World Academy of Science, Engineering and Technology
International Journal of Marine and Environmental Sciences
Vol:15, No:6, 2021

Impact of Climate Change on Sea Level Rise along the Coastline of Mumbai City, India

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Open Science Index, Marine and Environmental Sciences Vol:15, No:6, 2021 publications.waset.org/10012058.pdf

Abstract**—**Sea-level rise being one of the most important impacts of anthropogenic induced climate change resulting from global warming and melting of icebergs at Arctic and Antarctic, the investigations done by various researchers both on Indian Coast and elsewhere during the last decade has been reviewed in this paper. The paper aims to ascertain the propensity of consistency of different suggested methods to predict the near-accurate future sea level rise along the coast of Mumbai. Case studies at East Coast, Southern Tip and West and South West coast of India have been reviewed. Coastal Vulnerability Index of several important international places has been compared, which matched with Intergovernmental Panel on Climate Change forecasts. The application of Geographic Information System mapping, use of remote sensing technology, both Multi Spectral Scanner and Thematic Mapping data from Landsat classified through Iterative Self-Organizing Data Analysis Technique for arriving at high, moderate and low Coastal Vulnerability Index at various important coastal cities have been observed. Instead of data driven, hindcast based forecast for Significant Wave Height, additional impact of sea level rise has been suggested. Efficacy and limitations of numerical methods vis-à-vis Artificial Neural Network has been assessed, importance of Root Mean Square error on numerical results is mentioned. Comparing between various computerized methods on forecast results obtained from MIKE 21 has been opined to be more reliable than Delft 3D model.

Keywords**—**Climate change, coastal vulnerability index, global warming, sea level rise.

I. INTRODUCTION

SEA level rise is considered as one of the most important impacts of anthropogenic induced Climate Change and a serious threat to countries (including India) with human settlements and economic activities concentrated in coastal regions. Globally sea level has been rising during 2006–2015 at the rate of 3.6 mm per year which is accelerating in recent years and by 2100, the global mean sea level rise may exceed 1 m [1]. While exploring forthcoming Sea Level Rise at the coast of Mumbai, the authors have reviewed the related literature researched in the last decade (2010-2019) in a chronology aiming at ascertaining the efficacy of methods with various scenarios across the shorelines.

II. LITERATURE REVIEW

In the Mumbai City Report, Patankar et al. documented that the location of Mumbai being on the coast puts it at greater risk [2] of sea-level rise, flooding, high winds, cyclones and coastal erosion, due to its flood prone location and the landmass composed largely of reclaimed land. It was forecasted that Mumbai was going to be highly susceptible to global climate change with majority of its population living on the flood prone and reclaimed land. Being on the seacoast, the city experiences a tropical savanna climate with a heavy south-west monsoon rainfall of more than 2100 mm a year. The Risks and Vulnerabilities Plan that is an essential part under the Greater Mumbai Disaster Management Action Plan (DMAP) further envisages specific relief and mitigation measures for Mumbai on infrastructure improvements, contingency plan, land use policies and planning.

Kumar et al. studied 480 km at east coast of India, vulnerable to accelerated erosion hazard adding Tsunami run-up with short term data from remote sensing satellites and long-term data from numerical models to determine high, medium, and low Coastal Vulnerability Index (CVI) [3].

Saravanan et al. found that the oceanography of the Indian continental region is dominated by three seasons viz. SW monsoon (June to September), NE monsoon (October to January) and fair-weather period (February to May) [4]. They also studied the Potential littoral sediment transport along the SE Coast of India [5] in relation to wave activity and beach morpho-dynamics through wave refraction studies and opined that due to the presence of shallow Palk bay, Gulf of Mannaar and the Sri-Lanka Island the south Tamilnadu coast of India has comparatively lesser sediment transport.

Ranger et al. apprehends that 2005-like events will more than double by 2080 with potential increase in risks associated with heat waves, tropical cyclones and storm surges due to Sea Level Rise (SLR), which warrant significant revision in urban development & assimilate climate change adaptation measures [6].

Nicholls et al. illustrated serious concerns on the impact of SLR at London, New York, Tokyo, Shanghai, Mumbai, and Lagos [7].

Cazenave et al. studied causes for SLR based on satellite and in-situ data sets and suggested adaptation to threat, which matches with IPCC AR4 [8].

Balica et al. ranked Flood Vulnerability Index (FVI) in histogram for 9 cities: Buenos Aires, Kolkata (India), Casablanca, Dhaka, Manila, Marseille, Osaka, Shanghai and Rotterdam (Fig. 1). They project Shanghai and Dhaka to be most vulnerable by year 2100 followed by Manila and

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Kolkata, Casablanca, Rotterdam. Buenos Aires and Marseille will remain in the lower positions, Osaka being least vulnerable to floods [9].

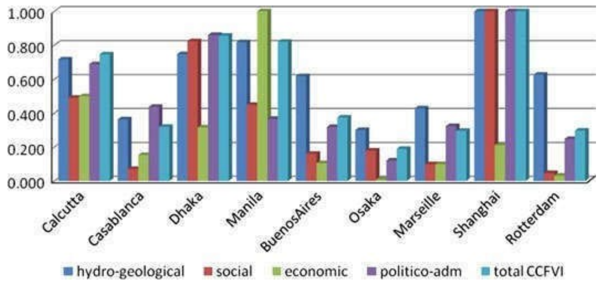

Fig. 1 Total FVI, ranking of coastal cities for different scenarios [9]

Radhika et al. preached evaluating the Significant Wave Height (Hs) on the basis of hindcast wave as inadequate, considered future Hs by downscaling wind information obtained from a General Circulation Model (GCM) run for various scenarios of global warming. Fitting the predicted Hs for next 30 years into Gumbel or Weibull distributions was compared with hindcast and Weibull distribution was found statistically more reliable [10].

Viviek et al. developed CVI using remote sensing and GIS for Southern tip of India at Tamil Nadu. MSS, TM5 and ETM+ from Landsat-1 were used to evaluate the annual shoreline change rate & ArcMap 9.0 was used for mapping the CVI. The southernmost part of India is exposed to the refracted and diverted waves from Sri Lanka [11].

Mahapatra et al. quantified that about 1.6 x 10^6 km of total global coastlines are the most damage-prone from both anthropogenic and natural causes by reviewing the available Assessment Tools and techniques such as CVI, Common Methodology (CM), Synthesis and Upscaling of SLR Vulnerability Assessment Studies (SURVAS) and Dynamic Interactive Vulnerability Assessment (DIVA). The authors found that due to the wind forced coastal circulation and the salinity gradient along the coast, the mean sea level in Bay of Bengal (BOB) is higher in comparison to that at Arabian Sea (AS) [12].

Rana et al. focused on future projections provided by GCMs for Mumbai and suggested that the probability of occurrence of intense rainfall will change in the future [13]. Usually, GCM data generally need to be downscaled and bias-corrected for impact studies. They applied a Distribution-based Scaling (DBS) procedure, with 1975–2004 as a reference period, for bias-correcting and downscaling daily rainfall data from nine global climate projections. Significant positive trend was found for four of the GCM projections. The authors have stressed the need to consider the implications of uncertainties in climate projections for adaptation planning in Mumbai. They advocated the use of multiple projections from a range of available Global Climate Models and Regional Climate Models as a single scenario of future climate is by itself not adequate to inform robust adaptation decisions, which differed from earlier analyses for future scenarios stated in [6]. Nevertheless, there are considerable sources of uncertainties in the results, related mainly to the climate projection ability of describing the probability of occurrence of extreme events. They stressed upon the need to incorporate detailed hydrological impact modelling studies to better assess the future impacts on the study area including climate projections by both hydraulic models of the drainage systems and by hydrological models for the Mumbai region.

Bhaskaran et al. based on satellite altimeter observations highlighted the impact of climate change on variability of maximum significant wave height and wind speeds at the Indian Ocean basin [14]. Data from 1992 until 2012 (21 years) from the eight satellite missions were processed using BRAT at two places, one in BOB and the other in AS. It revealed that the increased wave activity especially in Southern Ocean can generate intense swell field that can modulate and modify the local wind-waves in the North Indian Ocean whereas in the equatorial regions no significant impact of climate change cropped up [14].

Chenthamil et al. combined use of satellite imagery and Water Level Rise (WLR) method for shoreline change analysis at coast of Karnataka, India; using MSS, TM, ETM+ Scanner data from Landsat and GIS for studying the change of shoreline along the Karnataka coast. The shoreline rate of change was calculated by DSAS. WLR and End Point Rate (EPR) was adopted for long term and short-term change analysis respectively. Combination of Remote Sensing techniques and GIS including delineation was acknowledged to benefit semi-automatic determination of shorelines [15].

Changes in shoreline positions at western India were studied by Deepika et al. for a period of 98 years, using multi-dated satellite images and topographic maps [16]. EPR, Average of Rates (AOR) and Linear Regression (LR) were used for shoreline change rate at equidistant transects in four Littoral Cells. Authors concluded that 'shoreline changes at the Udupi coast' were consistent with Third Assessment of IPCC and the estimated change in shoreline was found to be in good agreement with values by EPR and LR models and the calculated RMS error was tolerable [16].

Revi earlier studied [17] on the adaptation needs and mitigation agenda for cities (where the urban population is likely to grow by around 500 million over the next 50 years) in India. They considered the likely changes in temperature, precipitation and extreme rainfall, drought, river and inland flooding, storms/storm surges/coastal flooding, SLR and environmental health risks due to climate change. Also, they attempted to explore who within urban populations are most at risk. The study revealed that Climate change is expected to increase the frequency and intensity of current hazards and the probability of extreme events, and also to spur the emergence of new hazards like SLR and new vulnerabilities with differential spatial and socioeconomic impacts. Three mega-urban regions: Mumbai–Pune (50 million), the national capital region of Delhi (more than 30 million) and Kolkata (20 million) will be among the largest urban concentrations in the world. By mid-century, India could have both the largest urban and rural populations of the time. Although over this century the period when for emergence of climate change

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would be an important risk in the Indian subcontinent is unpredictable, especially related to precipitation and SLR there also are considerable uncertainties concerning precise mechanisms and impacts. But it is certain that substantial increase in extreme precipitation (similar to that happened at Mumbai in 2005) is expected over a large area of the west coast. The expected scenario calls for significant revision of urban planning practices across city and neighborhood to integrate flood and climate change mitigation and adaptation measures into day-to-day urban development and services,

Singh et al. raised alarm over the effect of SLR even being at a height of 10-15 m above the Mean Sea Level (MSL). Mumbai city is vulnerable to cyclone. Sea Level Change from 1900 to 2011 were obtained from GLOSS for MSL data, DEM was followed using NASA- SRTM, whereas Ward Maps were taken from Municipal Corporation of Greater Mumbai (MCGM) and the data were analyzed by ESRI ArcGIS10.1 Software for SLR scenario using GIS and its effect on the 167 km coastline of Mumbai City surrounded by the AS to the west, the south by the Harbour Bay and the Thane Creek on the east. Administrative blocks under MCGM were compared for scenarios of SLR up to 1 m, 2 m and 3 m using ArcGIS10.1 software [18].

Unnikrishnan et al. deliberated SLR trends over the period 1993-2012 within the north Indian Ocean. Altimeter data analysis revealed that the rate of SLR is quite spatially homogeneous over most of the north Indian Ocean, reaching values on the brink of global MSL-rise trend (3.2 mm $yr.^{-1}$) estimated over an equivalent period. The estimated trends from both tide-gauge records and altimeter data suggest that the ocean level rose at a faster rate during the last 20 years than for the whole 20th century as a response to global warming. Another possible cause for this SLR acceleration may be the Himalayan glacier melt, reported to increase over the recent decade [19].

Misra et al. studied decadal (LULC) changes in the coastal zone in southern Gujarat, west of India. The area was 30 m deep into Gulf of Cambay exposed to strong semi-diurnal high range tides and associated current with erosion accretion. Shoreline change was analyzed using DSAS embedded in ArcGIS 10.1. Immense eroding trend is noticed due to anthropogenic effects and EPR of erosion was observed to be very high to the extent of 0.54 m/year [20].

Patil et al. by combining numerical and a special wavelet neural network [20] demonstrated predicting site-specific dependable forecasts of SST at six locations in the Indian Ocean over three-time scales (daily, weekly and monthly at AS, BOB, WEIO, EEIO THERMO (off the African Coast), and SOUTHIO produced accurate SST [21].

Saha et al. predicted ocean currents by combination of a numerical model and ANNs. At two deep-water locations (in the northern Indian Ocean near the equator and near the eastern edge of the thermocline ridge where the flow of currents here slowly moves away from the equator) and the results were found to be satisfactory up to 5 days [22].

Rajasree et al. studied shoreline changes along the west coast of India with past data from earlier satellite images and predicted future wave magnitude by running a numerical model simulating data from past 35 years as well as for future 35 years. Computations alternatively done by ANN with the help of past satellite images also established rising trend of erosion but at a smaller rate (1.66 m/yr.) than obtained from the numerically predicted one (2.21 m/yr.) [23].

Sunder et al. compared remote sensing-based shoreline mapping techniques at different coastal stretches of India and concluded that the AWEI is the most consistent index among all the four indices since it is showed more than 80% overall accuracy for all the test sites [24].

The studies [18] were further extended and GIS has been proved to be the finest tool in analyzing the changes due to climate and it was recommended for future studies the DEM with finer resolution should be used [25].

Rajshree et al. furthered their research [23] on straight coastline on central west coast of India to find changes in coastline with different geomorphologic features to predict shoreline changes for different coastal configurations using future climate projections [26]. Comparing predictions by satellite imageries, numerical models and ANN, it was observed that ANN predicted smaller rates than those obtained from the numerical model but higher than from satellite imageries. Near Mangalore Port through numerical modelling it was measured that a rise of 29% in the annual mean significant wave height over a period of next 36 years would contribute to a rise of sediment transport by 109% [26].

Ankita et al. generated satellite derived bathymetry maps at Ameland Inlet at the Netherlands by using Support Vector Regression (SVR) techniques. It was concluded that these free and easily available medium-resolution imageries from Landsat can help in determining long-term coastal analysis [27].

Kulkarni et al. quantified the benefit of skill addition of Regional Climate Models (RCMs) in simulating wind speed, direction and the wind energy & in particular evaluated utility of CORDEX in the parent GCMs. The study area at AS and BOB, on both sides of the Indian coastline were unique among the world's water basins as wind reverse semi-annually, blowing from the southwest during the northern summer and from the northeast during the northern winter. Around 70% of the Indian offshore locations in monsoon would experience mean wind potential greater than 200 W/m^2, as indicated by most of the RCMs and GCMs [28].

The study [27] was repeated in 2018 at the same coast near estuary of a River Gangavali using simple neural network as an alternative to empirical/numerical modelling based on traditional satellite imageries or field observations. Numerical wave model was simulated for waves for past and future time periods of 36 years each [29]. The shoreline changes in the past varied from -2.18 to +2.67 m/year whereas the numerical model indicated that the shoreline changes in future would vary from -2.11 to +3.52 m/year. The mean Hs may increase at a rate of 0.06 cm/year, whereas the maximum one may rise up to 0.38 cm/year. The future mean Hs in 36 years is expected to rise by 15.87% accompanied by a shift in the mean wave direction by 10.270. From past 36 years to future

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36 years it was predicted that an increase of 131.7% and 114.3% in the net and gross sediment transportation can take place. It was inferred that the Neural Network can be used to verify future changes predicted by Numerical Model for conformity [29].

Verne et al. [30] investigated the morphodynamical and hydrodynamic characteristics along the coast of Maharashtra running Delft 3D model to understand the nearshore bed level variations driven by seasonal cycle of hydrodynamic environment. The simulation was run for one-year period (2017) to assess the seasonal variation in the nearshore bed region. The sources for inputs like wind and wave, tidal elevation and bathymetry were ECMWF, GEBCO and NHO respectively. The inputs were validated with estimated results from literature and data observed from INCOIS and IHO. The hydrodynamic model was calibrated with temporally varying ECMWF inputs and the model performed satisfactorily as understood on comparing climate parameters like Hs, T and MWD from INCOIS wave rider buoys in Maharashtra, India [30].

The studies by Rajshree [23], [26] were further extended for a combined multicriteria-based CVI evaluation at central west coast of India along with a different team [31]. They assessed CVI, using projected as well as historical climate issues (wind, wave, shoreline changes) for two periods 1979-2017 and 2017-2052 by simulating a moderate global warming scenario executed for uninterrupted, naturally discontinuous, and artificially interrupted coastlines. For the purpose of the studies, MIKE 21SW (DHI) was used [31].

Dhiman et. al. provided an assessment regarding quantification, management and climate change impacts of flood risks in 4 most populated coastal cities in India including Mumbai [32]. Mumbai, being the most populous Indian city, located along the western coast of India, is having 2 large ports in western India and simultaneously known as the commercial and financial capital of India. The megacity ranks as the 5th largest city (in terms of the population) in the globe (2019) and the population is projected to pass 27 million in 2030. Anthropogenic reclamation primarily caused the original seven islets to merge and form the current Mumbai city (Fig. 2). Reasons for inundating also include inappropriate levels of outfalls, the increase in the run-off coefficient due to the urban landscape, the loss of holding ponds due to land development and encroachments on drains and obstructions caused by utility lines being crossed. The yearly flooding in Mumbai incurs huge economic losses due to the economical–social disorientation and associated shutdown, ultimately affecting the economy of the nation [32].

Abadie et al. proclaimed that there is a high degree of uncertainty associated with the potential mass loss of the Greenland and Antarctica ice-sheets and the extent of resultant future SLR [33]. The authors explored the impact of the uncertainty on economic damage due to SLR for 136 major coastal cities by comparing the probability distribution considering the stochastic model of expected damage and risk calculation, for two scenarios. One scenario for relative sea-level projections is the damage under the assumption of no adaptation (the RCP 8.5 scenario from the IPCC Fifth Assessment Report) and the other one is a high-end scenario that incorporates expert opinion on additional ice-sheet melting. The results suggest that it is critical to incorporate the possibility of High-end scenarios into coastal adaptation planning for future SLR, especially for risk-averse decision-making. In the analysis in both scenarios Guangzhou (in China) tops the list and next to Mumbai is New Orleans (in Louisiana, USA) which will face the highest risks. It was found that that among 136 coastal cities across the world, Mumbai is second-most at risk to climate-induced SLR and extreme weather events.

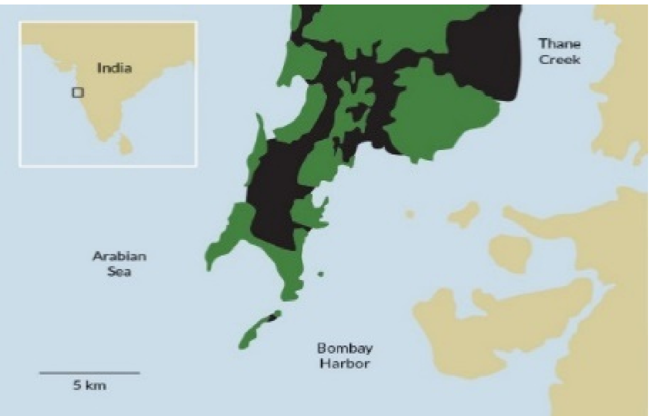

Fig. 2 The original seven islands (green) connected by reclamation (black) in Mumbai [38]

Dhiman et al. developed a systematic approach to link the critical gap between information, knowledge, data and GIS services in coastal cities [34]. They introduced an open-source Web-GIS based decision support framework stated as CMIS, to integrate data and knowledge plus GIS services for the Mumbai megacity. CMIS is developed using the open source platform supported PHP and Map Script. The three key components are – Data Centre (houses different datasets for expert stakeholders), Knowledge Centre (developed for common stakeholders), and Web-GIS based online mapping tool called CMIS Online which enables a user-friendly assessment of coastal resources. It can act as a dynamic mapping application for coastal features, incorporating advanced GIS functionalities. The authors further described the methodology for the existence and implementation of CMIS as a pilot initiative along the coastline. Such initiative can strengthen the institutional framework between associated government agencies, coastal planners, managers, and researchers. The study stimulated the employment of open source coupled GIS techniques, which might enhance the transparency within the allocations and utilization of coastal resources among various end users, and thereby the developed framework can curtail over-exploitation of resources to some extent and could aid the progression towards a more sustainable and resilient urban environment.

Garner et al. stated that as because projections of SLR from individual studies varies from and rather generally higher than upper projections, anticipated by the Intergovernmental Panel on Climate Change, in reality very often future SLR remains deeply uncertain and the upper projection windows for the SLR projections are not uniform across different studies. They distrusted the correctness of the research outputs. The widely varying range of these projections reflected gaps in scientific knowledge about the processes that contribute to SLR, reflected in assumptions used to produce projections [36]. Many projections for high emission scenarios from individual studies were found much greater than likely range of 1m of the 21st century SLR given in AR5 [35]. Moreover, due to the additional load from melt ice the SLR is escalating in recent years.

III. CONCLUSION

From the facts in the foregoing, it can be concluded that thorough research in this field it is necessary to ascertain CVI of coastal places including that in Mumbai.

The processes responsible for the monthly and seasonal variation in the morphology of a beach are controlled by wave, climate, tide and sediment characteristics [3]. In a study for impact of climate change on flood risk in Mumbai it is suggested the likelihood of a 2005-like event with 0.5 m to 1.5 m deep waterlogging in low-lying areas would be more than double by 2080 [6]. Neural Network also was used to conform future changes predicted by Numerical Model at places [29] for shoreline changes [26]. Morphodynamic Investigation along the Maharashtra Coast by running Delft 3D model (when corroborated with INCOIS & IHO), underestimated the net sediment transport and overestimated the total one [31]. For accommodating different risk tolerances under different scenarios, the climate simulator model prescribed by IPCC AR5 (Special Report on Emission Scenarios) at local level [37] reveals that under RCP 8.5 SLR at Mumbai coast is 1.24 m, under RCP 4.5 is 0.94 m whereas under RCP 2.6 with aggressive cuts in the carbon pollution, SLR reduces to be around 0.81 m above MSL (Fig. 3).

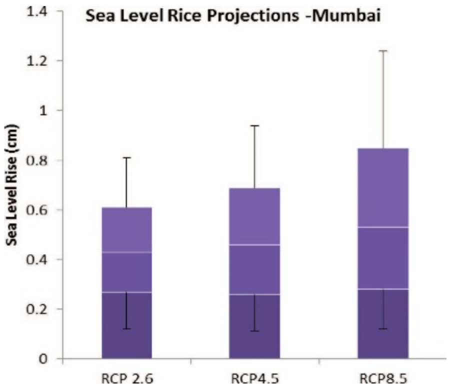

Fig. 3 SLR vis-a-vis Scenarios (Mumbai) [37]

It has been seen that in the later part of the last decade use of Remote Sensing, GIS, Satellite image mapping and computerized models gained more acceptance. It is generally believed that the correctness of the result largely depends on the model chosen for analysis. It is also established that further full-scale dedicated research is required to project the vulnerability of Mumbai due to climate change and its resultant impact on SLR in future decades, when CMIS type tools can be of convenience. It is obvious that more research is required after watching the actual scenario, and taking note of scenario which will arise at Mumbai in future.

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Open Science Index, Marine and Environmental Sciences Vol:15, No:6, 2021 publications.waset.org/10012058.pdf