulnerability; Nellore, Kothapatnam and Kakinada Southern part are highly vulnerable; Most parts of Sompeta, Koduru and Kothapatnam are moderately vulnerable; Vishakhapatnam and Vizianagaram coasts are very low vulnerability	[76]
CVI (summing of variables with weightage)	AP	Geomorphology, coastal slope, shoreline change, mean spring tide, significant wave height	Remote sensing and GIS	Considered sea-level rise as an indicator for coastal vulnerability. The Krishna–Godavari delta coast is notably very highly vulnerable due to its low flat terrain and mud flats	[73]
CVI–SRoP	Krishna–Godavari delta region, AP	Shoreline change rate, coastal elevation, slope, geomorphology, sea level rise, significant wave height, mean tidal range	Remote sensing and GIS	Tuni, Kundukur, Narsapur, Razole at low risk; Pithapuram, Amalapuram, Chirala at High risk; Kakinada, Machilipatnam, Bapatla, Ongole at medium risk; Mummidivaram, Avanigadda & Repalle at very high risk	[75]

Table 5. *Cont.*

Vulnerability Hazard	Location	Vulnerability Parameters	Technique	Remarks	Reference
Vulnerability from storm surges and cyclone wind fields on the coast	AP	Vulnerability measured for the situations—frequent (return period of 10 years), 50-year return period, global warming-likely scenario, global warming-extreme case	-	-	[77]
Cyclone Vulnerability and Risk Analysis	AP	Vulnerable locations, casualties' prediction and shelters for cyclone induced vulnerability mitigation	GIS mapping	Prime focus is on socio-economical assessment for mitigation purposes.	[80]
Vulnerability of Indian Coastal Districts to Sea-Level Rise and Climate Extremes	Entire India	Demographic: Population density, annual growth rate of population, population at risk due to sea-level rise. Physical: Coast length, insularity, frequency of cyclones based on historic data, probable maximum surge height, area at risk of inundation due to SLR, number of vulnerable houses Economic: Agricultural dependency, income and/or infrastructure index. Social: Literacy, spread of institutional set-up Life-Loss: Storms and human casualties	Available historic statistical data	The study finely described the adaptation and mitigation strategies along the Indian coast with policy issues	[78]

6. Discussion

Coastal management along CAP is very important due to its agricultural productivity and socioeconomic significance. However, the importance of coastal zone management and work towards adaptation and mitigation strategies along CAP is still in its infancy unlike other southern states of India. Objective coastal vulnerability assessments are necessary [73] due to the influence of a range of parameters along the coast.

6.1. CVI Analysis

The current study revealed the importance of coastal zone risks, management, and the primary challenges associated with it. Coastal Andhra Pradesh is mostly vulnerable to cyclones with their induced storm surges, floods and coastal erosion [81,82]. The importance is evidenced by historical hazards like the devastating 1997 Andhra Pradesh cyclone, 1999 Orissa cyclone, 2004 tsunami or most recent 2017 Chennai and 2018 Kerala floods. However, cyclone hazard assessments were not included in CVI assessments for CAP. For the CAP region, CVI criteria included basic parameters like shoreline-change assessment, sea-level-rise, coastal elevation, coastal geomorphology, bathymetry, significant wave height. Most of them were missing the following factors: tropical cyclone, tsunami and storm-surge run-up. However, even if these additional parameters are included in the evaluation, the studies are further limited as a result of the exclusion of social and economic factors. Disasters are often associated with human activities and the resultant stresses. Saxena et al. (2013) [36] described that the magnitude and risk of coastal disasters due to hazards should be addressed with the sensitivity and resilience of the exposed population, rather than the intensity of natural hazard. The protection of an area is deemed vulnerable if the area is sufficiently important to economic, cultural and environmental (ecological and biological) aspects [3,59]. Therefore, the CAP region needs better understanding of the human and economic damage/loss associated with it and studies should focus on a more integrated approach that combines natural, anthropogenic and climate change-induced vulnerabilities.

Rao et al. 2010 [73] showed that the risk levels were very high at Penna and Krishna-Godavari delta regions. These are very low-lying and almost flat areas with mudflats, mangrove swamps, and lagoons/backwaters. Whereas, a study by Basheer Ahammed et al. 2016 [76] showed that the Nellore region and Narsapur area are highly vulnerable. The reason for this difference in the risk rate evaluation can be the difference in the years of data as well as the approach. The CVI assessment by Rao et al. 2010 [69] was performed using a summation of parameters with weightage given to each factor; further SLR was considered as an indicator to give weightages to the parameters; whereas, for Ahammad et al. 2016, CVI analysis was based on the basic Gornitz 1998 formula. Rao et al. 2008, 2010 [58,73] provided the vulnerability maps for the storm surges and cyclone wind effect along CAP. Surge inundation is a very serious issue, as CAP has a history of inundation that lead to huge loss of life and property during the 1977 cyclone. His study showed that the East Godavari to Guntur stretch and Southern Nellore coast are under the widest surge inundation, while wind speeds are highest in Visakhapatnam, though the entire CAP stretch is not far behind. Cyclone vulnerability and risk analysis performed by Matta et al. 2015 [80] studied the population and land region exposed to cyclone and wind speed during the cyclones. These Mandals level maps revealed that out of 430 mandals, 190 are highly exposed to cyclone winds with speeds of 235 km/h. Such studies can be very useful for policy makers to mitigate future damage at a social level. Given the importance of cyclones and their influences on the CAP region, there exists a large gap in CVI estimations with cyclones as there were very few studies reported in this context.

Figure 5 provides some of the district-wise social parameters along CAP. From the figure, it is notable that almost all the districts are equally exposed to socioeconomic parameters. Nevertheless, households without proper drainage (West Godavari district) are at a higher risk of cyclone-induced storm surges and their inundation. Drinking water facility is not fully covered in any of the districts as most of the coastal villages depend upon wells. Additionally, over-pumping of well water along the coastal regions might further lead to salt water intrusion into ground water and land subsidence.

Population density accelerates the vulnerability risk rate further. In terms of population density per square km, the highest risk was observed for Krishna district, followed by East Godavari, Srikakulam and Guntur districts.

6.2. Mitigation Strategies and Approaches

Andhra Pradesh coastal management has developed some adaptive strategies for stresses such as provision of cyclone shelters, disaster response force for responsive activities, cyclone and tsunami warning centers [83]; likewise, protection works for rivers and seacoasts were implemented to improve resilience to flooding (National Disaster Management Authority, 2016 [69]. Mitigation of coastal land loss due to erosion is mostly through hard engineering interventions such as the construction of groynes, dykes and seacoasts (Bhattacharyya et al. 2016 [84]. However, the literature revealed no such mitigation strategies employed over the CAP region, instead most focused on the rate of vulnerability with respect to the parameters considered. Nevertheless, these engineering structures can help to reduce the erosion in the short-term due to longshore drift; however, in the longer-term, these engineering interventions may increase erosion rates further down the coast. Furthermore, maintenance of these artificial engineering structures is relatively expensive [85]. Therefore, a more effective and more affordable alternative might be required, such as the use of ecosystem-based green-infrastructure solutions, to improve resiliency and to reduce the impact of some coastal activities such as sand mining.

6.3. Data Gathering Techniques

The most common weakness of the many studies of hazards on the Indian coast is the relatively poor resolution of data. The major focus of existing research has mostly used data gathered from field observations or satellites. CAP, in particular has less data gathered compared to states like West Bengal, Odisha, Tamil Nadu, Kerala and Karnataka. The studies focusing on mitigation and adaptation strategies to CAP hazards are very few to none. Furthermore, temporal variations of coastal processes vary from a daily time period to many years at a climatic level; however, the current data gathering techniques do not accurately capture this temporality sufficiently. At a global level, there have been significant improvements in approaches to data gathering since the majority of these studies were undertaken, particularly using new digital technologies. There is a need to study CAP with better data and constant observation; emerging technologies such as Unmanned Aerial Vehicles (UAVs) with airborne and LiDAR sensors can help to achieve a better understanding of CAP. Such digital technologies can provide spatial data at a much higher level of resolution than existing approaches, allowing data specificity at a much more local level. Moreover, the cost of these technologies has reduced recently and is now a cost-effective means for gathering data.

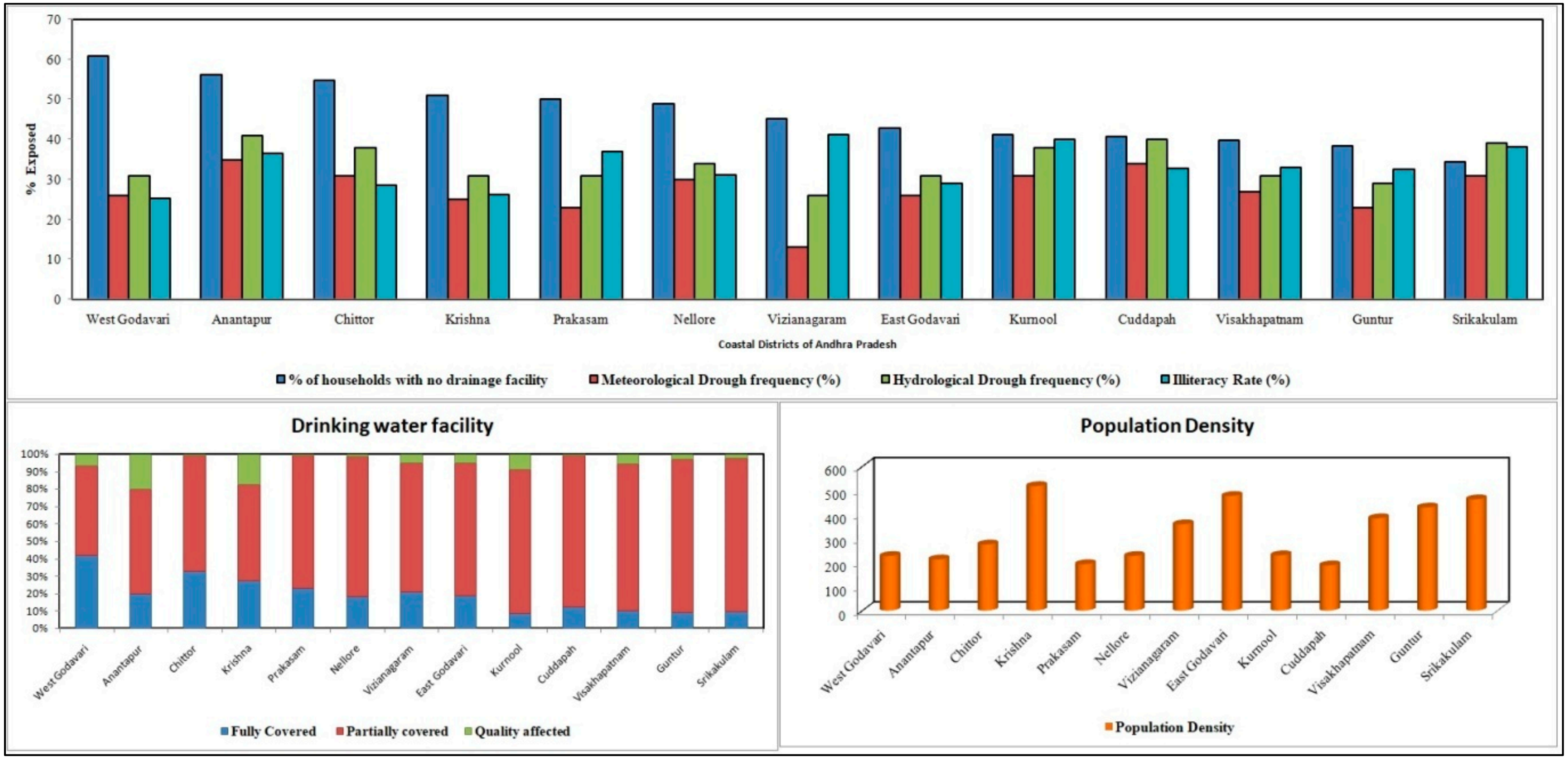

Figure 5. Social components exposed due to coastal vulnerability.

7. Conclusions

The current study research aims to generate up-to-date knowledge for use in the development and implementation of local, regional and national policies, and disaster and coastal risk management procedures. The current study systematically reviews existing literature to examine the occurrence, magnitude and impacts of the natural hazards affecting the Indian coast with special focus on Coastal Andhra Pradesh. Data collection methods and data sources are critically appraised as well as existing mitigation strategies proposed as a result of the analyses. The most recurrent natural hazards within the coastal Andhra Pradesh region are tropical cyclones, coastal inundation, monsoon-floods along the rivers and torrential rains. The present study highlights that, due to its geographical location on the Bay of Bengal Tectonic Plate, Coastal Andhra Pradesh is highly prone to natural coastal disasters. This study also distinguishes the probable long-term influence of sea level rise due to human-induced global warming and rapid urbanization on Coastal Andhra Pradesh in specific areas. The predicted sea level rise and temperatures are likely to result in the loss of residential and agricultural land, an upsurge in salinity and the decline of water quality, especially in agricultural fields, with predominantly negative impacts on the economy and population of coastal Andhra Pradesh.

The review reveals that the majority of existing data is collected from either satellite data or field observations that are very low in resolution, and are not continuous. This research can be used as a primary assessment for the design of a resiliency assessment framework for natural disaster management for the Andhra Pradesh region, and beyond. This resiliency assessment framework should play a vital role in decision-making within the reduction of coastal area vulnerability to natural hazards such as cyclones and floods, and also might improve its resilience capacity. Its application is likely to enable positive results regarding effective disaster management and control, by reducing harm to economies and safeguarding the security of local and regional communities. The current review of the coastal vulnerability of coastal Andhra Pradesh will be of interest to researchers, coastal engineers, environmentalists and government officials, who want to evaluate the prospective consequences of multiple disasters for coastal geographical areas across the world. The study shows that very little has been done to study the overall coastal vulnerability along CAP with only a few of the CVI parameters being accounted for, and based on relatively low resolution data. More research is required to observe, measure, and assess adaptation and mitigation measures in this area to improve resiliency.

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References

1. Sekovski, I.; Newton, A.; Dennison, W.C. Megacities in the coastal zone: Using a driver-pressure-state-impact-response framework to address complex environmental problems. *Estuar. Coast. Shelf Sci.* **2012**, *96*, 48–59. [CrossRef]
2. Gari, S.R.; Newton, A.; Icely, J.D. A review of the application and evolution of the DPSIR framework with an emphasis on coastal social-ecological systems. *Ocean Coast. Manag.* **2015**, *103*, 63–77. [CrossRef]
3. Rani, N.S.; Satyanarayana, A.; Bhaskaran, P.K. Coastal vulnerability assessment studies over India: A review. *Nat. Hazards* **2015**, *77*, 405–428. [CrossRef]
4. Paula, J. Overall assessment of the state of the coast in the Western Indian. *Ocean Reg. State Coast Rep.* **2016**, 500–527. [CrossRef]
5. Kantamaneni, K.; Gallagher, A.; Du, X. Assessing and mapping regional coastal vulnerability for port environments and coastal cities. *J. Coast. Conserv.* **2019**, *23*, 59–70. [CrossRef]

6. Brown, S.; Nicholls, R.J.; Lázár, A.N.; Hornby, D.D.; Hill, C.; Hazra, S.; Addo, K.A.; Haque, A.; Caesar, J.; Tompkins, E.L. What are the implications of sea-level rise for a 1.5, 2 and 3 °C rise in global mean temperatures in the Ganges-Brahmaputra-Meghna and other vulnerable deltas? *Reg. Environ. Chang.* **2018**, *18*, 1829–1842. [CrossRef]
7. Sahoo, B.; Bhaskaran, P.K. Multi-hazard risk assessment of coastal vulnerability from tropical cyclones—A GIS based approach for the Odisha coast. *J. Environ. Manag.* **2018**, *206*, 1166–1178. [CrossRef] [PubMed]
8. UNEP. Global Environment Outlook 3: Past, Present and Future Perspectives. UNEP/Earthscan: Nairobi, Kenya, 2012. Available online: https://wedocs.unep.org/bitstream/handle/20.500.11822/8609/GEO-3%20REPORT_English.pdf?sequence=7&isAllowed=y (accessed on 12 September 2014).
9. Vivek, G.; Mahendra, R.S.; Mohanty, P.C.; Srinivasa Kumar, T. Sachikanta Nanda Coastal Vulnerability Assessment for North East Coast of Andhra Pradesh, India. *Int. J. Remote Sens. Geosci. (IJRSG)* **2016**, *5*, 1–7.
10. Patwardhan, A.; Semenov, S.; Schnieder, S.; Burton, I.; Magadza, C.; Oppenheimer, M.; Pittock, B.; Rahman, A.; Smith, J.; Suarez, A. Assessing key vulnerabilities and the risk from climate change. *Clim. Chang.* **2007**, 779–810.
11. Few, R. Flood hazards, vulnerability and risk reduction. In *Flood Hazards and Health*; Routledge: London, UK, 2013; pp. 20–39. [CrossRef]
12. Elliott, M.; Cutts, N.D.; Trono, A. A typology of marine and estuarine hazards and risks as vectors of change: A review for vulnerable coasts and their management. *Ocean Coast. Manag.* **2014**, *93*, 88–99. [CrossRef]
13. Ramesh, R.; Chen, Z.; Cummins, V.; Day, J.; D'Elia, J.; Dennison, B.; Forbes, D.L.; Glaeser, B.; Glaser, M.; Glavovic, B.; et al. Land–ocean interactions in the coastal zone: Past, present & future. *Anthropocene* **2015**, *12*, 85–98.
14. Nicholls, R.J.; Wong, P.P.; Burkett, V.R.; Codignotto, J.O.; Hay, J.E.; McLean, R.F.; Ragoonaden, S.; Woodroffe, C.D. Coastal systems and low-lying areas. In *Climate Change 2007: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E., Eds.; Cambridge University Press: Cambridge, UK, 2017; pp. 315–356.
15. Schuur, E.A.G.; McGuire, A.D.; Schädel, C.; Grosse, G.; Harden, J.W.; Hayes, D.J.; Hugelius, G.; Koven, C.D.; Kuhry, P.; Lawrence, D.M.; et al. Climate change and the permafrost carbon feedback. *Nature* **2015**, *520*, 171–179. [CrossRef] [PubMed]
16. Dow, K.; Downing, T.E. *The Atlas of Climate Change: Mapping the World's Greatest Challenge*; University of California Press: Brighton, UK, 2016.
17. Lal, M. Global climate change: India's monsoon and its variability. *J. Environ. Stud. Policy* **2003**, *6*, 1–34.
18. Lioubimtseva, E.; Henebry, G.M. Climate and environmental change in arid Central Asia: Impacts, vulnerability, and adaptations. *J. Arid Environ.* **2009**, *73*, 963–977. [CrossRef]
19. Karim, M.F.; Mimura, N. Impacts of climate change and sea-level rise on cyclonic storm surge floods in Bangladesh. *Glob. Environ. Chang.* **2008**, *18*, 490–500. [CrossRef]
20. Knutson, T.R.; McBride, J.L.; Chan, J.; Emanuel, K.; Holland, G.; Landsea, C.; Held, I.; Kossin, J.P.; Srivastava, A.K.; Sugi, M. Tropical cyclones and climate change. *Nat. Geosci.* **2010**, *3*, 157–163. [CrossRef]
21. Vousdoukas, M.I.; Mentaschi, L.; Voukouvalas, E.; Verlaan, M.; Jevrejeva, S.; Jackson, L.P.; Feyen, L. Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. *Nat. Commun.* **2018**, *9*, 2360. [CrossRef] [PubMed]
22. The South Asian Disaster Report (SADR), Changing Limits, Impeding Risks, Emerging Perspectives. 2010. Available online: http://www.ndma.gov.pk/Publications/South%20Asia%20Disaster%20Report%202010%20unisdr.pdf (accessed on 12 March 2016).
23. McCarthy, J.J.; Canziani, O.F.; Leary, N.A.; Dokken, D.J.; White, K.S. *Climate Change 2001: Impacts, Adaptation, and Vulnerability: Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2001; Volume 2.
24. Moss, R.H.; Edmonds, J.A.; Hibbard, K.A.; Manning, M.R.; Rose, S.K.; van Vuuren, D.P.; Carter, T.R.; Emori, S.; Kainuma, M.; Kram, T.; et al. The next generation of scenarios for climate change research and assessment. *Nature* **2010**, *463*, 747–756. [CrossRef] [PubMed]
25. Neumann, B.; Vafeidis, A.T.; Zimmermann, J.; Nicholls, R.J. Future coastal population growth and exposure to sea-level rise and coastal flooding-a global assessment. *PLoS ONE* **2015**, *10*, e0118571. [CrossRef] [PubMed]

26. Chen, W.-Y.; Suzuki, T.; Lackner, M. *Sea-Level Rise and Hazardous Storms: Impact Assessment on Coasts and Estuaries*; Springer: New York, NY, USA, 2016.
27. Arkema, K.K.; Griffin, R.; Maldonado, S.; Silver, J.; Suckale, J.; Guerry, A.D. Linking social, ecological, and physical science to advance natural and nature-based protection for coastal communities. *Ann. N. Y. Acad. Sci.* **2017**, *1399*, 5–26. [CrossRef] [PubMed]
28. Kantamaneni, K.; Phillips, M.; Thomas, T.; Jenkins, R. Assessing coastal vulnerability: Development of a combined physical and economic index. *Ocean Coast. Manag.* **2018**, *158*, 164–175. [CrossRef]
29. Blaikie, P.; Cannon, T.; Davis, I.; Wisner, B. *At Risk: Natural Hazards, People's Vulnerability and Disasters*, 1st ed.; Routledge: London, UK, 1994. [CrossRef]
30. Parry, M.; Parry, M.L.; Canziani, O.; Palutikof, J.; Van der Linden, P.; Hanson, C. *Climate Change 2007-Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Fourth Assessment Report of the IPCC*; Cambridge University Press: Cambridge, UK, 2007; Volume 4.
31. Nguyen, T.T.; Bonetti, J.; Rogers, K.; Woodroffe, C.D. Indicator-based assessment of climate-change impacts on coasts: A review of concepts, methodological approaches and vulnerability indices. *Ocean Coast. Manag.* **2016**, *123*, 18–43. [CrossRef]
32. Kumar, P.D. Potential vulnerability implications of sea level rise for the coastal zones of Cochin, southwest coast of India. *Environ. Monit. Assess.* **2006**, *123*, 333. [CrossRef] [PubMed]
33. Kanakara, R.; Subramanian, B. Oil spill sensitivity analysis and risk assessment for Gulf of Kachchh, India, using integrated modeling. *J. Coast. Res.* **2007**, *14*, 1251–1258. [CrossRef]
34. Chandrasekar, N.; Joevivek, V. *John Prince Soundaranayagam DC Geospatial Analysis of Coastal Geomorphological Vulnerability along Southern Tamil Nadu Coast*; Geospatial World Forum: Hyderabad, India, 2011.
35. ManiMurali, R.; Ankita, M.; Amrita, S.; Vethamony, P. Coastal Vulnerability Assessment of Puducherry Coast, India, using the Analytical Hierarchical Process. *Nat. Hazards Earth Syst. Sci.* **2013**, *13*, 3291–3311. [CrossRef]
36. Saxena, S.; Purvaja, R.; Suganya, G.M.D.; Ramesh, R. Coastal hazard mapping in the Cuddalore region, South India. *Nat. Hazards* **2013**, *66*, 1519–1536. [CrossRef]
37. Appelquist, L.R.; Balstrøm, T. Application of a new methodology for coastal multi-hazard-assessment & management on the state of Karnataka, India. *J. Environ. Manag.* **2015**, *152*, 1–10.
38. Appelquist, L.R. Generic framework for meso-scale assessment of climate change hazards in coastal environments. *J. Coast. Conserv.* **2013**, *17*, 59–74. [CrossRef]
39. Gilard, O. Hazards, Vulnerability and Risk. In *Climate Change and Agriculture Worldwide*; Springer: New York, NY, USA, 2016; pp. 19–29.
40. Thieler, E.R.; Hammar-Klose, E.S. *National Assessment of Coastal Vulnerability to Sea-level Rise: Preliminary Results for the US Gulf of Mexico Coast*; Geological Survey Open-File Report; U.S. Geological Survey: Woods Hole, MA, USA, 2000.
41. Boruff, B.J.; Emrich, C.; Cutter, S.L. Erosion hazard vulnerability of US coastal counties. *J. Coast. Res.* **2005**, *21*, 932–942. [CrossRef]
42. Szlafsztein, C.; Sterr, H. A GIS-based vulnerability assessment of coastal natural hazards, state of Pará, Brazil. *J. Coast. Conserv.* **2007**, *11*, 53–66. [CrossRef]
43. Abuodha, P.A.; Woodroffe, C.D. Assessing vulnerability to sea-level rise using a coastal sensitivity index: A case study from southeast Australia. *J. Coast. Conserv.* **2010**, *14*, 189–205. [CrossRef]
44. Torresan, S.; Critto, A.; Rizzi, J.; Marcomini, A. Assessment of coastal vulnerability to climate change hazards at the regional scale: The case study of the North Adriatic Sea. *Nat. Hazards Earth Syst. Sci.* **2012**, *12*, 2347–2368. [CrossRef]
45. Ahsan, M.N.; Warner, J. The socioeconomic vulnerability index: A pragmatic approach for assessing climate change led risks—A case study in the south-western coastal Bangladesh. *Int. J. Disaster Risk Reduct.* **2014**, *8*, 32–49. [CrossRef]
46. Cui, L.; Ge, Z.; Yuan, L.; Zhang, L. Vulnerability assessment of the coastal wetlands in the Yangtze Estuary, China to sea-level rise. *Estuar. Coast. Shelf Sci.* **2015**, *156*, 42–51. [CrossRef]
47. Satta, A.; Snoussi, M.; Puddu, M.; Flayou, L.; Hout, R. An index-based method to assess risks of climate-related hazards in coastal zones: The case of Tetouan. *Estuar. Coast. Shelf Sci.* **2016**, *175*, 93–105. [CrossRef]

48. Coletti, A.; De Nicola, A.; Villani, M.L. Building climate change into risk assessments. *Nat. Hazards* **2016**, *84*, 1307–1325. [CrossRef]
49. Ciccarelli, D.; Pinna, M.S.; Alquini, F.; Cogoni, D.; Ruocco, M.; Bacchetta, G.; Sartic, G.; Fenu, G. Development of a coastal dune vulnerability index for Mediterranean ecosystems: A useful tool for coastal managers? *Estuar. Coast. Shelf Sci.* **2017**, *187*, 84–95. [CrossRef]
50. Ghoussein, Y.; Mhawej, M.; Jaffal, A.; Fadel, A.; El Hourany, R.; Faour, G. Vulnerability assessment of the South-Lebanese coast: A GIS-based approach. *Ocean Coast. Manag.* **2018**, *158*, 56–63. [CrossRef]
51. Vittal Hegde, A.; Radhakrishnan Reju, V. Development of coastal vulnerability index for Mangalore coast, India. *J. Coast. Res.* **2007**, *23*, 1106–1111. [CrossRef]
52. Dwarakish, G.S.; Vinay, S.A.; Natesan, U.; Asano, T.; Kakinuma, T.; Venkataramana, K.; Pai, B.J.; Babita, M.K. Coastal vulnerability assessment of the future sea level rise in Udupi coastal zone of Karnataka state, west coast of India. *Ocean Coast. Manag.* **2009**, *52*, 467–478. [CrossRef]
53. Kumar, T.S.; Mahendra, R.; Nayak, S.; Radhakrishnan, K.; Sahu, K. Coastal vulnerability assessment for Orissa State, east coast of India. *J. Coast. Res.* **2010**, *26*, 523–534. [CrossRef]
54. Kumar, A.A.; Kunte, P.D. Coastal vulnerability assessment for Chennai, east coast of India using geospatial techniques. *Nat. Hazards* **2012**, *64*, 853–872. [CrossRef]
55. Klemas, V.V. Coastal and environmental remote sensing from unmanned aerial vehicles: An overview. *J. Coast. Res.* **2015**, *31*, 1260–1267. [CrossRef]
56. Prabhakara Rao, P.; Nair, M.; Raju, D. Assessment of the role of remote sensing techniques in monitoring shoreline changes: A case study of the Kerala coast. *Int. J. Remote Sens.* **1985**, *6*, 549–558. [CrossRef]
57. Pavri, F. Urban expansion and sea-Level rise related flood vulnerability for Mumbai (Bombay), India using remotely sensed data. In *Geospatial Techniques in Urban Hazard and Disaster Analysis*; Springer: Dordrecht, The Netherlands, 2009; pp. 31–49.
58. Rao, K.N.; Subraelu, P.; Rao, T.V.; Malini, B.H.; Ratheesh, R.; Bhattacharya, S.; Rajawat, A. Sea-level rise and coastal vulnerability: An assessment of Andhra Pradesh coast, India through remote sensing and GIS. *J. Coast. Conserv.* **2008**, *12*, 195–207.
59. Jana, A.; Bhattacharya, A.K. Assessment of coastal erosion vulnerability around Midnapur-Balasore Coast, Eastern India using integrated remote sensing and GIS techniques. *J. Indian Soc. Remote Sens.* **2013**, *41*, 675–686. [CrossRef]
60. Kaliraj, S.; Chandrasekar, N.; Ramachandran, K.; Srinivas, Y.; Saravanan, S. Coastal landuse and land cover change and transformations of Kanyakumari coast, India using remote sensing and GIS. Egypt. *J. Remote Sens. Space Sci.* **2017**, *20*, 169–185.
61. Thakur, S.; Dey, D.; Das, P.; Ghosh, P.; De, T. Shoreline change detection using Remote Sensing in the Bakkhali Coastal Region, West Bengal, India. *Indian J. Geosci.* **2017**, *71*, 611–626.
62. Venkataraman, C.; Mishra, T.; Ghosh, S.; Karmakar, S. *Climate Change Signals and Response: A Strategic Knowledge Compendium for India*; Springer: Singapore, 2018.
63. Mujabar, P.S.; Chandrasekar, N. Coastal erosion hazard and vulnerability assessment for southern coastal Tamil Nadu of India by using remote sensing and GIS. *Nat. Hazards* **2013**, *69*, 1295–1314. [CrossRef]
64. Mahendra, R.; Mohanty, P.; Bisoyi, H.; Kumar, T.S.; Nayak, S. Assessment and management of coastal multi-hazard vulnerability along the Cuddalore–Villupuram, east coast of India using geospatial techniques. *Ocean Coast. Manag.* **2011**, *54*, 302–311. [CrossRef]
65. Poompavai, V.; Ramalingam, M. Geospatial analysis for coastal risk assessment to cyclones. *J. Indian Soc. Remote Sens.* **2013**, *41*, 157–176. [CrossRef]
66. AP (Andhra Pradesh). State Portal. AP at a Glance. 2017. Available online: https://www.ap.gov.in/?page_id=30 (accessed on 25 March 2018).
67. Rani, M.; Rehman, S.; Sajjad, H.; Chaudhary, B.; Sharma, J.; Bhardwaj, S.; Kumar, P. Assessing coastal landscape vulnerability using geospatial techniques along Vizianagaram–Srikakulam coast of Andhra Pradesh, India. *Nat. Hazards* **2018**, *94*, 711–725. [CrossRef]
68. NRSC (National Remote sensing Centre). AP at a Glance. 2014. Available online: https://nrsc.gov.in/uim_2014_proceedings/papers_ppts/UIM2014_US5_EVinodKumar.pdf (accessed on 24 June 2016).
69. National Disaster Management Authority (NDMA). Annual Report for 2016–2017-Government of India. 2016. Available online: https://ndma.gov.in/images/annreport/ENG-2016-17-AR.pdf (accessed on 25 March 2018).

70. The Ministry of Environment & Forests, Govt. of India. Coastal Zones of India. 2012. Available online: http://www.moef.nic.in/sites/default/files/Coastal_Zones_of_India.pdf (accessed on 26 June 2017).
71. AP State Disaster Management Authority. Revenue Department. 2017. Available online: http://www.apsdma.ap.gov.in (accessed on 22 March 2018).
72. Gornitz, V. Vulnerability of the East Coast, USA to future sea level rise. *J. Coast. Res.* **1990**, *9*, 201–237.
73. Rao, A.; Babu, S.; Prasad, K.; Murty, T.R.; Sadhuram, Y.; Mahapatra, D. Investigation of the generation and propagation of low frequency internal waves: A case study for the east coast of India. *Estuar. Coast. Shelf Sci.* **2010**, *88*, 143–152. [CrossRef]
74. Krishnan, P.; Ananthan, P.S.; Purvaja, R.; Joyson Joe Jeevamani, J.; Amali Infantina, J.; Srinivasa Rao, C.; Anand, A.; Mahendra, R.S.; Sekar, I.; Kareemulla, K.; et al. Framework for mapping the drivers of coastal vulnerability and spatial decision making for climate-change adaptation: A case study from Maharashtra, India. *Ambio* **2018**, *48*, 192–212. [CrossRef] [PubMed]
75. Pramanik, M.K.; Biswas, S.S.; Mondal, B.; Pal, R. Coastal vulnerability assessment of the predicted sea level rise in the coastal zone of Krishna–Godavari delta region, Andhra Pradesh, east coast of India. *Environ. Dev. Sustain.* **2016**, *18*, 1635–1655. [CrossRef]
76. Basheer Ahammed, K.; Mahendra, R.; Pandey, A. Coastal Vulnerability Assessment for Eastern Coast of India, Andhra Pradesh by Using Geo-Spatial Technique. *Geoinform. Geostat. Overv.* **2016**, *4*. [CrossRef]
77. Unnikrishnan, A.; Shankar, D. Are sea-level-rise trends along the coasts of the north Indian Ocean consistent with global estimates? *Glob. Planet. Chang.* **2007**, *57*, 301–307. [CrossRef]
78. Kumar, K.K.; Tholkappian, S. Relative vulnerability of Indian coastal districts to sea-level rise and climate extremes. *Int. Rev. Environ. Strat.* **2006**, *6*, 3–22.
79. Matta, S.; Tejaswi Baddam, S. Cyclone Vulnerability and Risk Analysis for Coastal Districts of Andhra Pradesh. 2015. Available online: http://imetsociety.org/wp-content/pdf/vayumandal/2015/2015_6.pdf (accessed on 26 March 2017).
80. NRSC-ISRO. NATURAL RESOURCES CENSUS Ninth Cycle (2012-13) NATIONAL LAND USE AND LAND COVER MAPPING USING MULTI-TEMPORAL AWiFS DATA (LULC-AWiFS) Remote Sensing Applications Area & Regional Remote Sensing Centres NATIONAL REMOTE SENSING CENTER & North Eastern Space Applications Centre (NESAC) Indian Space Research Organisation. 2013. Available online: https://bhuvan-noeda.nrsc.gov.in/gis/thematic/tools/document/LULC250/1213.pdf (accessed on 23 February 2019). [CrossRef]
81. Kavya, A.; Bhavani, A.G.; Rao, P.J.; Chandrudu, V.B. Impact of Land Use/Land Cover and Mangrove Degradation on Coastal Erosion in Godavari Delta Region, Andhra Pradesh—A Geospatial Approach. In *Proceedings of International Conference on Remote Sensing for Disaster Management*; Springer Series in Geomechanics and Geoengineering; Springer: Cham, Switzerland, 2019; pp. 413–421.
82. Kumari, K.P.; Srinivas, K. Applications of RS and GIS Techniques for Disaster Studies in East Godavari District, Andhra Pradesh, India. In *Proceedings of International Conference on Remote Sensing for Disaster Management*; Springe Series in Geomechanics and Geoengineering; Springer: Cham, Switzerland, 2019; pp. 199–214.
83. Topno, P.N. Multi-stakeholder Support in Disaster Risk Governance in India. In *Disaster Risk Governance in India and Cross Cutting Issues*; Springer: Singapore, 2018; pp. 127–142.
84. Bhattacharyya, R.; Ghosh, B.N.; Dogra, P.; Mishra, P.K.; Santra, P.; Kumar, S.; Fullen, M.A.; Mandal, U.K.; Anil, K.S.; Lalitha, M.; et al. Soil conservation issues in India. *Sustainability* **2016**, *8*, 565. [CrossRef]
85. FAOUN (The Food and Agriculture Organization of the United Nations). Chapter-4: Protection from Coastal Erosion. 2016. Available online: http://www.fao.org/docrep/010/ag127e/AG127E09.htm (accessed on 10 August 2017).