Coastal Vulnerability Index and Its Projection for Odisha Coast, East Coast of India

Bishnupriya Sahoo, Prasad K. Bhaskaran

Abstract—Tropical cyclone is one among the worst natural hazards that results in a trail of destruction causing enormous damage to life, property, and coastal infrastructures. In a global perspective, the Indian Ocean is considered as one of the cyclone prone basins in the world. Specifically, the frequency of cyclogenesis in the Bay of Bengal is higher compared to the Arabian Sea. Out of the four maritime states in the East coast of India, Odisha is highly susceptible to tropical cyclone landfall. Historical records clearly decipher the fact that the frequency of cyclones have reduced in this basin. However, in the recent decades, the intensity and size of tropical cyclones have increased. This is a matter of concern as the risk and vulnerability level of Odisha coast exposed to high wind speed and gusts during cyclone landfall have increased. In this context, there is a need to assess and evaluate the severity of coastal risk, area of exposure under risk, and associated vulnerability with a higher dimension in a multi-risk perspective. Changing climate can result in the emergence of a new hazard and vulnerability over a region with differential spatial and socio-economic impact. Hence there is a need to have coastal vulnerability projections in a changing climate scenario. With this motivation, the present study attempts to estimate the destructiveness of tropical cyclones based on Power Dissipation Index (PDI) for those cyclones that made landfall along Odisha coast that exhibits an increasing trend based on historical data. The study also covers the futuristic scenarios of integral coastal vulnerability based on the trends in PDI for the Odisha coast. This study considers 11 essential and important parameters; the cyclone intensity, storm surge, onshore inundation, mean tidal range, continental shelf slope, topo-graphic elevation onshore, rate of shoreline change, maximum wave height, relative sea level rise, rainfall distribution, and coastal geomorphology. The study signifies that over a decadal scale, the coastal vulnerability index (CVI) depends largely on the incremental change in variables such as cyclone intensity, storm surge, and associated inundation. In addition, the study also performs a critical analysis on the modulation of PDI on storm surge and inundation characteristics for the entire coastal belt of Odisha State. Interestingly, the study brings to light that a linear correlation exists between the storm-tide with PDI. The trend analysis of PDI and its projection for coastal Odisha have direct practical applications in effective coastal zone management and vulnerability assessment.

Keywords—Bay of Bengal, coastal vulnerability index, power dissipation index, tropical cyclone.

I. INTRODUCTION

WORLD wide coastal belts are densely populated. Based on the 2011 Census by the Government of India, the center for Coastal Zone Management and Coastal Shelter belt by the Ministry of Earth Sciences (MOES), India [1] has reported that 14.2% of human population resides in the coastal districts and this trend is increasing at present. The high population density along coastal belt definitely poses a high degree of socio-economic risks associated with natural hazards such as tropical cyclones. Archive records depict that the state of Odisha accounts the highest frequency land-falling cyclones along the east coast of India. In the past four decades, 29% of cyclones in the Bay of Bengal have impacted the coast of Odisha alone [2]. In addition, the vulnerability of the state multiplies due to the high population density in the coastal districts. The census of India reports that around 33% of the total population of Odisha inherited in the coastal districts. The very severe cyclones notable are the 1999 Odisha Super Cyclone and 2013 Phailin Cyclone. During the 1999 Odisha cyclone, around 12.9 million population were affected and the physical destruction amounted was more than $4.44 billion, whereas the timely warnings and alerts by the National Disaster Management Authorities (NDMA) massive evacuation measures were very effective in minimizing human lives for 2013 Phailin cyclone. More details on above cyclones can be found in literature [3], [4]. There is a drastic increment found in the potential of the cyclones in the basin in last four decades [3]. The futuristic projection based on theory and high-resolution dynamical models with greenhouse warming depicts the averaged intensity of tropical cyclones to shift towards stronger storms, and the intensity to be around 2-11% by 2100 [5]. Based on the study, a 20% increase in the precipitation rate within 100 km of the storm center is also expected in the future. There is found an increase in the size of the cyclone in the past few years which designates the larger portion of the coastline being exposed during the cyclonic landfall [6]. Above facts are the clear indication towards an amplified vulnerability along the coast expected in the future. Hence, there is an acute need for an accurate assessment of coastal vulnerability prior to any cyclonic event, which can help in the coastal zone management and evacuation planning. Hence, the study plans to assess the risk associated with the tropical cyclones for the highly vulnerable coast of Odisha along the east coast of India. For this, the study generated a database of storm surge and inundations maps along the Odisha state using the state of art Advance Circulation (ADCIRC) model using the wind forcing along the synthetic cyclone tracks generated by the authors [2]. The risk is assessed in terms of CVI using standard formula of Gorintz [7]. Along with cyclone intensity, storm surge, onshore inundation, the composite risk from mean tidal range, continental shelf slope, topo-graphic elevation onshore, rate of shoreline change, maximum wave height, relative sea level

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rise, rainfall distribution, and coastal geomorphology are used to estimate the CVI. For a futuristic projection of vulnerability along the coast, the study analyses the trend of PDI associated with cyclones those had their landfall at Odisha coast. From the trend analysis of PDI along the coast, a projection of PDI for coming two decades is drawn. This projected PDI is undergone back propagation to obtain the peak intensity of cyclones associated. Using this intensity, the storm surge and inundation all along Odisha coast is estimated using state of art Advance Circulation (ADCIRC) model [8], [9] with the wind forcing from multiple synthetic cyclone tracks generated from the synthetic cyclone track for Odisha state [2]. Using the projected storm surge and inundation and 10-20% increased rainfall, the CVI is estimated for Odisha coast, which is considered as the projected CVI in climate change scenario. This projection is essential in terms of preparedness planning and coastal zone management along Odisha coast for the increasing trend of tropical cyclone intensities.

II. DATA AND METHODOLOGY

Present study estimates the CVI using the 11 parameters such as cyclone intensity in terms of PDI, storm surge, onshore inundation, continental shelf slope, onshore elevation, coastal geomorphology, relative sea level rise, rate of shoreline change, mean tidal range, mean wave height. Details on the storm surge height, inundation extent are obtained from set of ADCIRC simulations forced with Holland parametric wind along synthetic cyclone tracks along the coast. Mean tidal range is obtained from one year tidal simulation using ADCIRC along the state of Odisha. The slope of continental shelf, topographic slope, and rate of shoreline changes are estimated using Google Earth imageries and bathymetry from NOAA. The geomorphology along the coastline is from Google Earth and the rainfall data is obtained from TRMM and IMD records. The variables such as maximum wave height and relative sea level change are adopted from existing literature [10].

The study used trend of PDI to estimate the projected CVI. Hence, present study estimates the PDI for cyclones generated in the Bay of Bengal basin and cyclones those had landfall over Odisha coast. To define PDI, PDI is the net destructiveness potential of the cyclone based on the integrated power dissipation over the lifetime of a cyclone. The study used the established formula [11] of PDI to estimate the decadal destructiveness potential of cyclones in the BoB during past 44 years. The expression of PDI is given by

$$PDI = 2\Pi \int_0^\tau \int_0^{r_0} C_D \rho |v|^3 \, r dr dt$$, which can be approximated

by $PDI = \int_0^\tau v_{max}^3 dt$; where, C_D is the drag coefficient; ρ is

the water density; $|v|$ is the cyclone surface wind; v_{max} is the maximum sustained wind speed; r is the radius of maximum winds; r_0 is the radius to the outer storm limit; and τ is life span of the cyclone. The trend of PDI is estimated from the

decadal PDI for Odisha coast. The study performs a back propagation to estimate the intensity of cyclones associated with the projected PDI. With this intensity, the authors estimate the storm surges and inundations expected along the coast. The augmented storm surge and inundation are used to estimate the CVI along the coast which in turn provides the projection of CVI in a climatic scale. It can be noted that the modulation of CVI with respect to cyclone intensity, rainfall, storm surge and coastal inundation is very high compared to the other fair weather parameters such as tidal range, significant wave height, coastal slope, sea level change, shore line change. Hence, for the projection of CVI, the authors used projected values of storm surge, inundation, cyclone intensity and 20% higher rainfall rate.

III. RESULTS AND DISCUSSION

For the projection of storm surge, coastal inundation, present study uses the trend of PDI along Odisha coast. The projected storm surge and inundation estimates the projected coastal vulnerability when combined in terms of CVI. To estimate the PDI, present study uses the one minute sustained wind speed of cyclones from JTWC (Joint Typhoon Warning Center) cyclone database. The estimated PDI for BoB basin during past five decades are shown in Fig. 1. A clear increasing trend in PDI is found over the basin. The trend comprehends around 600% increase in the PDI of cyclones in the past decades compared to cyclone activity during the late 1990's [2]. The increased destructiveness of the cyclones are well interpreted from the sever destruction during the very sever cyclonic storms such as the 1999 Odisha Super cyclone, Phailin (2013), HudHud (2014) during past two decades.
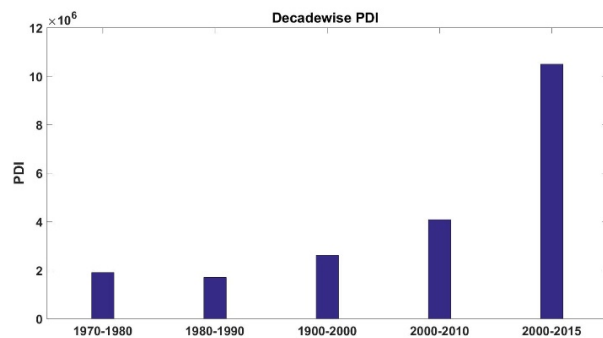

Fig. 1 Decadal PDI over entire Bay of Bengal basin

The study estimated PDI for cyclones that made landfall over Odisha coast which also show an increasing trend. A trend analysis of PDIs' along Odisha coast is performed which shows the PDI for Odisha to follow a quadratic trend. The PDI for Odisha state and the quadratic trend are shown in Fig. 2. Projected PDI for the coming two decades is calculated from this trend of PDI. The projected PDI is shown in red color in Fig. 2. This projected PDI is used to project storm surge and inundation expected in a climate change scenario. To justify the fact of using PDI for the projection is supported from the analysis carrying the relation between PDI and storm tide. The

authors found that there exists a linear relation between storm tide and PDI, which is shown in Fig. 3 (a). Fig. 3 (a) shows a linear trend of PDI with storm tide at four major coastal locations along Odisha coast. Also, PDI being a cubic function of wind speed, the water level along the coast is found to fit a cubic polynomial of wind speed. Fig. 3 (b) shows the cubic fit of storm tide with respect to wind speed at the same coastal locations as of in Fig. 3 (a). This correlation supports to use the trend of PDI for the estimation of projected storm surge height. On this ground, the study applied a back propagation technique to map the maximum wind speed associated with the projected PDI. This maximum wind speed is found to be 78 m/s which is around 7% higher wind speed recorded in recent cyclones. This wind speed is forced to ADCIRC model to estimate projected storm surge and coastal inundation using synthetic cyclone tracks along Odisha coast to obtain the worst possible scenario along the coast. With the reference of this projected intensity and estimated scenarios of storm surges and inundations, CVI is calculated for Odisha coast using Gorintz's formula [7]. This CVI is referred as projected CVI which contains the information of projected cyclone intensity, storm tide, coastal inundation, and 20% higher rate of rainfall. Table I and Fig. 4 show the standardized CVI at 15 major locations along the coast in present scenario (when the maximum wind speed-72 m/s) and its projection in climate change scenario (when the maximum wind speed-78 m/s).
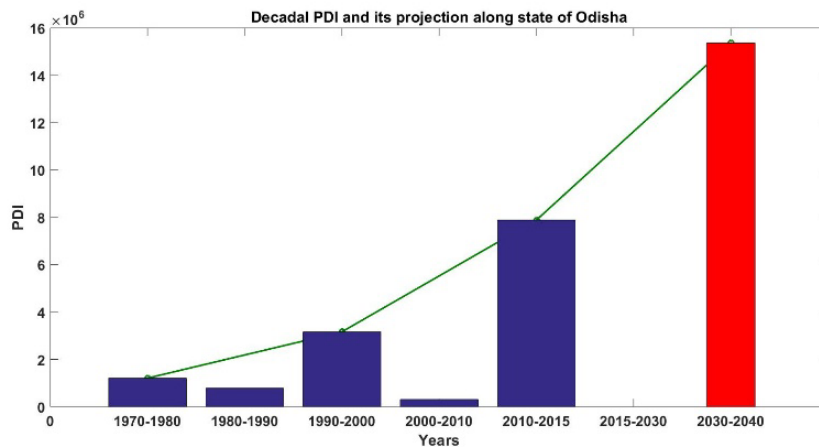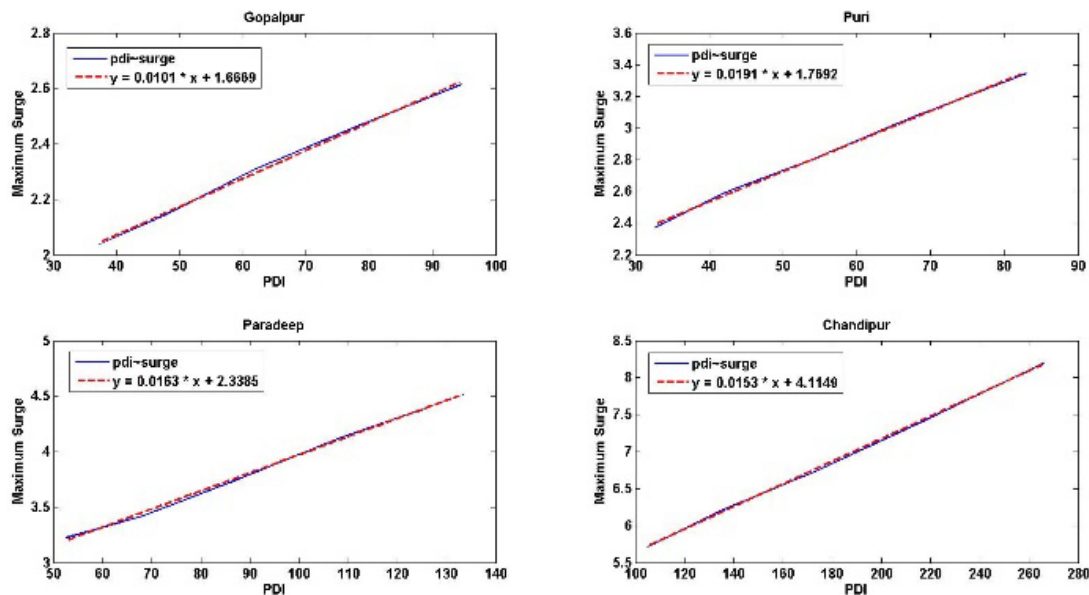

Fig.2 Decadal PDI over Odisha coast
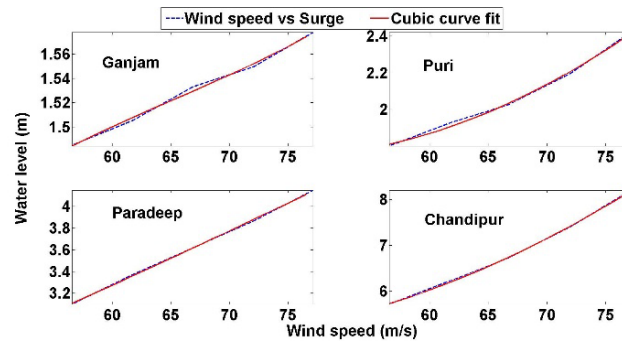

Fig. 3 (a) Linear relation between PDI and storm tide

Fig. 3 (b) Cubic fit of storm tide with wind speed

TABLE I
CVI ALONG ODISHA COAST

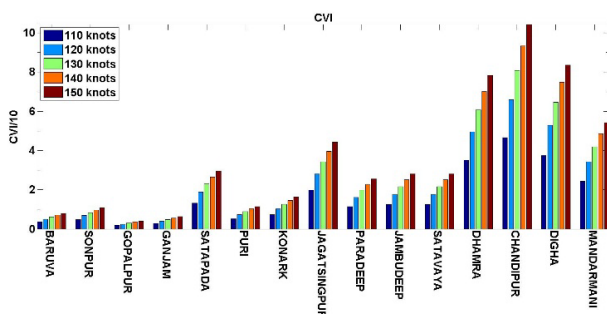| Locations	CVI for intensities	
	72 m/s	78 m/s
Baruva	6.82	7.63
Sonpur	9.34	10.45
Gopalpur	3.41	3.81
Ganjam	5.39	6.03
Satapada	25.58	28.60
Puri	9.91	11.08
Konark	14.01	15.67
Jagatsingpur	38.14	42.64
Paradeep	22.02	24.62
Jambudeep	24.12	26.97
Satavaya	24.12	26.97
Dharma	67.42	75.38
Chandipur	89.89	100
Digha	71.91	80.40
Mandarmani	46.71	52.22

Fig. 4 CVI for different cyclone intensity along Odisha coast

It is noticed that there is an increase of 11.8% found in CVI for a 7% increment in the intensity along Odisha coast. This shows the sensitivity of the coast in climate change scenario and also distinguish the locations with potential risk.

IV. CONCLUSION

The accumulated population density in the coastal area is at high risk from tropical cyclone induces storm surges and inland flooding of sea water. The coast of Odisha bordering the Bay of Bengal is highly vulnerable coast from tropical cyclones. Also an increased rate of vulnerability is expected due to the increasing trend in the intensity and size of cyclone in climate change scenario. Hence, along with the prediction of risk associated with tropical cyclones, the expected threat to the coast in case of a highly intensified cyclones is highly essential towards the coastal zone management and preparedness planning. On this ground, the study computes the CVI for cyclones of existing intensity for Odisha coast and attempts to project the CVI for a period of two decades. The major factors contributes to the CVI are storm surge, onshore inundation, continental shelf slope, onshore elevation, coastal geomorphology, relative sea level rise, rate of shoreline change, mean tidal range, mean wave height. Other than cyclone intensity, storm surge height, inundation and cyclonic rainfall, there is no much modulation found in the variables along the coast for period of two decades. Hence, the projection is drawn based on the above four variables. From the trend analysis of past five decades' PDI of cyclones over Odisha coast, a projection of PDI is performed for Odisha coast for coming two decades. The maximum intensity of cyclones associated with the projected PDI is calculated and used to compute the storm surge and inundation using ADCIRC model with the wind forcing through synthetic cyclones tracks generated for southern to northern boundary of Odisha coast. With 7% increment of wind speed, and generated storm surge and inundation and 10-20% increased rate of cyclonic rainfall the optimum CVI is computed along the coast and referred as the projected CVI. This projected CVI can be used by the coastal zone management authorities, scientific communities and public awareness purpose.

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